ASTROPARTICLE PHYSICS WITH H.E.S.S.: DARK MATTER AND LORENTZ INVARIANCE VIOLATION STUDIES

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H.E.S.S. is an array of four imaging atmospheric Cherenkov telescopes (IACTs) detecting γ rays in the very high energy (VHE, E_γ >100 GeV) domain. The astroparticle physics program with HESS includes the search for dark matter (DM) and the study of possible Lorentz invariance violation. I will review latest results on both topics.

1 Dark matter searches

1.1 γ-ray flux from dark matter annihilation

The γ-ray flux expected from the self-annihilation of DM particles of mass $m_{\rm DM}$ can be decomposed into a particle physics term and an astrophysical term as

$$\frac{{\rm d}\Phi_\gamma(\Delta\Omega, E_\gamma)}{{\rm d}E_\gamma} = \frac{1}{8\pi}\ \underbrace{\frac{\langle\sigma v\rangle}{m_{\rm DM}^2}\frac{{\rm d}N_\gamma}{{\rm d}E_\gamma}}_{Particle\,Physics} \times \underbrace{\int_{\Delta\Omega}\int_{LOS}\rho(r[s])^2 ds\, d\Omega}_{Astrophysics}\,, \tag{1}$$

where $\langle\sigma v\rangle$ is the velocity-weighted annihilation cross section and ${\rm d}N_\gamma/{\rm d}E_\gamma$ the annihilation spectrum. The astrophysical term expresses the integral of the squared density over the line of sight (LOS) and the solid integration angle $\Delta\Omega$.

Indirect detection of DM with γ-rays is based on the search for γ-ray emission arising from the hadronization and/or decays of the cascading annihilation products. Observing strategies for searching this dim radiation include targeted searches or wide-field surveys. IACTs are well suited for deep observations of selected sources due to their very large collection area. Searches for DM substructures can be however efficiently carried out with sufficiently-large fields of view due to the random nature of the substructure positions.

DM particle annihilations are expected to occur in dense regions of the Galactic halo, dwarf spheroidal galaxies (dSphs) and other types of substructures in galactic halos. In the absence of a clear signal, modeling the DM distribution in these objