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Gamma rays from the Galactic Centre region

Rayons gamma de la région du centre galactique

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A B S T R A C T

During the last decades, increasingly precise astronomical observations of the Galactic Centre region at radio, infrared, and X-ray wavelengths laid the foundations for a detailed understanding of the high-energy astroparticle physics of this most remarkable location in the Galaxy. Recently, observations of this region in high energy (HE, 10 MeV–100 GeV) and very high energy (VHE, > 100 GeV) γ-rays added important insights into the emerging picture of the Galactic nucleus as a most violent and active region where acceleration of particles to highest energies and their transport can be studied in great detail. We review the current understanding of the γ-ray emission emanating from the Galactic Centre.

R É S U M É

Pendant les dernières décennies, la région du centre galactique a fait l'objet d'observations astronomiques de plus en plus précises en radio, en infrarouge et en rayons X, qui ont fourni les bases de l'étude des phenoménes de haute énergie à l'oeuvre dans cette partie remarquable de notre galaxie. Récemment, les observations de cette région dans le domaine des rayons gamma de haute et de très haute énergie (HE, 10 MeV–100 GeV, et VHE au-dessus de 100 GeV) ont apporté d'importantes informations, donnant du noyau galactique l'image d'une région active et violente où l'on peut étudier en détail l'accélération des particules aux très hautes énergies et leur transport. Cet article présente les interprétations actuelles des émissions gamma issues du centre galactique.

1. Introduction: the Galactic Centre environment

The innermost part of the Milky Way, including the Galactic nucleus with its multi-million solar mass black hole (BH), cannot be observed with the naked eye or with classical optical telescopes, because it is obscured by a thick layer of dust present along the Galactic Plane. It was therefore only in the 1950's that the Galactic nucleus was discovered by detection of intense radio emission from the barycentre of the Milky Way [1,2]. It is its relative proximity to Earth that makes the Galactic nucleus an ideal laboratory to study the astrophysics of galactic nuclei in general: the Galactic nucleus is located

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about 8.5 kpc (or roughly 27,000 light years) away from Earth (the distance to our neighbour galaxy Andromeda, which also hosts a supermassive BH is about 770 kpc). Today, the central Galaxy is studied in a broad range of the electromagnetic spectrum, as the Galactic dust torus is mostly transparent to low-energy (radio and far infrared) radiation as well as to high-energy photons (X-rays up to multi-TeV γ-rays).

The dynamics of the inner (roughly 300 pc in radius) region of the Galaxy is largely driven by the presence of the supermassive BH, identified with the strong radio source Sgr A* [3]. Besides the BH, there is a wealth of other interesting phenomena observed in this region, such as places where new stars are being born (star formation regions), the remnants of massive explosions of stars terminating their life (supernova remnants, SNRs), rotating neutron stars that release tremendous energy into their surroundings, thereby forming pulsar wind nebulae (PWNe), and populations of high-mass X-ray luminous binary stars (for a review, see, e.g., [4,5]). The density of the interstellar medium (ISM) is on average about an order of magnitude larger than in other parts of the Galactic disk, and the region is pervaded by strong magnetic fields, probably by far exceeding the level of 5 nT [6] (as compared to typically a few hundred pT in the Galactic disk), leading to the observation of radiation from large-scale filamentary structures.

While far-infrared (IR) emission traces sites of ongoing star formation, non-thermal radio, X-ray and γ-ray emission indicate populations of charged particles that underwent acceleration to supra-thermal energies in cosmic accelerators such as SNRs, PWNe, in the vicinity of the supermassive BH or in colliding winds driven by massive stars in star-forming regions. It is therefore clear that observing the Galactic Centre (GC) region at these photon energies gives access to a completely different view of the inner Galaxy than the one expected to be seen by an optical telescope. In this context, observation of γ-rays at energies of a few GeV and beyond are key to characterise the high-energy astrophysical phenomena at work, as they trace the most violent phenomena at place in the GC region. Since about a decade, a new generation of sensitive HE and VHE γ-ray telescopes is in place, which give unprecedented access to the various high-energy processes in the GC: the Large Area Telescope (LAT, [7], onboard the Fermi satellite) and the ground-based telescope arrays H.E.S.S. [8], MAGIC [9] and VERITAS [10] enable detailed spectral, morphological and temporal studies of Galactic and extragalactic γ-ray-emitting sources in an energy range of 20 MeV to several 10 TeV. In the GC region, several new sources of high-energy γ-ray emission have been discovered and characterised by these instruments, thereby significantly advancing our knowledge about the astrophysical phenomena taking place in this region. Still, the angular resolution of these instruments is relatively moderate compared to instruments at other wavelengths: while X-ray telescopes routinely achieve arcsecond resolution, and infrared observations with a resolution of few 10 milliarcsecond are possible, the detection of HE and VHE γ-ray telescopes currently allows for a resolution of $\sim 0.05°$–$0.2°$ only (strongly dependent on the γ-ray energy). For the GC region, this means that the smallest physical structures that can be probed are of size ~ 10 pc, limiting the direct comparison of γ-ray sources to possible counterparts observed at smaller energies via their morphology or spatial coincidence.

In this article we give an overview, based on γ-ray observations, of our current understanding of the high-energy astrophysics of the inner few 100 pc region of the Milky Way and summarise the progress made in the last years.

1.1. The Central Molecular Zone and inner 50 pc region

The first large-scale image of radio observations of the GC region is shown in Fig. 1, covering a sky area of several degrees across. The bulk of the emission is aligned with the Galactic plane and extends over about 300 pc in Galactic longitude, a region which is called the Central Molecular Zone (CMZ). The emission is largely dominated by non-thermal synchrotron radiation, suggesting that acceleration of electrons to supra-thermal energies takes place throughout the region, possibly to energies of a few 10 TeV and beyond. Within the CMZ, numerous sites of radio emission can be observed, which are at least partly connected to sites of ongoing particle acceleration. Several structures have clearly been identified as SNRs, and also the PWN inside the SNR G 0.9+0.1 is well visible. The regions denoted by Sgr B1, Sgr B2, Sgr C and Sgr D contain large concentrations of ionised or molecular material, with gas densities of more than 10^4 cm^{-3}, exceeding by far the density of clouds at other locations in the Galaxy. Several thread-like filaments, notably the GC arc, are oriented perpendicular to the Galactic plane. The Galactic nucleus itself is located within the complex radio structure Sgr A.

The molecular cloud content of the CMZ has been mapped by measuring excitation lines from different molecules, most importantly *CO* [12,13] and *CS* [14]. From these measurements, the CMZ is estimated to host about 10% of the total molecular material of the Galaxy. Based on models of gas kinematics in the inner Galaxy [15] or OH absorption measurements [16], the measured Doppler shifts of the emission lines (which encode the radial velocity of the gas with respect to the observer) have been translated into distance information. Because the interaction of cosmic ray particles with ambient gas is a source of diffuse γ-ray emission, the resulting 3-dimensional maps are an important input to study cosmic ray transport. The gas maps suggest that the bulk of the gas content is located within a line-of-sight distance of 200 pc from the GC, with the eastern part containing the Sgr B complex being located in front, and the western part behind the position of the Galactic nucleus.

The inner 50 pc region of the CMZ is dominated by the Sgr A radio complex (see Fig. 1), which can be substructured [17] into (i) the bright compact radio source Sgr A* at the dynamical centre of the Galaxy, (ii) the extended, non-thermal source Sgr A East (at a projected distance of 2.5 pc from the centre), which encloses in projection (iii) Sgr A West, a three-armed H II region (the *minispiral*) which rotates around the GC and exhibits a thermal radio spectrum. Sgr A West itself is surrounded by the so-called (iv) Circum Nuclear Disk of molecular gas of mass $\sim 10^4 M_{\odot}$. Based on X-ray [18–20] and radio [21,22] observations, Sgr A East is nowadays identified as the remnant of a supernova event that took place about

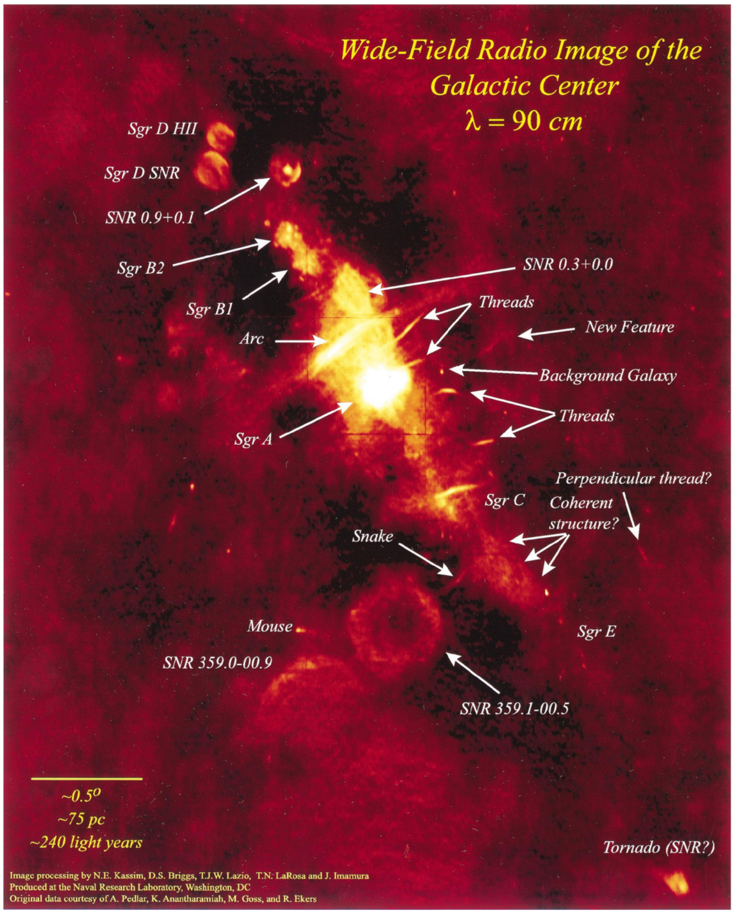

Fig. 1. (Colour online.) Large-scale compilation of 90-cm radio observations of the Galactic Centre region [11] performed by the Very Large Array. The distance scale is given on the bottom–left. The Galactic Plane is oriented top–left to bottom–right. Various SNRs and PWNe are labelled, emitting non-thermal synchrotron radiation caused by relativistic electrons. Several thread-like filaments, notably the so-called *arc*, radiate synchrotron emission as well. The Galactic nucleus itself is located inside the Sgr A complex, which is the brightest in this image. The full region, from the Sgr D molecular cloud in the east up to the radio source Sgr E in the west, has a diameter of about 300 pc and is known as the Central Molecular Zone.

10,000 years ago. Given an overabundance of heavy elements in this object, Sgr A East is probably the remains of a supernova type II explosion of a 13–20 $M_\odot$ progenitor star. This interpretation is supported by the presence of a pointlike and offset X-ray source (the so-called *cannonball*), which is assumed to be the neutron star left over from the explosion event. Sgr A East is a good candidate source for GeV and TeV γ-rays, based on the fact that (i) many Galactic SNRs are established emitters of HE and VHE γ-rays, and (ii) a rather large magnetic field of several hundred nT is in support of an efficient acceleration of relativistic particles at the shock of Sgr A East.

1.2. The Galactic supermassive black hole and its immediate vicinity

Since it is known that the dynamics of (active) galactic nuclei are largely driven by the presence of BHs in their cores, the Galactic Centre region offers the unique possibility to study in close view processes that are presumably at work in a large class of extragalactic nuclei as well (with the caveat that the energy output of the latter is typically much larger). Today, a wealth of precise astronomical observations support the idea that the bright and ultra-compact radio source Sgr A* is indeed a supermassive BH. Key to these findings are observations with modern telescopes providing intrinsic resolution up to sub-milli-arcseconds. One of the most impressive studies is the measurement of the orbits of young stars in the direct (as close as 0.1″ in projection) vicinity of Sgr A*, from which the mass of the central compact object, $M_{\mathrm{A}^*} \sim 4 \times 10^6\ M_\odot$, can be inferred with great accuracy [23–26]. The measurements have been using the infrared emission from these stars, as infrared light (contrary to visible light) can readily pass the Galactic dust torus, and hence be observed on Earth. The studies show that the stars' orbits are consistent with a purely Keplerian motion around a point mass centred on the Sgr A* radio position. At a wavelength of 7 mm, observations have resolved the size of the radio emission region to 24 ± 2 Schwarzschild radii [27]. Combining these findings, there is not much doubt that Sgr A* can only be a supermassive BH.

While being relatively bright at radio wavelengths, Sgr A* is only a faint X-ray emitter [28], but shows bright outbursts on time scales of a few minutes to several hours [29–32]. From causality arguments, these short flare durations limit the size of the emission region to less than 10 BH Schwarzschild radii. Non-thermal processes near the event horizon might produce relativistic electrons and thus explain the X-ray short-time variability (e.g., [33–35]). To a certain extent, flares in the near-infrared band are predicted by these models, and such flares have been observed [36]. Observations in the hard X-ray/soft γ-ray band by the INTEGRAL instrument, on the contrary, show a faint, but steady emission from the direction of the GC [37].

Overall, Sgr A* is currently in a rather low state of emission, since its bolometric luminosity is only at a fraction of 10^{-8} of that maximally allowed for a $10^6\ M_\odot$ BH. It is suggested that the BH is currently accreting only a moderate amount of gas from the winds of massive young stars populating the inner ∼1 pc region [38]. This does not exclude that the GC was much more active in the past: indeed, there is evidence of recent (∼100 years ago) activity deduced from the presence of X-ray reflection nebulae [39–41] in nearby molecular clouds, and even of times of much longer activity during the last 10^7 years, as suggested by the presence of giant outflows from the GC region (e.g., [42]).

2. A gamma-ray point source at the barycentre of the Milky Way

Given the importance of the GC as a possible multi-TeV particle accelerator, the region has always been a prime target for HE and VHE instruments. Observations of γ-ray emission from the inner Galaxy date back to the COS-B [43,44] and SAS-2 [45] instruments, launched in the 1970's and 1980's, respectively (see, e.g., [46] for a review). These instruments, with degree-scale angular resolution, provided among others the first γ-ray map of the Galaxy. In the 1990's, the EGRET experiment aboard the Compton Gamma-Ray Observatory extended observations to energies of up to 30 GeV, i.e. to the high-energy side of the π^0 bump [47,48]. Nowadays, the Fermi-LAT (launched in June 2008, see [49] for a review) provides greatly improved data up to energies of ∼100 GeV, with sufficient angular resolution and sensitivity to map out interesting γ-ray structures [7].

At even larger energies, from ∼100 GeV up to several 10 TeV, ground-based Imaging Atmospheric Cherenkov Telescopes [50] provide the best sensitivity to observe the γ-ray sky. The Galactic Centre region was in the focus of these instruments since the successful start of operation of the Whipple telescope in 1968. It took, however, until 2004 that a point-like VHE γ-ray signal from the GC was detected by the three instruments Whipple, H.E.S.S. and Cangaroo-II almost simultaneously [51–53] (and only a few months later by MAGIC [54]), thereby finally proving that particle acceleration to at least several 10 TeV of energy is taking place at the centre of the Milky Way.

Since that time, the GC keeps staying in the focus of all major ground-based γ-ray instruments. Due to its location in the southern hemisphere, the H.E.S.S. instrument has currently the best view onto the region, as it can observe the GC in culmination close to the zenith. H.E.S.S. phase-I observations of HESS J1745-290 therefore cover a large range of photon energies (from an energy threshold of ∼200 GeV up to the largest energies at ∼30 TeV), making the data well suited for spectral studies. Based on about 100 hours of observations taken during the years 2004–2006, it was found that the photon flux per unit of γ-ray energy can be described by a modified power-law in the γ-ray energy E_γ

$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \sim \left(\frac{E_\gamma}{1\ \mathrm{TeV}}\right)^{-\Gamma} \mathrm{e}^{-\frac{E_\gamma}{E_\mathrm{c}}}$$

with a (hard) spectral index $\Gamma = 2.10 \pm 0.04$, and a break-down in the spectrum towards largest energies, characterised by an exponential cut-off at a photon energy of $E_\mathrm{c} = (14.70 \pm 3.41)$ TeV [55]. The power-law form of the spectrum is consistent with the idea that the emission is produced by relativistic particles that underwent Fermi-type acceleration in an astrophysical particle accelerator, and the break-down of the spectrum might be caused by either an absorption of high-energy photons close to the source (due to scattering off the infrared photon field) or by limited acceleration capabilities of the accelerator. A recent (yet preliminary) update of the H.E.S.S. flux spectrum [56] suggests that the cut-off moves to lower values, $E_\mathrm{c} \sim 7$ TeV, when correcting the source spectrum for contamination by underlying diffuse γ-ray emission.

At GeV energies, the γ-ray map of the inner Galaxy is dominated by diffuse emission, making the detection and characterisation of individual sources much more difficult than at TeV energies. The reason is that the energy spectrum of the Galactic diffuse emission falls off much more steeply than the spectra of typical Galactic γ-ray sources when energy increases. Hence, diffuse emission plays only a minor role at TeV energies, whereas at GeV energies a careful modelling of this component is almost always unavoidable. Especially towards the very centre of the Milky Way, systematic uncertainties on the spectrum and morphology of the diffuse component are large, complicating detailed studies of the GC GeV emission.

Nevertheless do observations at GeV energies provide a wealth of valuable data to study the astrophysics of the GC. Recently, [57] reported the Fermi-LAT detection of a hard-spectrum HE γ-ray source coincident with the position of the VHE source HESS J1745-290. The authors extracted the γ-ray spectrum of this source (named 2FGL J1745.6-2858 in the 2nd source catalog of Fermi-LAT sources [58]) in the energy range 0.3–100 GeV by performing a global fit to the γ-ray count map (including a model of diffuse emission as well as known point sources). The spectrum of 2FGL J1745.6-2858 is best described by a broken power law with spectral indexes $\Gamma = 2.20 \pm 0.04$ and $\Gamma = 2.68 \pm 0.05$ below and above, respectively, a break energy of $E_\mathrm{b} = 2$ GeV. No hint for flux variability is found. Although the flux spectrum at its high energy end is

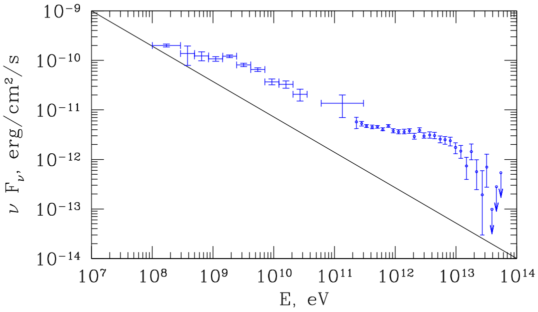

Fig. 2. Spectral energy distribution of the HE and VHE γ-ray emission from the direction of the GC. Data points up to an energy of ∼100 GeV are those of the Fermi-LAT source 2FGL J1745.6-2858 [57], and data points above that energy are from H.E.S.S. [55]. Despite known caveats in flux extraction such as different flux integration regions due to different angular resolutions of the instruments, the energy spectra match well, suggesting a common origin of the emission.
Figure after [57].

significantly steeper than that of HESS J1745-290, the spectra of the two sources connect well (see Fig. 2), suggesting a possible common production mechanism of the HE and VHE emission.

2.1. The nature of the central particle accelerator

Despite the wealth of data from radio wavelengths to γ-ray energies, a mechanism that naturally explains the total emission from the GC in terms of a single source is not (yet) identified. While it seems clear that emission at infrared and X-ray energies is mostly connected to the accretion of matter onto the BH, a firm identification of the HE and VHE emission with Sgr A* is experimentally hampered by the – compared to radio or X-ray instruments – modest angular resolution of the current generation of γ-ray instruments, giving rise to source confusion in this densely populated part of the Galaxy. In particular, it is not clear whether or not the γ-ray emission observed by Fermi-LAT and ground-based Cherenkov instruments is produced by the same astrophysical object, and how the high-energy photons might be connected to phenomena observed at smaller energies.

Detection of flux variability in the γ-ray lightcurves would be a strong indication that the γ-ray production happens in the vicinity of Sgr A*. The most convincing signature would be the discovery of correlated flaring in X-rays (or near IR) and VHE/HE γ-rays. Such searches have been carried out. In a coordinated multi-wavelength campaign [59], Sgr A* was targeted both by the Chandra satellite and the H.E.S.S. instrument. A major outburst with a factor-9 increase in the X-ray flux was detected from the direction of Sgr A*. However, the VHE γ-ray flux stayed constant, and a doubling of the VHE flux was excluded at 99% CL. Further long-term searches for γ-ray variability have been carried out by the VERITAS collaboration [60], also with negative results.

Although an association of the γ-ray emission with Sgr A* is compelling, there are at least two other objects in direct vicinity of the BH (and well within the angular resolutions of the instruments) which may explain the observed γ-ray signal in parts or in total: the SNR Sgr A East and the PWN G359.95-0.04 [61]. Alternatively, the signal could also be produced by cumulative emission of many sources, such as a large population of millisecond pulsars at the GC [62].

The presence of relativistic electrons in its remnant (as observed by synchrotron radiation) and a large magnetic field make the SNR Sgr A East an excellent candidate γ-ray emitter. Besides, Sgr A East is in contact with dense molecular material, providing a target for protons that might have undergone Fermi acceleration in the shock fronts of the remnant (see [63] for a review on γ-ray SNRs). For a 400-nG magnetic field, the estimated maximum energy to which protons can get accelerated is $\sim 10^{19}$ eV [64], supporting the idea that VHE emission could possibly be observable from this source. At least for the VHE source HESS J1745-290, this seems, however, difficult to reconcile with the experimental finding that the centroid of the point-like emission is not centred on the radio shell of Sgr A East where the most intense synchrotron radiation is produced, but rather directly on the position of Sgr A* (Fig. 3). As the radio shell surrounds Sgr A* in projection, the hypothesis that Sgr A East is the bulk producer of the VHE γ-ray emission can be ruled out at a level of almost four standard deviations. No such strong conclusion can be drawn for the HE emission yet, since photon statistics is small compared to the VHE data set and the underlying diffuse γ-ray emission introduces systematic errors on the centroid position of the emission.

As an alternative to Sgr A East, the X-ray-faint PWN G359.95-0.04 may be capable of delivering the bulk emission of HESS J1745-290. Even though the vicinity of this object is pervaded by large magnetic fields, giving rise to strong synchrotron cooling of the electrons accelerated in the nebula, it is suggested that the stellar radiation fields in the central parsec around the GC provide enough photon density that even a small amount of relativistic electrons is enough to provide the observed TeV luminosity of HESS J1745-290 in the form of inverse Compton emission [68]. Since the PWN is located only 8.7″ in projection away from Sgr A* (see Fig. 3), its contribution to HESS J1745-290 cannot be disproven by positional arguments. However, inverse Compton emission cannot account for the γ-ray flux observed at MeV and GeV energies, as the typical spectral shape of inverse Compton emission shows a pronounced peak-like structure rather than a power-law

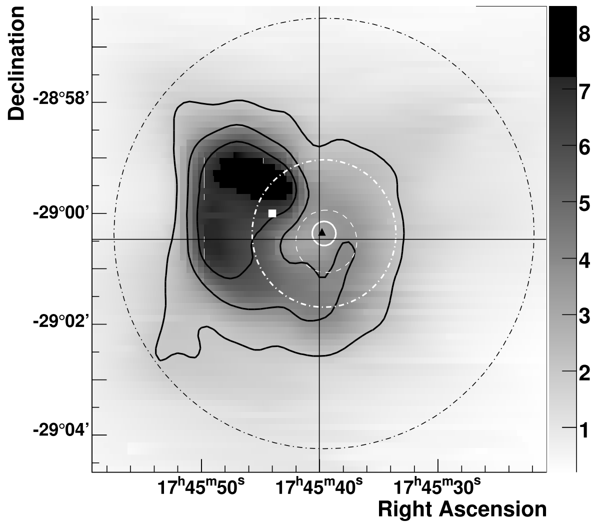

Fig. 3. Radio flux density map of the innermost 20 pc of the GC, showing synchrotron emission from the SNR Sgr A East. The centre of the SNR [65] is marked by the white square, and the positions of Sgr A* [66] and G395.95-0.04 [61] are given by the cross hairs and the black triangle, respectively. Despite the fact that the angular resolution of the VHE data set (black dashed–dotted contour) is poor compared to the radio data, the centroid of the VHE emission can be measured quite accurately (white solid contour). The while dashed–dotted circle denotes the 95% CL upper limit the VHE γ-ray source extension. Figure from [67].

shape that extends over four orders of magnitude in energy (cf. Fig. 2). Therefore, if indeed both HESS J1745-290 and 2FGL J1745.6-2858 are driven by the same emission mechanism, a PWN scenario is likely excluded [57].

Despite the absence of variability in the γ-ray lightcurves, a multitude of models is put forward to explain the observed HE and VHE emission from the GC in the context of particle acceleration close to Sgr A*. Due to its low bolometric luminosity, the photon density in the immediate vicinity of the BH is considered low enough that high-energy photons do not get absorbed by pair production processes. As such, the vicinity of the BH becomes essentially transparent to high-energy γ-rays, and photons with energies of up to several TeV are expected to escape a region as small as several Schwarzschild radii around the BH almost unabsorbed [34], making HE and VHE γ-rays a unique probe for particle acceleration and radiation processes close to the BH surface. The experimental data collected by Fermi-LAT and the ground-based Cherenkov telescopes can be confronted with model predictions such as the proposed energy flux distribution of the photons, their spatial morphology and predicted temporal variability.

Models in which the γ-ray production happens close to the BH surface include [34] acceleration of ultrarelativistic protons by strong magnetic fields in the vicinity of the BH and their interaction with the IR radiation field or surrounding plasma. As an alternative, electrons might get accelerated; this scenario, however, requires well-ordered magnetic or electric fields to prevent radiation losses during the acceleration process. All models, in which the γ-ray production happens close to the BH, predict to some extent correlated X-ray/γ-ray variability. An acceleration scenario with two different electron populations [57] can in principle account for both the observed HE and VHE γ-ray spectra, while other models underestimate the HE γ-ray flux.

Alternatively, γ-ray production might happen within a ∼10 pc zone around the BH due to the interaction of run-away protons with the ambient medium [69–72,57,73,74]. The protons are either injected continuously into the medium or impulsively during an event of sudden increase in accretion onto Sgr A*. Due to the relatively large time (compared to typical flare durations) that the particles need to diffuse out of the central BH region, this scenario naturally explains the absence of significant variability in the HE and VHE data. The complicated transition from the HE to the VHE part of the γ-ray spectrum (Fig. 2) can be accounted for by energy-dependent diffusion time scales and/or different scattering zones where the proton–proton interactions take place.

The absence of γ-ray variability can also be explained by electrons being accelerated in termination shocks driven by strong winds from the BH [75] or being injected into the vicinity of Sgr A*, where they produce the observed infrared and X-ray flares by synchrotron radiation, and from which they eventually escape [76]. In these scenarios the production of γ-rays happens via the inverse Compton process. Because of the bump-like spectral shape of the γ-rays produced in this process, these scenarios cannot easily account for the HE and VHE emission at the same time. Emission across the entire energy range can be explained by hybrid models, in which a mix of relativistic protons and electrons are accelerated during an event of suddenly increased accretion [77]. By diffusion processes, the protons and electrons move away from the vicinity of the BH and interact with surrounding gas or radiation fields, respectively.

Due to the fact that the angular resolution of γ-ray instruments covers a region of several pc diameter at the GC distance, the observed γ-ray emission could in principle stem from a combination of multiple emitters (like, e.g., the discrete objects presented above). In particular, as was argued recently [62], the emission might be explained by the cumulative effort of

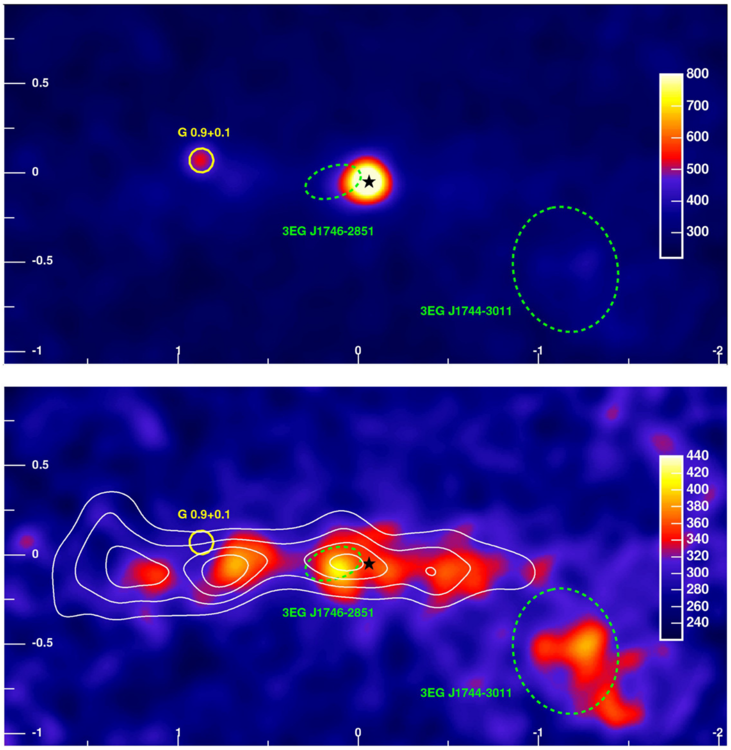

Fig. 4. (Colour online.) H.E.S.S. VHE γ-ray images of the Galactic Centre region [79]. Top: smoothed γ-ray count map (above a γ-ray energy of 380 GeV, without background subtraction) showing emission from the GC point source HESS J1745-290 and the SNR/PWN G0.9+0.1. The position of Sgr A* is marked by the black star. Bottom: same map after subtraction of the two (assumed point-like) sources, showing an extended band of highly significant γ-ray emission and the unidentified source HESS J1745-303 (south–west of Sgr A*). The white contours show velocity integrated CS line emission [14], smoothed to match the angular resolution of the γ-ray measurement. The positions of two unidentified EGRET sources are shown by green ellipses.

a few thousand millisecond pulsars (MSPs) in the central star cluster surrounding Sgr A*. While it is not clear whether or not such a population of MSPs is indeed present within the central pc of the GC, globular clusters contain a large number of these objects and are established GeV γ-ray emitters [78]. In the model proposed by [62], the MSP population at the GC could be the result of a past merger of globular clusters, and the HE and VHE emission due to the MSPs themselves and inverse-Compton scattered electrons accelerated in the wind regions of the MSPs. As the total emission is resulting from a large number of different sources spread over a pc size region, no variability is expected in this scenario.

3. The Central Molecular Zone in VHE γ-ray light

Whilst the early detections of the GC at VHE energies were based on data sets of limited statistics and/or high energy threshold, and concentrated on studying the properties of the GC point source, follow-up observations provide a much more detailed picture of the central region, and especially of the CMZ. Both the VERITAS and H.E.S.S. collaborations have published such VHE γ-ray maps of the region, the most detailed one being based on 49 h of GC observations conducted with the H.E.S.S. array in the year 2004 [79].

Fig. 4 (top) displays the (smoothed) γ-ray count map above an energy of 380 GeV. It shows, besides the already discussed GC point source HESS J1745-290, another discrete source ∼1° to the east of Sgr A*, positionally coincident with G0.9+0.1, a well-known [80] composite SNR with a clear shell-like radio morphology (Fig. 1) and a compact core. X-ray studies of G0.9+0.1 [81,82] have identified the radio core as a pulsar wind nebula. This notion is supported by the recent discovery of a highly energetic pulsar (PSR J1747-2809) in the centre of the SNR [83] (it should, however, be noted that PSR J1747-2809 is possibly located well behind the GC, at a distance of ∼13 kpc, although a location at the GC cannot be excluded). The morphology of the VHE γ-ray emission is compatible with a point source centred on the PWN position, excluding a large contribution from the extended shell of the SNR [84]. The γ-ray spectrum extends up to an energy of 6 TeV and is best described by a power-law, $\mathrm{d}N_\gamma/\mathrm{d}E_\gamma \sim E_\gamma^{-\Gamma}$, with a spectral index of $\Gamma = 2.40$, which is typical for PWNe and Galactic γ-ray sources in general.

When subtracting the emission from both HESS J1745-290 and G0.9+0.1 from the γ-ray count map, a band of diffuse γ-ray emission along the Galactic Plane gets visible, extending across the entire CMZ (Fig. 4, bottom). Another region of extended γ-ray emission, denoted HESS J1745-303 [85], emerges about 1.4° south–west of Sgr A*, which, despite detailed multi-wavelength studies [86,87], lacks solid identification: the morphology suggests that the emission might be produced by several objects, among them the shell of the SNR G359.1-0.5 (easily recognised in the radio image, see Fig. 1). Southern parts of the VHE emission might be produced by the nebulae of one or two energetic pulsars [86]. An analysis of Fermi-LAT data of this region [57,88] shows extended emission, too, with an energy spectrum that connects well to the VHE flux found for the northern part of HESS J1745-303. A firm association between the HE and the VHE γ-ray sources is hampered by the fact that the angular resolution is poor and no clear alignment of the HE emission with one of the VHE source components is observed.

3.1. TeV diffuse emission along the GC ridge

The extended band of VHE γ-ray emission in the CMZ (Fig. 4, bottom) provides important insights into an understanding of the large-scale high-energy astroparticle physics processes at work in this region. The emission spans a region of roughly 300×30 pc^2. As can be seen in Fig. 4, the morphology of the γ-ray emission is very similar to that of the giant molecular clouds present in the CMZ (at least within the inner 1° region). This suggests that the emission is very likely produced by the interaction of relativistic protons with the molecular material. The γ-ray spectrum of the emission is well described by a (hard) power law with spectral index $\Gamma \sim 2.3$.

Cosmic ray protons from the Galaxy-at-large cannot account for the observed emission, since the measured γ-ray flux is both larger and harder than expected if the molecular material was bathed in a sea of cosmic-ray protons that already propagated through the entire Galactic disk. This strongly suggests the presence of one or more proton accelerators close to the CMZ, such that cosmic ray propagation effects that lead to spectral steepening do not play a significant role. Given the similarity between the spectral indexes of the γ-ray spectra of HESS J1745-290 and the surrounding diffuse emission, it is tempting to explain the diffuse γ-ray morphology by the interaction of high-energetic protons stemming from the same acceleration process that is ultimately responsible for the emission of HESS J1745-290. Protons might then escape from the acceleration region and penetrate the surrounding medium, giving rise to the diffuse emission. This standard scenario, brought up by the H.E.S.S. collaboration [79], has been investigated (and challenged) by a large number of different studies, mostly in the context of diffusion processes in the central 10 pc region and within the turbulent CMZ magnetic field.

In the context of identifying the accelerator, the fact that the emission concentrates on a 1° region around the GC, while the molecular cloud environment extends further out, is particularly interesting. A simple explanation could be that the cosmic ray protons were accelerated by an object close to the GC such as Sgr A*or Sgr A East. The protons then diffused away from the accelerator into the CMZ. If the protons were accelerated only recently, they may not have had enough time to reach the outer parts of CMZ, which would result in the observed lack of VHE emission in these parts. Adopting diffusion time scales typical for TeV cosmic rays in the Galactic disk, an accelerator of age $\sim 10^4$ years can reproduce the observed γ-ray morphology, and in particular the lack of emission beyond 1° distance from the centre. From the γ-ray spectrum, the energy needed to fill the entire region with energetic protons can be estimated to be $\sim 10^{43}$ J above an energy of 1 GeV. The value is close to the energy transferred into cosmic rays in a typical galactic supernova event. While this simple estimate is no proof that it is indeed a supernova remnant that accelerated protons to multi-TeV energies, it seems at least plausible that a single accelerator can in principle account for the particle population in total.

The question of whether or not this simple proton diffusion picture holds in the turbulent magnetic fields of the CMZ can be addressed in simulations, in which individual protons are propagated through the field. This method was used, e.g., by [89], who showed that for realistic magnetic fields of 1–10 nT relativistic protons injected at the inner GC cannot diffuse out to distance scales of a degree, since they scatter with the ambient medium (and get lost) on much smaller scales. Hence, the idea that a central accelerator is responsible for the observed diffuse γ-ray morphology appears difficult to realise. Using the same arguments, this also holds for a collection of individual particle accelerators distributed along the CMZ, which would produce a γ-ray map with much more compact emission close to the position of these accelerators. A feasible way might be stochastic acceleration of protons throughout the inter-cloud medium, an idea that was followed up by various authors [89–92], with the result that stochastic acceleration should in general allow proton acceleration to multi-TeV energies in this region. Still, it remains an open question how the relativistic particles get injected into the intercloud medium in the first place.

4. The Fermi bubbles

While the GC is currently in a phase of relative quiescence, observations at infrared wavelengths reveal evidence for past activities towards the inner Galaxy. Infrared observations with the *Midcourse Space Experiment* combined with *IRAS* data confirms the existence of a limb-brightened bipolar structure, the so-called Galactic Centre lobe (GCL), with origin at the GC on the *degree* scale [94]. More evidence of past Galactic Centre activities have been found in X-ray. Fe Kα echoes from molecular clouds around Sgr A* have been understood as relics of activity in the past few hundred years [95,96]. On a longer timescale, one might expect relics of past activity in high-energy cosmic rays (CRs) and hot gas, perhaps far off the disk. The most obvious observables signing the presence of electron CR are their microwave synchrotron radiation, gamma rays produced by inverse Compton scattering, as well as their thermal emission (X rays).

Electron CRs at 10–100 GeV primarily lose energy in the diffuse interstellar medium (ISM) by (1) emitting microwave synchrotron radiation through interaction with the Galactic magnetic field, and (2) inverse-Compton (IC) scattering on the interstellar radiation field (ISRF), producing gamma rays. The total energy loss rate due to synchrotron is proportional to the

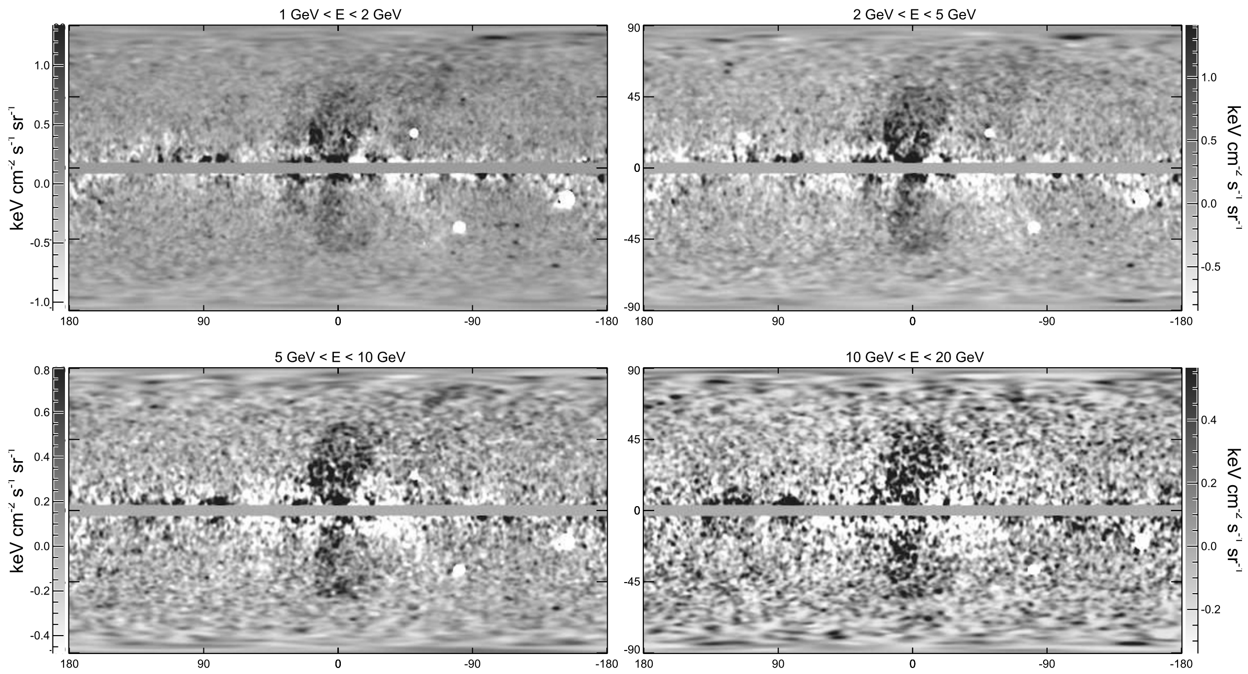

Fig. 5. All-sky residual maps after subtracting the *Fermi* diffuse Galactic model from the LAT 1.6 year maps in 4 energy bins. Two bubble structures extending to $b \pm 50°$ appear above and below the GC, symmetric about the Galactic plane.
Figure from [93].

magnetic field energy density, $U_B = B^2/(2\mu_0)$; IC losses are proportional to the ISRF energy density, U_{ISRF}, in the Thomson limit (low electron energy), and less in the Klein–Nishina regime where the product of the initial electron and photon energies becomes comparable to the electron mass squared. The electron CRs also lose energy via bremsstrahlung (free–free emission) interactions with the ambient ionized gas, but this is expected to be sub-dominant in the regions of interest.

Indeed, microwave observations also provide intriguing indications of energy release toward the GC. At tens of GHz, the *Wilkinson Microwave Anisotropy Probe* (*WMAP*) provides sensitive degree resolution full sky maps of diffuse microwave emission. By subtracting templates including Galactic Hα (tracer of Galactic free–free emission), soft synchrotron (traced by 408 MHz radio observations [97]), and thermal dust emission (the Schleger–Finkbeiner–Davis (SFD) dust map based on 100 μm far IR data [98]) to remove the different known emission mechanisms in these maps, a microwave residual excess (named "the microwave haze") with spherical (non-disklike) morphology about ∼4 kpc in radius toward the GC (visible up to at least $|b| \approx 30°$) has been recognized [99]. It has a spectrum of about $I_\nu \sim \nu^{-0.5}$, harder than a typical synchrotron, but softer than free–free. The microwave haze was later interpreted as synchrotron emission from a hard spectrum of e^- cosmic rays. Other hypotheses such as free–free, spinning dust, or thermal dust have failed to explain its morphology, spectrum, or both [100,101]. If the *WMAP* haze is synchrotron radiation from a hard electron population located around the GC, the same CRs would also produce IC scattered gammas, allowing an independent probe of the electron CR population. IC photons would provide valuable complementary information about the spatial distribution of the e^- CR (given a model for the ISRF), which in turn can constrain hypotheses about their origin. The unprecedented angular resolution and sensitivity of *Fermi*-LAT allows us to probe the γ-ray counterpart to the microwave haze in detail for the first time.

Two giant γ-ray bubbles strongly correlated with the *WMAP* haze structure have been found and named the *Fermi* bubbles [93] (shown in Fig. 5). This structure extends 50 degrees above and below the GC, with a width of about 40 degrees in longitude. These two "bubble"-like structures have relatively sharp edges and are symmetric with respect to the galactic plane and the minor axis of the galactic disk. The γ-ray signal reveals similar morphology to the *WMAP* haze (the comparison is shown in Fig. 6), and is also suggestive of a common origin with features in the *ROSAT* X-ray maps at 1.5 keV towards the GC [93]. The sharp edges, bilobular shape, and apparent centering on the GC of these structures suggest that they were created by some large episode of energy injection in the GC region, such as a past accretion onto the central black hole, or a nuclear starburst in the last ∼10 Myr. It is well known that the GC hosts a massive black hole and massive clusters of recently formed stars [102]. Either of these could potentially provide the necessary energy injection by driving large-scale galactic winds or producing energetic jets.

4.1. Multiwavelength observations

The *Fermi* bubbles seem most likely to be originated from IC scattering of high-energy CR electrons. The required electron CR population can also naturally generate the *WMAP* haze as a synchrotron counterpart. The *ROSAT* X-ray mea-

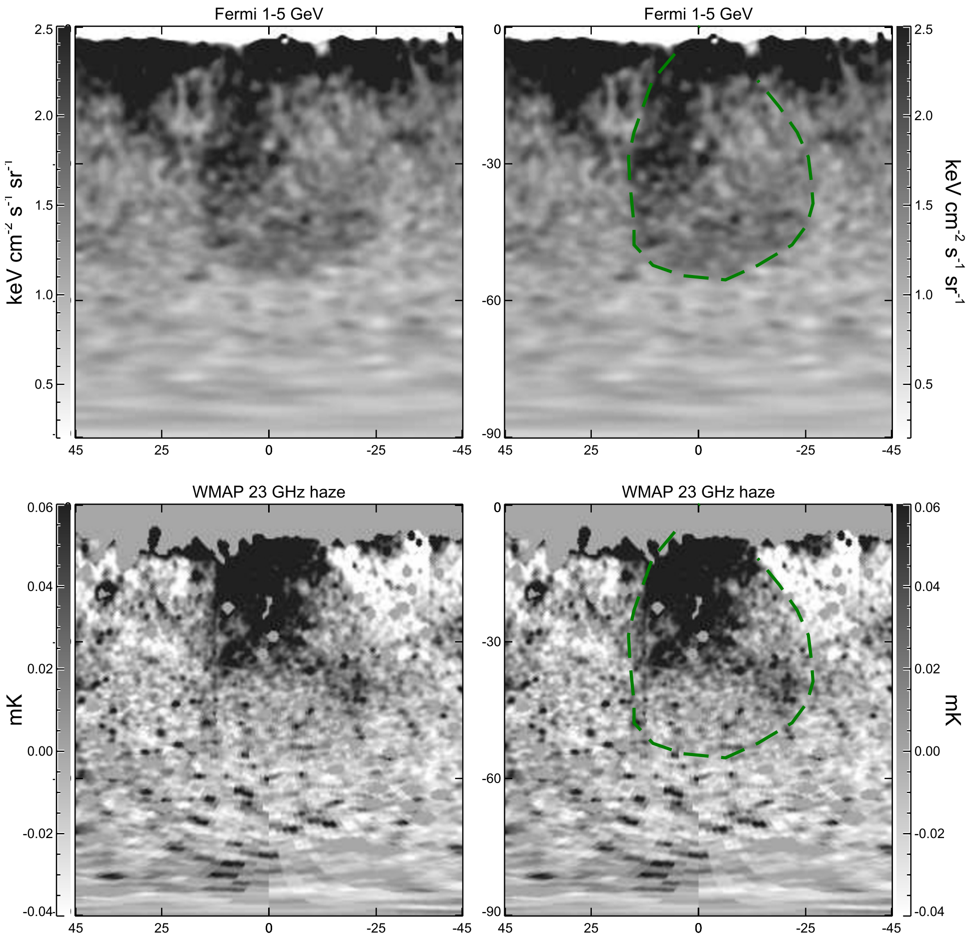

Fig. 6. The *Fermi* bubbles at 1–5 GeV (the residual map obtained by subtracting the Schleger–Finkbeiner–Davis map of Galactic dust, based on 100 μm far IR data [98] and the disk template) compared with the *WMAP* K-band (23 GHz) haze [101]. *Top row:* The 1–5 GeV map with $\ell = [-45°, 45°]$ and $b = [-90°, 0°]$ (*left* panel) with the *Fermi* south bubble edge overplotted in green dashed line (*right* panel). *Bottom row:* Same sky region as *top row* but displaying the *WMAP* haze at 23 GHz (*left* panel), with the *Fermi* south bubble edge overplotted in green dashed line (*right* panel).
Figure from [93].

surements suggest that the bubbles are hot and *underdense* regions, and thus argue against the gamma rays originating from bremsstrahlung or π^0 decay. The π^0 and bremsstrahlung γ-ray emission both scaling as the CR density and the gas density, an underdense region cannot be brighter unless the cosmic ray densities are greatly increased to compensate. Furthermore, the propagation lengths of CR protons are much larger compared to the sharp bubble edges observed in the γ-ray data, if the bubbles are in a steady state. However, if the bubbles are expanding rapidly and highly accelerated protons responsible for the γ-ray emission are trapped behind shock fronts, then sharp edges for the *Fermi* bubbles could occur naturally. But in the presence of such a shock, electrons would also be accelerated, and would generally produce more γ-rays than the protons via IC scattering (since the cooling time for electron CRs is much shorter than the cooling time for proton CRs of comparable energy). Therefore electrons are more likely to be the origin of the gamma-ray emissions from the *Fermi* bubbles.

The *Fermi* bubble features do *not* appear to be associated with *Loop I*, a giant radio loop spanning over 100 degrees, which is thought to be generated from the local *Sco-Cen* OB association. Detections of *Loop I* in high-energy γ-rays have been claimed by [103] and also recently by *Fermi* [104]. The *Fermi* bubbles are morphologically and spectrally distinct from both the π^0 emission and the IC and bremsstrahlung emission from the disk electrons. The bubbles have a distinctly hard spectrum, $dN_\gamma/dE \sim E^{-2}$, with no evidence of spatial variation across the bubbles. As shown in Fig. 7, an electron population with $dN_e/dE \sim E^{-2-2.5}$ is required to produce the γ-ray spectrum by IC scattering: this is comparable to the spectrum of electrons accelerated by supernova shocks or polar cap acceleration of pulsars [105]. The facts strongly suggest that a distinct electron component with a harder spectrum than the steady-state Galactic cosmic ray electrons is responsible for the *Fermi* bubbles and associated signals in microwave and X-ray.

How could the electron CRs possess the same hard spectrum everywhere within the bubble and extend up to 10 kpc, while experiencing a steep fall-off at the bubble edge? A large population of CRs might be entrained in large-scale Galac-

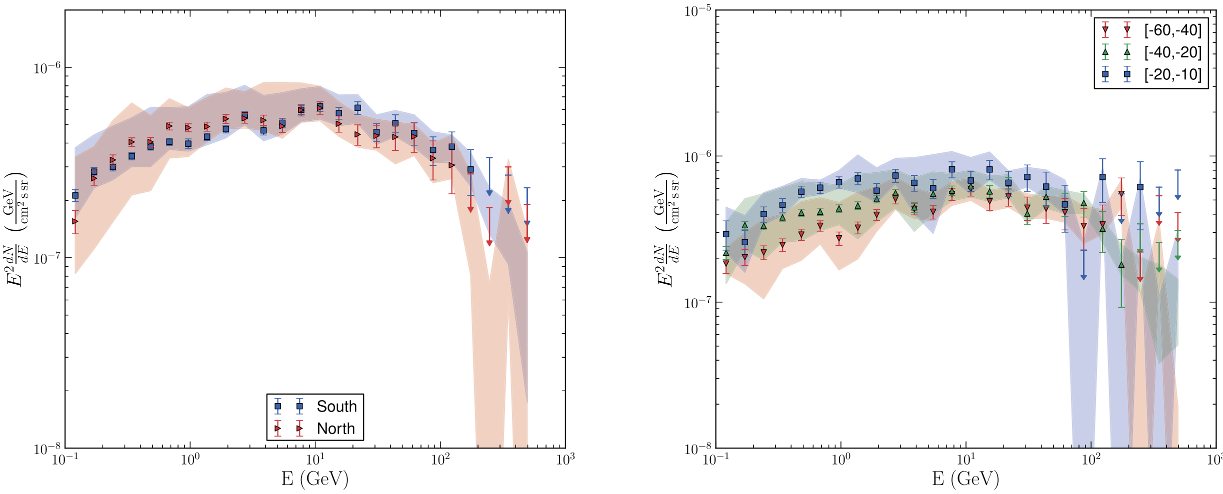

Fig. 7. (Colour online.) The left panel shows the SED for the northern and southern bubbles from the Fermi-LAT data. The points with statistical error bars correspond to the baseline SED. The bands represent an envelope of the SEDs for different derivations of the Galactic foreground emission and the definitions of the template of the bubbles. The right panel shows the SED of the southern *Fermi* bubble in latitude strips.
Figure from [106].

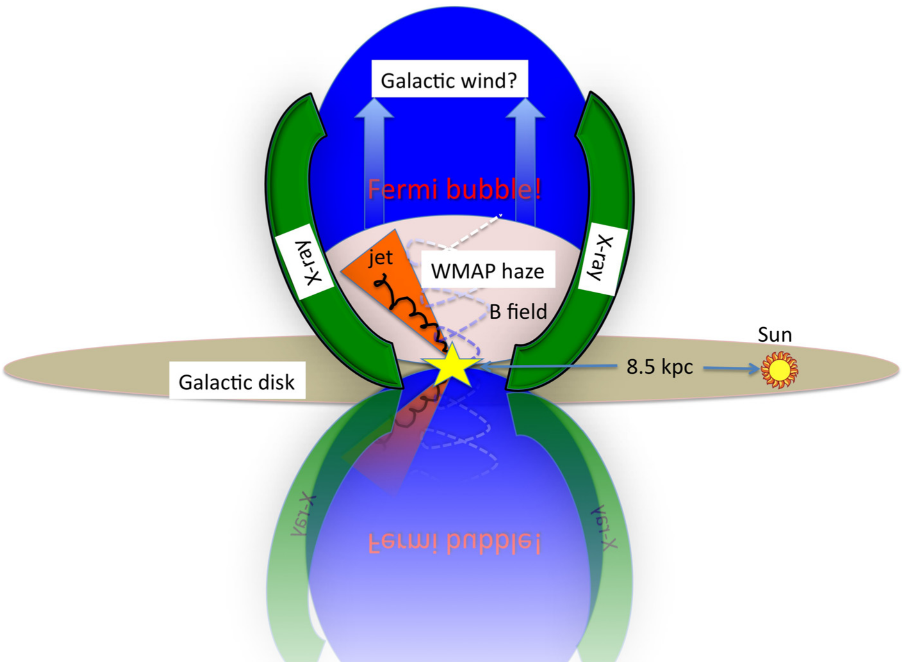

Fig. 8. (Colour online.) A cartoon picture to summarize the observations of the *Fermi* bubble structures. Two blue bubbles symmetric to the Galactic disk indicate the geometry of the γ-ray bubbles observed by the *Fermi*-LAT. Morphologically, we see corresponding features in *ROSAT* soft X-ray maps, shown as green arcs embracing the bubbles. The *WMAP* haze shares the same edges as the *Fermi* bubbles (the pink egg inside the blue bubbles) with smaller extension in latitude. These related structures may have the same physical origin: past AGN activities or a nuclear starburst in the GC (the yellow star) [93].

tic outflows from the GC and enrich the bubbles. CRs could be produced along with jets, or shock accelerated CRs from magnetic reconnection inside the bubble or near its surface. However, it is challenging to produce a flat intensity profile for the bubble interior with a sharp edge. The ambient gas should be compressed to a higher density on the shell by shocks (probably also enhancing the magnetic field), and brighter synchrotron emission on the shell would then be expected, but the haze emission observed in *WMAP* is not limb-brightened and shows no evidence of a shell of finite thickness (although we do see shell structure in the X-rays). A cartoon picture summarizing the morphology of the *Fermi* bubbles and associated signals at other wavelengths is shown in Fig. 8.

4.2. The interpretation of this unexpected structure

The *Fermi* bubble structures were likely created by some large episode of energy injection in the GC region, such as a past accretion event onto the central massive black hole, or a nuclear starburst in the last $\sim$10 Myr. However, there are shortcomings in each scenario; it seems likely that either significant modifications to one of these ideas, or some combination of different mechanisms, will be necessary. Jets originating from AGN activity can potentially accelerate CR electrons to high energies, and transport them rapidly away from the GC; the cooling time of electrons at 100–1000 GeV is only 10^{5-6} years, so if the CRs are injected and accelerated only in the GC, a very fast bulk transport mechanism is required to convey them throughout the bubbles before they lose a significant fraction of their energy. However, filling the bubbles completely, with $n \lesssim 10^{-2}$ cm^{-3} gas, would require a mass injection of $\sim 10^8$ solar masses, so in any case it is more reasonable for the bulk of the material in the bubbles to be swept up and accelerated as the bubbles expand. Energetic shocks associated with jets can have high Mach number and thus efficiently accelerate CR electrons, producing hard spectra with $\mathrm{d}N/\mathrm{d}E \sim E^{-2}$, and the total energy required to heat the bubbles is also readily achievable by accretion events onto the central BH. However, the north–south symmetry of the bubbles has no obvious explanation in the context of an AGN jet: there is no reason for one jet to be oriented perpendicular to the Galactic plane. The large width and rounded shape of the bubbles are also not typical of jets, which are generally much more collimated, although a precessing jet might help explain the wide opening angle of the bubbles. If the central BH becomes active on a relatively short timescale, the *Fermi* bubbles may be created by a number of past jets, which combine to give rise to the symmetric and uniform *Fermi* bubbles.

An alternate source for the large required energy injection is a nuclear starburst. The wide opening angle of the bubbles is not a problem in this case; the bubble shape is similar to that observed in NGC 3079, and the X-ray features observed by *ROSAT* are similar to those observed in other nearby starburst galaxies [93]. However, no corresponding Hα signal of the *Fermi* bubbles is observed, in contrast to other known starburst galaxies: this problem might potentially be resolved if the Hα-emitting gas has cooled in the time since the starburst phase (gas hot enough to emit the X-rays observed by *ROSAT* has a considerably longer cooling time). Also, generally gas filaments and clumps are observed in the X-rays in starburst galaxies, and it would seem that a relic of a past starburst should become more clumpy with gas clouds and filaments due to cooling of the gas. However, while no such structures are obvious in the *ROSAT* maps, the signal-to-noise is insufficient to place strong constraints. The absence of any such filamentary structures inside the *Fermi* bubbles, on the other hand, argues against a hadronic origin for the bubble gamma-ray emission. Hadronic jets might accelerate protons to high energies, and the interactions of these protons with the ISM could then produce hard π^0 gammas and secondary e^+e^-, which would scatter on the ISRF to produce more gamma rays. In this scenario, however, the gamma ray emission should trace the gas density, which we would not expect to be smooth and homogeneous.

In the case of the starburst scenario, the cosmic ray acceleration would be due to shocks at the edge of the bipolar wind. However, the shocks expected in this scenario would be relatively weak and slow-moving, and thus may not be capable of generating a sufficiently hard electron spectrum to reproduce the signal. For example, in first-order Fermi acceleration, a shock Mach number of $\sim$3.3 is needed to obtain an electron spectral index of 2.4, as required for the synchrotron explanation of the *WMAP* haze. The *Fermi* bubbles have sharp edges, also suggesting the presence of a shock at the bubble walls. If the CRs producing the gamma rays have a multi-kpc diffusion length (which is not expected to be the case for 1 TeV electrons, for example), then the edges can still be sharp if the bubble edge is moving outward faster than they can diffuse. If we assume the *Fermi* bubbles are projected structures from three-dimensional symmetric blobs towards the GC, the flat intensity profile of the bubbles requires the emissivity to rise at the bubble walls, but remain non-negligible in the bubble interior; the lack of spatial variation in the spectral index may also constrain models where the electrons diffuse long distances from an injection point. Magnetic reconnection in the interior of the bubbles, or some other mechanism such as dark matter annihilation, may help maintain a hard spectrum throughout the bubbles by accelerating existing lower-energy electrons or injecting electrons *in situ*.

Finally, dark matter annihilation or decay, while an effective mechanism for injecting hard electron CRs at high latitudes, cannot *by itself* produce the features in the *ROSAT* X-ray maps correlated with the bubbles, and would not be expected to result in sharp cutoffs in γ-ray emission at the bubble edges. It seems like large scale astrophysical outflows are required to transport CRs to high latitude and produce the observed morphological features of the *Fermi* bubbles. On the other hand, it cannot be excluded that dark matter annihilation or decay may be *contributing* to the γ-ray emission within the bubbles, or to γ-ray emission towards the inner Galaxy that is not well subtracted by either the bubble structure template or the models for known diffuse emission mechanisms. Apparently constraints on dark matter physics based on the observed γ-ray intensity spatial distribution and energy spectrum towards the Galactic Centre are unreliable in the presence of the *Fermi* bubble as a new component of foreground, which implies recent dynamical environment in the inner galaxy. Even if the annihilation of concentrated dark matter created particles subsequently producing gamma rays, these particles would be possibly entrained in the Galactic outflow to higher latitude. Detailed knowledge of the *Fermi* bubbles will be a necessary step before extracting any such dark matter signal. In the next section, we will discuss a γ-ray excess from the GC region which was revealed exactly by removing the best fit *Fermi* bubble template.

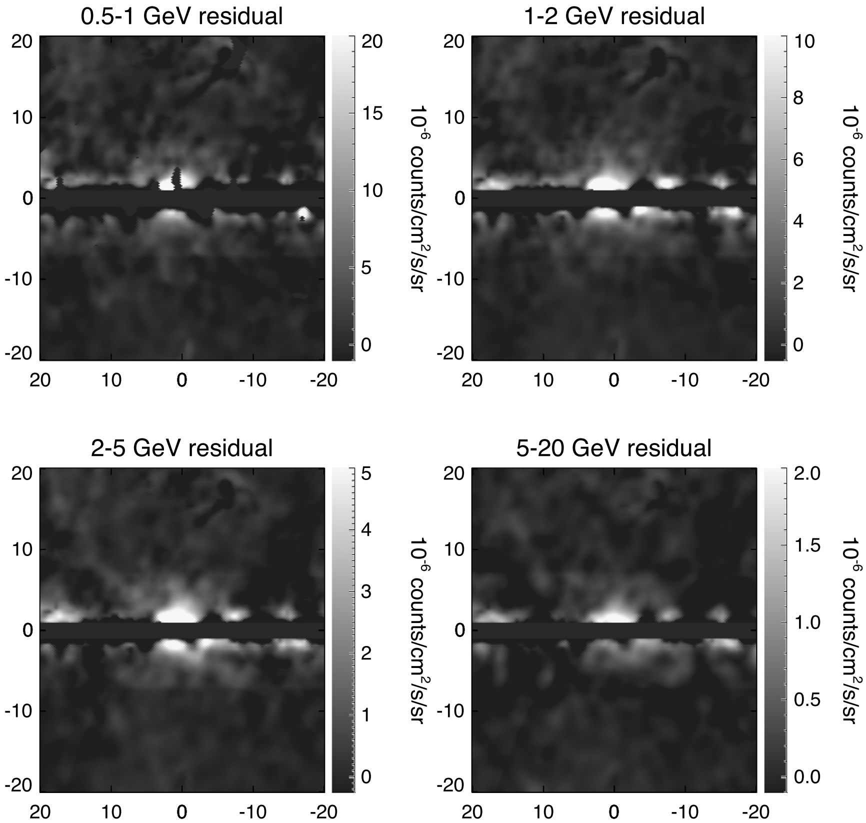

Fig. 9. Intensity maps (in galactic coordinates) after subtracting the best-fit Galactic diffuse model, *Fermi* bubbles, and isotropic templates. At energies between ∼0.5–5 GeV (i.e. in the first three frames), the dark-matter-like emission is clearly visible around the Galactic Centre.
Figure from [118].

5. The GeV excess at the Galactic Centre

Although the state-of-the-art diffuse γ-ray models are in agreement with the data within about 15% in most regions of the sky, a remarkable exception is the fact that the models tend to systematically under-estimate the measured γ-ray flux by *Fermi* above a few GeV in the Galactic plane region, most notably towards the inner Galaxy. On the other hand, a wide range of cosmological and astrophysical observations have shown that about 85% of the matter content in the Universe is non-baryonic. The currently leading candidates for this "dark matter" component are Weakly Interacting Massive Particles (WIMPs), which appear in a large number of scenarios of particle physics beyond the standard model. If the dark matter consists of such particles, then their annihilations are predicted to produce potentially observable fluxes of energetic particles, including gamma rays, cosmic rays, and neutrinos. Of particular interest are gamma rays from the region of the Galactic Centre due to its proximity and high dark matter density [107].

Recently, a number of groups have reported the detection of an extended diffuse and spherical emission component peaked around ∼1–3 GeV from the inner few degrees around the Galactic Centre, on top of the standard astrophysical backgrounds [108–111]. Both the spatial distribution (radial volume emissivity) and spectral shape is claimed to be broadly consistent with the expected signal from dark matter annihilation, although other source spectra (a log-parabola or a power-law with exponential cutoff) can be accommodated by the data [112–117]. This "GeV excess" signal has been recently confirmed by producing higher spatial resolution γ-ray maps from Fermi-LAT data with events selected on the basis of a better reconstruction, thus suppressing tails of the pointspread function [118,119].

5.1. The morphology and spectrum of this residual signal

The "GeV excess" from the inner Galaxy is statistically significant, with a spectrum and angular distribution that is consistent with that expected from annihilating dark matter models. The signal is spatially distributed with approximate spherical symmetry around the Galactic Centre (within ∼0.05° of Sgr A*) showing no sign of elongation along or perpendicular to the Galactic Plane. The flux falls off as $F_\gamma \propto r^{-(2.2-2.6)}$, implying a dark matter distribution of $\rho \propto r^{-\gamma}$, with $\gamma \simeq 1.1$–1.3 [118]. The signal is observed to extend to at least ≃10° from the Galactic Centre, disfavouring the possibility that this emission originates from millisecond pulsars (see Fig. 9) [120,121]. Furthermore, the spectrum of the excess peaks at ∼1–3 GeV,

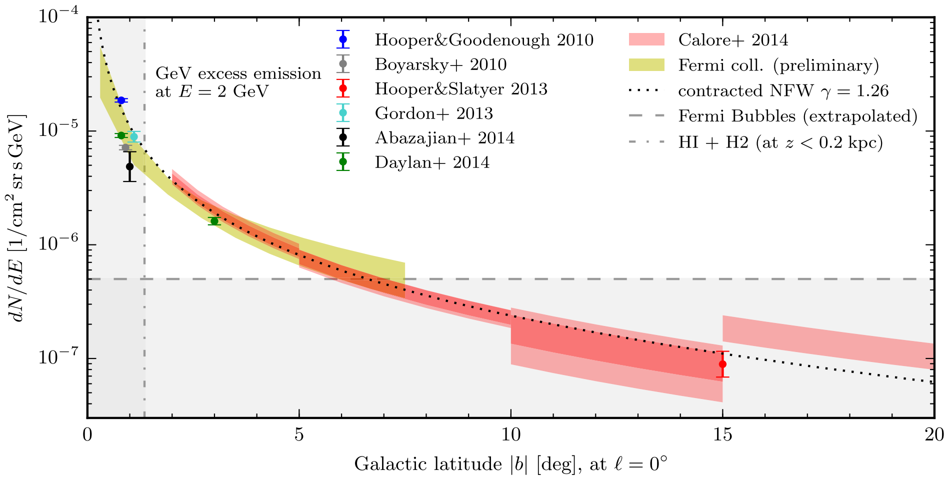

Fig. 10. (Colour online.) Intensity of the *Fermi* GeV excess at 2 GeV as function of Galactic latitude (see text for details), compared with the expectations for a contracted NFW profile (*dotted line*). *Grey areas* indicate the intensity level of the *Fermi* bubbles, extrapolated from $|b| > 10°$, and the region where HI and H2 gas emission from the inner Galaxy becomes important.
Figure from [122].

and is well fit by, e.g., 30–40 GeV dark matter particles annihilating to $b\bar{b}$ with an velocity-averaged annihilation cross section of $\langle \sigma v \rangle = (1.4\text{–}2.0) \times 10^{-26}$ cm^3/s (normalized to a local dark matter density of 0.3 GeV/cm^3). In particular, a dark matter particle with this cross section will freeze-out from the thermal equilibrium in the early universe to yield a dark matter abundance consistent with what has been observed. Most of the published results as summarized in Fig. 10 agree within a factor of about two with a signal morphology that is compatible with a contracted Navarro–Frenk–White (NFW) profile with slope $\gamma = 1.26$. The higher-latitude tail of the GeV excess profile is a rather non-trivial test for the dark matter interpretation and provides a serious benchmark for any astrophysical explanation of the excess emission.

However, the modelling of the Galactic diffuse emission is very uncertain in the inner few hundred pc of the GC (150 pc projected distance corresponds to about 1°) and is strongly affected by systematics related to point source subtraction and the modelling of diffuse backgrounds. The exact assumptions on CR propagation and Galactic properties along the line-of-sight can impact both the spectrum and the morphology of the individual γ-ray emission maps. Complementary observations, like local measurements of CRs, are not able to set strong constraints on the CR propagation properties or gas densities in that region. Moreover, the magnetic field intensity can be only indirectly constrained by the synchrotron emission at microwaves for given assumptions on high-energy electrons. It seems far from surprising that residuals were found above the expected astrophysical emission due to the high density of γ-ray-emitting objects and unconstrained CR properties at the GC, given the unprecedented sensitivity of Fermi-LAT. The large effective area of Fermi-LAT provides a good statistics of photon events in this region of interest. Generally the error bars of the analysis are dominated by the systematic uncertainties related to the modelling of diffuse backgrounds, as shown in Fig. 11. Similar works in the literature generally confirm that the signal is present throughout the Galactic Centre and Inner Galaxy on top of the standard astrophysical background (extending out to angles of at least 10° from the Galactic Centre). In particular, they characterize its spectral and morphological properties, given the current knowledge of the expected γ-ray foreground templates and using simplified physical models for the production and propagation of CRs in the Galaxy. The estimation of the systematic errors can only be obtained empirically by spanning the full range of possible parameters in the cosmic ray production and propagation modelling, gas 3D distribution, exploring a large number of test regions along the Galactic disk, and check if the spectral shape and spatial distribution of each individual component of the diffuse γ-ray emission is consistent with the observations.

5.2. Possible explanations

While a population of several thousand yet unresolved millisecond pulsars (MSPs) located in the bulge of the Milky Way could have plausibly been responsible for much of the anomalous "GeV excess" observed around the Galactic Centre, the extension of this signal into regions well beyond the confines of the central stellar cluster strongly disfavours such objects as the primary source of this signal [121,113]. However, the conclusions strongly depend on the details of the MSP luminosity function (in particular, its high luminosity end) as well as on the possible secondary emission of the MSP population. Within current uncertainties, a large if not dominant contribution to the excess cannot be excluded [124–126].

Another possible explanation of the GC excess relies on the interactions of CRs with gas, for example non-thermal bremsstrahlung from a population of electrons scattering off neutral molecular clouds in the inner 2° or interactions between the gas and protons accelerated by the super-massive black hole sitting at the GC. In general, those mechanisms would lead to an excess emission correlated with the gas distribution itself. In particular, the former process could not only explain part of the GeV excess emission in the Galactic ridge region, but also the excess at TeV energies as seen by HESS, as

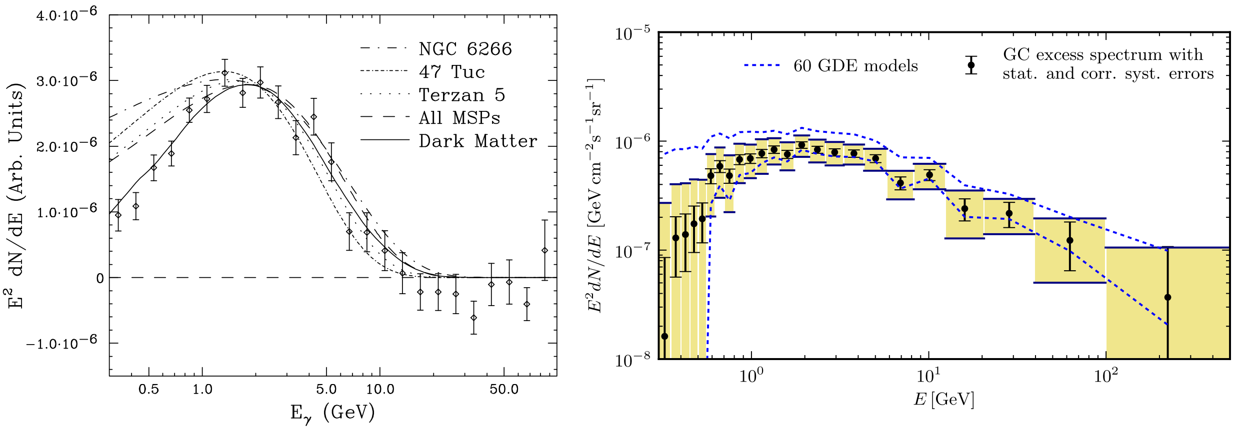

Fig. 11. (Colour online.) The left panel shows a comparison of the spectral shape of the γ-ray excess described [118] to the spectrum measured from a number of high-significance globular clusters (NGC 6266, 47 Tuc, and Terzan 5), and from the sum of all millisecond pulsars detected as individual point sources by *Fermi*. The γ-ray spectrum measured from millisecond pulsars and from globular clusters (whose emission is believed to be dominated by millisecond pulsars) is consistently softer than that of the observed excess at energies below ∼1 GeV. The right panel shows the spectrum of the GeV excess emission for a typical model in (*black dots*) together with statistical and systematical (*yellow boxes*) errors and the blue dashed envelope shows the results from 60 different Galactic diffuse emission models (see [123] for details).

we have already described. However, in both cases an extended signal up to a few kpc is excluded, unless a large amount of unidentified spherically distributed gas is present towards the inner Galaxy. It has also been suggested that burst-like events during an active past of our Galaxy may represent a viable mechanism for producing gamma rays in the inner Galaxy with the observed spectrum and morphology [127,128]. Hadronic or leptonic scenarios might explain some of the observed excess features at high latitudes.

The near future offers encouraging prospects for discriminating the nature of the “GeV excess”. The range in masses of dark matter particles and in annihilation cross sections implied by the gammaray excess is comparable to that obtained from Fermi observations of dwarf spheroidal galaxies. Although the *Fermi*-LAT Collaboration has reported a modestly statistically significant excess (∼2–3σ) in their earlier search for dark matter particles in dwarf galaxies, the most recent analysis with updated reconstructed events (so-called Pass-8 events) shows less than 1σ significance. With the full dataset anticipated from *Fermi*'s 10 year mission, it may be possible to make statistically significant detections of dark matter annihilation products from a few of the brightest dwarf galaxies, galaxy clusters, and perhaps nearby dark matter subhalos.

6. Conclusions and prospects

The Galactic centre is one of the most interesting regions of the high-energy γ-ray sky. It hosts a high concentration of star forming regions, pulsar wind nebulae, supernova remnants, and the central supermassive black hole Sgr A*. All of these sources are potential γ-ray emitters from sub-GeV to multi-TeV energies. In addition to some expected contribution from unresolved point sources, a very large proportion of the γ-ray emission comes from extended diffuse emission, which is assumed to be generated from cosmic ray interactions with the molecular clouds. The study of the Galactic centre in the TeV band allows for a characterization of the cosmic ray flux in this region.

During the last decade, the current generation of space-borne and ground-based γ-ray instruments has very much improved our understanding of the high-energy astrophysics of this most complicated region of the Galaxy. Despite the progress, current γ-ray instruments still lack the sensitivity, angular and energy resolution to allow for an even deeper understanding of the GC constituents and their interplay. Due to limited angular resolution, source confusion often prevents solid identification of γ-ray sources with counterparts at larger wavelengths, and better sensitivity would enable more detailed investigations of source morphologies and temporal variability (besides detecting more sources). Especially at MeV to GeV energies, however, sensitivity is often limited by the presence (and still incomplete understanding) of diffuse γ-ray emission. It seems, however, clear that instruments with better resolution and sensitivity would be able to provide much more detailed information also on the diffuse emission, thereby further reducing systematic uncertainties in the modelling of this component.

Future space-borne and ground-based γ-ray telescopes are therefore expected to significantly improve our knowledge of the γ-ray sky, in particular the Galactic centre region (see [129] for a review). At energies of 10 MeV up to a few GeV, PANGU (the PAir-productioN Gamma-ray Unit), a small astrophysics mission with wide field of view optimized for spectro-imaging, timing and polarisation studies, proposed for the joint ESA-CAS mission [130], will map the γ-ray sky with unprecedented spatial resolution. The mission will provide the most accurate sub-GeV spectral characterisation of cosmic-ray sources in the Galactic centre region and of the Fermi bubbles and related Galactic wind, to single out the pion-decay signature of accelerated nuclei. It will resolve the diffuse Galactic interstellar emission with unprecedented details to probe the distribution of Galactic cosmic rays towards the Galactic centre, and it is unique to probe the GeV excess as a potential signature from the annihilation of dark matter candidates. The space-borne GAMMA-400 instrument [131], currently planned for launch in 2019, will observe the γ-ray sky in the energy range of 100 MeV up to several TeV, and is at the same time able to detect electrons, protons and nuclei up to a few PeV. For γ-ray observations, it features a smaller effective collection area than Fermi-LAT, but at the same time is expected to improve significantly in cosmic ray background rejection, and outperform Fermi-LAT by a large factor both in angular and energy resolution. The ground-based Cherenkov Teleskope Array (CTA, [132]), for which construction of a first partial array may start already in 2016, will cover an energy range from several 10 GeV to more than 100 TeV. In its core energy range, it will outperform existing VHE γ-ray instruments by a factor ∼10 better flux sensitivity as well as improved angular resolution. Compared to its predecessors, CTA will therefore improve in resolving extended sources and their energy-dependent morphology in the inner Galaxy, and significantly enhance the capability to detect flares at TeV energies. Finally, from ∼2020, the Large High Altitude Air Shower Observatory (LHAASO, [133]) will extend the energy range up to 1 PeV, with a 10 times better sensitivity than the HAWC extensive air shower array.

We expect our knowledge of the γ-ray emission of the Galactic Centre will be soon improved with the exciting future facilities.

References

[1] J.H. Piddington, H.C. Minnett, Observations of galactic radiation at frequencies of 1200 and 3000 Mc/s, Aust. J. Sci. Res., A Phys. Sci. 4 (1951) 459.
[2] R.X. McGee, J.G. Bolton, Probable observation of the galactic nucleus at 400 Mc/s, Nature 173 (4) (1954) 985–987.
[3] B. Balick, R.L. Brown, Intense sub-arcsecond structure in the Galactic Center, Astrophys. J. 194 (1974) 265–270.
[4] P.G. Mezger, W.J. Duschl, R. Zylka, The Galactic Center: a laboratory for AGN?, Astron. Astrophys. Rev. 7 (4) (1996) 289–388.
[5] Mark Morris, Eugene Serabyn, The Galactic Center environment, Annu. Rev. Astron. Astrophys. 34 (1996) 645–702.
[6] Roland M. Crocker, et al., A lower limit of 50 microgauss for the magnetic field near the Galactic Centre, Nature 463 (7) (2010) 65–67.
[7] W.B. Atwood, et al., The large area telescope on the Fermi gamma-ray space telescope mission, Astrophys. J. 697 (2009) 1071–1102.
[8] J.A. Hinton, for the HESS Collaboration, The status of the HESS project, New Astron. Rev. 48 (2004) 331–337.
[9] J. Aleksić, et al., Performance of the MAGIC stereo system obtained with Crab Nebula data, Astropart. Phys. 35 (2012) 435–448.
[10] J. Holder, et al., Status of the VERITAS observatory, in: F.A. Aharonian, W. Hofmann, F. Rieger (Eds.), American Institute of Physics Conference Series, in: AIP Conf. Series, vol. 1085, December 2008, pp. 657–660.
[11] T.N. LaRosa, et al., A wide-field 90 centimeter VLA image of the Galactic Center region, Astron. J. 119 (1) (2000) 207–240.
[12] T.M. Bania, Carbon monoxide in the inner Galaxy, Astrophys. J. 216 (1977) 381–403.
[13] H.S. Liszt, et al., Kinematics of carbon monoxide observed within one degree of the Galactic Center, Astrophys. J. 213 (1977) 38–42.
[14] M. Tsuboi, T. Handa, N. Ukita, Dense molecular clouds in the Galactic Center region. I. Observations and data, Astrophys. J. Suppl. 120 (1999) 1–39.
[15] Y. Sofue, Galactic-Center molecular arms, ring, and expanding shell. I. Kinematical structures in longitude–velocity diagrams, Publ. Astron. Soc. Jpn. 47 (1995) 527–549.
[16] T. Sawada, et al., A molecular face-on view of the Galactic Centre region, Mon. Not. R. Astron. Soc. 349 (2004) 1167–1178.
[17] D. Downes, A.H.M. Martin, Compact radio sources in the Galactic Nucleus, Nature 233 (1971) 112–114.
[18] Y. Maeda, et al., A Chandra study of Sagittarius A East: a supernova remnant regulating the activity of our Galactic Center?, Astrophys. J. 570 (2) (2002) 671–687.
[19] S. Park, et al., A candidate neutron star associated with Galactic Center supernova remnant Sagittarius A East, Astrophys. J. 631 (2005) 964–975.
[20] K. Koyama, et al., X-ray spectrum of Sagittarius A East, Publ. Astron. Soc. Jpn. 59 (2007) 237–243.
[21] T.W. Jones, On the nature of the nonthermal radio emission from the Galactic Center, Astron. Astrophys. 30 (1974) 37.
[22] R.D. Ekers, J.H. van Gorkom, U.J. Schwarz, W.M. Goss, The radio structure of SGR A, Astron. Astrophys. 122 (1983) 143–150.
[23] R. Schödel, et al., A star in a 15.2-year orbit around the supermassive black hole at the centre of the Milky Way, Nature 419 (2002) 694–696.
[24] A.M. Ghez, et al., Full three dimensional orbits for multiple stars on close approaches to the central supermassive black hole, Astron. Nachr. Suppl. 324 (2003) 527–533.
[25] F. Eisenhauer, et al., SINFONI in the Galactic Center: young stars and IR flares in the central light month, Astrophys. J. 628 (2005) 246–259.
[26] S. Gillessen, et al., Monitoring stellar orbits around the massive black hole in the Galactic Center, Astrophys. J. 692 (2009) 1075–1109.
[27] G.C. Bower, et al., Detection of the intrinsic size of Sagittarius A* through closure amplitude imaging, Science 304 (2004) 704–708.
[28] G.K. Skinner, et al., Hard X-ray images of the Galactic Centre, Nature 330 (1987) 544–547.
[29] F.K. Baganoff, et al., Rapid X-ray flaring from the direction of the supermassive black hole at the Galactic Centre, Nature 413 (2001) 45–48.
[30] D. Porquet, et al., XMM-Newton observation of the brightest X-ray flare detected so far from Sgr A*, Astron. Astrophys. 407 (2003) L17–L20.
[31] J. Neilsen, et al., A Chandra/HETGS census of X-ray variability from Sgr A* during 2012, Astrophys. J. 774 (2013) 42.
[32] N. Degenaar, et al., The X-ray flaring properties of Sgr A* during six years of monitoring with swift, Astrophys. J. 769 (2013) 155.
[33] S. Markoff, et al., The nature of the 10 kilosecond X-ray flare in Sgr A*, Astron. Astrophys. 379 (2001) L13–L16.
[34] F. Aharonian, A. Neronov, High-energy gamma rays from the massive black hole in the Galactic Center, Astrophys. J. 619 (2005) 306–313.
[35] S. Liu, F. Melia, V. Petrosian, Stochastic electron acceleration during the near-infrared and X-ray flares in Sagittarius A*, Astrophys. J. 636 (2006) 798–803.
[36] R. Genzel, et al., Near-infrared flares from accreting gas around the supermassive black hole at the Galactic Centre, Nature 425 (2003) 934–937.
[37] G. Bélanger, et al., A persistent high-energy flux from the heart of the Milky Way: INTEGRAL's view of the Galactic Center, Astrophys. J. 636 (2006) 275–289.
[38] J. Cuadra, S. Nayakshin, V. Springel, T. Di Matteo, Galactic Centre stellar winds and Sgr A* accretion, Mon. Not. R. Astron. Soc. 366 (2006) 358–372.
[39] G. Ponti, R. Terrier, A. Goldwurm, G. Belanger, G. Trap, Discovery of a superluminal Fe K echo at the Galactic Center: the Glorious Past of Sgr A* preserved by molecular clouds, Astrophys. J. 714 (2010) 732–747.
[40] R. Terrier, G. Ponti, G. Bélanger, A. Decourchelle, V. Tatischeff, A. Goldwurm, G. Trap, M.R. Morris, R. Warwick, Fading hard X-ray emission from the Galactic Center molecular cloud Sgr B2, Astrophys. J. 719 (2010) 143–150.
[41] M. Clavel, R. Terrier, A. Goldwurm, M.R. Morris, G. Ponti, S. Soldi, G. Trap, Echoes of multiple outbursts of Sagittarius A⋆ revealed by Chandra, Astron. Astrophys. 558 (2013) A32.
[42] M. Su, T.R. Slatyer, D.P. Finkbeiner, Giant gamma-ray bubbles from Fermi-LAT: active galactic nucleus activity or bipolar galactic wind?, Astrophys. J. 724 (2010) 1044–1082.
[43] A.W. Strong, COS-B studies of high-latitude gamma rays, Adv. Space Res. 3 (1984) 87–89.

[44] A.W. Strong, H.A. Mayer-Hasselwander, J.B.G.M. Bloemen, W. Hermsen, F. Lebrun, The final COS-B database – in-flight calibration of sensitivity and instrumental background behaviour, Astron. Astrophys. Suppl. 67 (1987) 283–296.
[45] C.E. Fichtel, R.C. Hartman, D.A. Kniffen, D.J. Thompson, H. Ogelman, M.E. Ozel, T. Tumer, G.F. Bignami, High-energy gamma-ray results from the second small astronomy satellite, Astrophys. J. 198 (1975) 163–182.
[46] H. Bloemen, Diffuse Galactic gamma-ray emission, Annu. Rev. Astron. Astrophys. 27 (1989) 469–516.
[47] A. Smialkowski, A.W. Wolfendale, L. Zhang, The 'extragalactic' diffuse gamma ray intensity, Astropart. Phys. 7 (1997) 21–25.
[48] D.D. Dixon, D.H. Hartmann, E.D. Kolaczyk, J. Samimi, R. Diehl, G. Kanbach, H. Mayer-Hasselwander, A.W. Strong, Evidence for a Galactic gamma-ray halo, New Astron. 3 (1998) 539–561.
[49] D.J. Thompson, Space detectors for gamma rays (100 MeV–100 GeV): from EGRET to Fermi LAT, C. R. Physique 16 (2015) 600–609, in this issue.
[50] M. de Naurois, D. Mazin, Ground-based detectors in very-high-energy gamma-ray astronomy, C. R. Physique 16 (2015) 610–627, in this issue.
[51] K. Kosack, et al., Astrophys. J. 608 (2004) L97–L100.
[52] F. Aharonian, et al., Astron. Astrophys. 425 (2004) L13–L17.
[53] Ken'ichi Tsuchiya, et al., Astrophys. J. 606 (2004) L115–L118.
[54] J. Albert, et al., Astrophys. J. 638 (2006) L101–L104.
[55] F. Aharonian, et al., Spectrum and variability of the Galactic Center VHE γ-ray source HESS J1745-290, Astron. Astrophys. Rev. 503 (2009) 817–825.
[56] A. Viana, M. Moulin, H.E.S.S. Collaboration, in: Proc. 33rd International Cosmic Ray Conference, 2013, in press.
[57] M. Chernyakova, et al., The high-energy, arcminute-scale Galactic Center gamma-ray source, Astrophys. J. 726 (2011) 60.
[58] P.L. Nolan, et al., Fermi large area telescope second source catalog, Astrophys. J. Suppl. 199 (2012) 31.
[59] F. Aharonian, et al., Simultaneous HESS and Chandra observations of Sagittarius A^* during an X-ray flare, Astron. Astrophys. 492 (2008) L25–L28.
[60] The VERITAS Collaboration, Very-high energy observations of the Galactic Center region by VERITAS in 2010–2012, arXiv e-prints, June 2014.
[61] Q. Daniel Wang, F.J. Lu, E.V. Gotthelf, Mon. Not. R. Astron. Soc. 367 (2006) 937–944.
[62] W. Bednarek, T. Sobczak, Gamma-rays from millisecond pulsar population within the central stellar cluster in the Galactic Centre, Mon. Not. R. Astron. Soc. 435 (2013) L14–L18.
[63] J.W. Hewitt, M. Lemoine-Goumard, Observations of supernova remnants and pulsar wind nebulae at gamma-ray energies, C. R. Physique 16 (2015) 674–685, in this issue.
[64] R.M. Crocker, et al., The AGASA and SUGAR anisotropies and TeV gamma rays from the Galactic Center: a possible signature of extremely high energy neutrons, Astrophys. J. 622 (2005) 892–909.
[65] D.A. Green, A revised Galactic supernova remnant catalogue, Bull. Astron. Soc. India 37 (2009) 45.
[66] M.J. Reid, et al., Astrophys. J. 524 (1999) 816–823.
[67] F. Acero, et al., Localizing the VHE γ-ray source at the Galactic Centre, Mon. Not. R. Astron. Soc. 402 (2010) 1877–1882.
[68] J.A. Hinton, F.A. Aharonian, Astrophys. J. 657 (2007) 302–307.
[69] F. Aharonian, A. Neronov, TeV gamma rays from the Galactic Center direct and indirect links to the massive black hole in Sgr A, Astrophys. Space Sci. 300 (2005) 255–265.
[70] S. Liu, et al., Stochastic acceleration in the Galactic Center HESS source, Astrophys. J. 647 (2006) 1099–1105.
[71] Y.-P. Wang, Y. Lu, L. Chen, Injected spectrum for TeV γ-ray emission from the Galactic Center, Res. Astron. Astrophys. 9 (2009) 761–769.
[72] D.R. Ballantyne, M. Schumann, B. Ford, Modelling the time-dependence of the TeV γ-ray source at the Galactic Centre, Mon. Not. R. Astron. Soc. 410 (2011) 1521–1526.
[73] M. Fatuzzo, F. Melia, Diffusive cosmic-ray acceleration in Sagittarius A^*, Astrophys. J. Lett. 757 (2012) L16.
[74] T. Linden, E. Lovegrove, S. Profumo, The morphology of hadronic emission models for the gamma-ray source at the Galactic Center, Astrophys. J. 753 (2012) 41.
[75] A. Atoyan, C.D. Dermer, TeV emission from the Galactic Center black hole plerion, Astrophys. J. 617 (2004) L123–L126.
[76] M. Kusunose, F. Takahara, A leptonic model of steady high-energy gamma-ray emission from Sgr A^*, Astrophys. J. 748 (2012) 34.
[77] Y.-Q. Guo, Q. Yuan, C. Liu, A.-F. Li, A hybrid model of GeV–TeV gamma ray emission from the Galactic Center, J. Phys. G, Nucl. Phys. 40 (6) (2013) 065201.
[78] A.A. Abdo, Fermi LAT Collaboration, A population of gamma-ray emitting globular clusters seen with the Fermi Large Area Telescope, Astron. Astrophys. 524 (2010) A75.
[79] F. Aharonian, et al., Nature 439 (2006) 695–698.
[80] D.J. Helfand, R.H. Becker, G0.9+0.1 and the emerging class of composite supernova remnants, Astrophys. J. 314 (1987) 203–214.
[81] B.M. Gaensler, M.J. Pivovaroff, G.P. Garmire, Chandra observations of the pulsar wind nebula in supernova remnant G0.9+0.1, Astrophys. J. 556 (2001) L107–L111.
[82] D. Porquet, A. Decourchelle, R.S. Warwick, XMM-Newton spectral analysis of the Pulsar Wind Nebula within the composite SNR <ASTROBJ>G0.9+0.1</ASTROBJ>, Astron. Astrophys. 401 (2003) 197–203.
[83] F. Camilo, S.M. Ransom, B.M. Gaensler, D.R. Lorimer, Discovery of the energetic pulsar J1747-2809 in the supernova remnant G0.9+0.1, Astrophys. J. Lett. 700 (2009) L34–L38.
[84] F. Aharonian, et al., Astron. Astrophys. 432 (2005) L25–L29.
[85] F. Aharonian, et al., The H.E.S.S. survey of the inner Galaxy in very high energy gamma rays, Astrophys. J. 636 (2006) 777–797.
[86] F. Aharonian, et al., Exploring a SNR/molecular cloud association within HESS J1745-303, Astron. Astrophys. 483 (2008) 509–517.
[87] A. Bamba, R. Yamazaki, K. Kohri, H. Matsumoto, S. Wagner, G. Pühlhofer, K. Kosack, X-ray observation of very high energy gamma-ray source, HESS J1745-303, with Suzaku, Astrophys. J. 691 (2009) 1854–1861.
[88] C.Y. Hui, et al., Exploring the dark accelerator HESS J1745-303 with the Fermi Large Area Telescope, Astrophys. J. 735 (2011) 115.
[89] E. Wommer, F. Melia, M. Fatuzzo, Diffuse TeV emission at the Galactic Centre, Mon. Not. R. Astron. Soc. 387 (2008) 987–997.
[90] F. Melia, M. Fatuzzo, Diffusive cosmic-ray acceleration at the Galactic Centre, Mon. Not. R. Astron. Soc. 410 (2011) L23–L27.
[91] M. Fatuzzo, F. Melia, Assessing the feasibility of cosmic-ray acceleration by magnetic turbulence at the Galactic Center, Astrophys. J. 750 (2012) 21.
[92] T. Amano, K. Torii, T. Hayakawa, Y. Fukui, Stochastic acceleration of cosmic rays in the Central Molecular Zone of the Galaxy, Publ. Astron. Soc. Jpn. 63 (2011) L63–L66.
[93] M. Su, T.R. Slatyer, D.P. Finkbeiner, Giant gamma-ray bubbles from Fermi-LAT: active galactic nucleus activity or bipolar galactic wind?, Astrophys. J. 724 (2010) 1044–1082.
[94] C.J. Law, A multiwavelength view of a mass outflow from the Galactic Center, Astrophys. J. 708 (2010) 474–484.
[95] R.A. Sunyaev, M. Markevitch, M. Pavlinsky, The center of the Galaxy in the recent past – a view from GRANAT, Astrophys. J. 407 (1993) 606–610.
[96] K. Koyama, Y. Maeda, T. Sonobe, T. Takeshima, Y. Tanaka, S. Yamauchi, ASCA view of our Galactic Center: remains of past activities in X-rays?, Publ. Astron. Soc. Jpn. 48 (1996) 249–255.
[97] C.G.T. Haslam, U. Klein, C.J. Salter, H. Stoffel, W.E. Wilson, M.N. Cleary, D.J. Cooke, P. Thomasson, A 408 MHz all-sky continuum survey, Astron. Astrophys. 100 (1981) 209–219.

[98] D.J. Schlegel, D.P. Finkbeiner, M. Davis, Map of dust IR emission for use in estimation of reddening and CMBR foregrounds, in: 191st AAS Meeting, Bull. Am. Astron. Soc., vol. 29, December 1997, p. 1354.
[99] Douglas P. Finkbeiner, Microwave ISM emission observed by WMAP, Astrophys. J. 614 (2004) 186–193.
[100] Douglas P. Finkbeiner, WMAP Microwave Emission Interpreted as Dark Matter Annihilation in the Inner Galaxy, 2004.
[101] G. Dobler, D.P. Finkbeiner, Extended anomalous foreground emission in the WMAP three-year data, Astrophys. J. 680 (2008) 1222–1234.
[102] T. Paumard, R. Genzel, F. Martins, S. Nayakshin, A.M. Beloborodov, Y. Levin, S. Trippe, F. Eisenhauer, T. Ott, S. Gillessen, R. Abuter, J. Cuadra, T. Alexander, A. Sternberg, The two young star disks in the central parsec of the Galaxy: properties, dynamics, and formation, Astrophys. J. 643 (2006) 1011–1035.
[103] C.L. Bhat, M.R. Issa, C.J. Mayer, A.W. Wolfendale, Acceleration of cosmic rays in the Loop I 'supernova remnant'?, Nature 314 (1985) 515–517.
[104] J.-M. Casandjian, I. Grenier, for the Fermi Large Area Telescope Collaboration, High energy gamma-ray emission from the Loop I region, arXiv e-prints, December 2009.
[105] I.A. Grenier, A.K. Harding, Gamma-ray pulsars: a gold mine, C. R. Physique 16 (2015) 641–660, in this issue.
[106] M. Ackermann, A. Albert, W.B. Atwood, L. Baldini, J. Ballet, G. Barbiellini, D. Bastieri, R. Bellazzini, E. Bissaldi, R.D. Blandford, E.D. Bloom, E. Bottacini, T.J. Brandt, J. Bregeon, P. Bruel, R. Buehler, S. Buson, G.A. Caliandro, R.A. Cameron, M. Caragiulo, P.A. Caraveo, E. Cavazzuti, C. Cecchi, E. Charles, A. Chekhtman, J. Chiang, G. Chiaro, S. Ciprini, R. Claus, J. Cohen-Tanugi, J. Conrad, S. Cutini, F. D'Ammando, A. de Angelis, F. de Palma, C.D. Dermer, S.W. Digel, L. Di Venere, E.d.C.e. Silva, P.S. Drell, C. Favuzzi, E.C. Ferrara, W.B. Focke, A. Franckowiak, Y. Fukazawa, S. Funk, P. Fusco, F. Gargano, D. Gasparrini, S. Germani, N. Giglietto, F. Giordano, M. Giroletti, G. Godfrey, G.A. Gomez-Vargas, I.A. Grenier, S. Guiriec, D. Hadasch, A.K. Harding, E. Hays, J.W. Hewitt, X. Hou, T. Jogler, G. Jóhannesson, A.S. Johnson, W.N. Johnson, T. Kamae, J. Kataoka, J. Knödlseder, D. Kocevski, M. Kuss, S. Larsson, L. Latronico, F. Longo, F. Loparco, M.N. Lovellette, P. Lubrano, D. Malyshev, A. Manfreda, F. Massaro, M. Mayer, M.N. Mazziotta, J.E. McEnery, P.F. Michelson, W. Mitthumsiri, T. Mizuno, M.E. Monzani, A. Morselli, I.V. Moskalenko, S. Murgia, R. Nemmen, E. Nuss, T. Ohsugi, N. Omodei, M. Orienti, E. Orlando, J.F. Ormes, D. Paneque, J.H. Panetta, J.S. Perkins, M. Pesce-Rollins, V. Petrosian, F. Piron, G. Pivato, S. Rainò, R. Rando, M. Razzano, S. Razzaque, A. Reimer, O. Reimer, M. Sánchez-Conde, M. Schaal, A. Schulz, C. Sgrò, E.J. Siskind, G. Spandre, P. Spinelli, Ł. Stawarz, A.W. Strong, D.J. Suson, M. Tahara, H. Takahashi, J.B. Thayer, L. Tibaldo, M. Tinivella, D.F. Torres, G. Tosti, E. Troja, Y. Uchiyama, G. Vianello, M. Werner, B.L. Winer, K.S. Wood, M. Wood, G. Zaharijas, The spectrum and morphology of the Fermi Bubbles, Astrophys. J. 793 (2014) 64.
[107] P. Brun, J. Cohen-Tanugi, to be published in a forthcoming dossier of C. R. Physique, continuation of the present one (2016).
[108] L. Goodenough, D. Hooper, Possible evidence for dark matter annihilation in the inner Milky Way from the Fermi gamma ray space telescope, arXiv e-prints, October 2009.
[109] D. Hooper, L. Goodenough, Dark matter annihilation in the Galactic Center as seen by the Fermi gamma ray space telescope, Phys. Lett. B 697 (2011) 412–428.
[110] D. Hooper, T. Linden, Origin of the gamma rays from the Galactic Center, Phys. Rev. D 84 (12) (2011) 123005.
[111] K.N. Abazajian, M. Kaplinghat, Detection of a gamma-ray source in the Galactic Center consistent with extended emission from dark matter annihilation and concentrated astrophysical emission, Phys. Rev. D 86 (8) (2012) 083511.
[112] D. Hooper, T.R. Slatyer, Two emission mechanisms in the Fermi bubbles: a possible signal of annihilating dark matter, Phys. Dark Universe 2 (2013) 118–138.
[113] C. Gordon, O. Macías, Dark matter and pulsar model constraints from Galactic Center Fermi-LAT gamma-ray observations, Phys. Rev. D 88 (8) (2013) 083521.
[114] W.-C. Huang, A. Urbano, W. Xue, Fermi bubbles under dark matter scrutiny. Part I: Astrophysical analysis, arXiv e-prints, July 2013.
[115] K.N. Abazajian, N. Canac, S. Horiuchi, M. Kaplinghat, Astrophysical and dark matter interpretations of extended gamma-ray emission from the Galactic Center, Phys. Rev. D 90 (2) (2014) 023526.
[116] T. Lacroix, C. Boehm, J. Silk, Fitting the Fermi-LAT GeV excess: on the importance of including the propagation of electrons from dark matter, Phys. Rev. D 90 (4) (2014) 043508.
[117] B. Zhou, Y.-F. Liang, X. Huang, X. Li, Y.-Z. Fan, L. Feng, J. Chang, GeV excess in the Milky Way: depending on diffuse Galactic gamma ray emission template?, arXiv e-prints, June 2014.
[118] T. Daylan, D.P. Finkbeiner, D. Hooper, T. Linden, S.K.N. Portillo, N.L. Rodd, T.R. Slatyer, The characterization of the gamma-ray signal from the central Milky Way: a compelling case for annihilating dark matter, arXiv e-prints, February 2014.
[119] S.K.N. Portillo, D.P. Finkbeiner, Sharper Fermi LAT images: instrument response functions for an improved event selection, Astrophys. J. 796 (2014) 54.
[120] K.N. Abazajian, The consistency of Fermi-LAT observations of the Galactic Center with a millisecond pulsar population in the central stellar cluster, J. Cosmol. Astropart. Phys. 3 (2011) 10.
[121] D. Hooper, I. Cholis, T. Linden, J.M. Siegal-Gaskins, T.R. Slatyer, Millisecond pulsars cannot account for the inner Galaxy's GeV excess, Phys. Rev. D 88 (8) (2013) 083009.
[122] F. Calore, I. Cholis, C. McCabe, C. Weniger, A tale of tails: dark matter interpretations of the Fermi GeV excess in light of background model systematics, Phys. Rev. D 91 (6) (2015) 063003.
[123] F. Calore, I. Cholis, C. Weniger, Background model systematics for the Fermi GeV excess, arXiv e-prints, August 2014.
[124] Q. Yuan, B. Zhang, Millisecond pulsar interpretation of the Galactic Center gamma-ray excess, J. High Energy Astrophys. 3 (2014) 1–8.
[125] J. Petrovic, P.D. Serpico, G. Zaharijas, Millisecond pulsars and the Galactic Center gamma-ray excess: the importance of luminosity function and secondary emission, arXiv e-prints, November 2014.
[126] S.K. Lee, M. Lisanti, B.R. Safdi, Distinguishing dark matter from unresolved point sources in the inner Galaxy with photon statistics, arXiv e-prints, December 2014.
[127] E. Carlson, S. Profumo, Cosmic ray protons in the inner Galaxy and the Galactic Center gamma-ray excess, Phys. Rev. D 90 (2) (2014) 023015.
[128] J. Petrovic, P. Dario Serpico, G. Zaharijas, Galactic Center gamma-ray "excess" from an active past of the Galactic Centre?, arXiv e-prints, May 2014.
[129] J. Knödlseder, C. R. Physique (2016), in press (special issue), continuation of the present one.
[130] X. Wu, M. Su, A. Bravar, J. Chang, Y. Fan, M. Pohl, R. Walter, PANGU: a high resolution gamma-ray space telescope, in: Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol. 9144, July 2014.
[131] A.M. Galper, et al., The space-based gamma-ray telescope GAMMA-400 and its scientific goals, arXiv e-prints, June 2013.
[132] B.S. Acharya, et al., Introducing the CTA concept, Astropart. Phys. 43 (2013) 3–18.
[133] Min Zha, ARGO-YBJ experiment results and prospects in LHAASO project, Int. J. Mod. Phys. Conf. Ser. 10 (2012) 147–158.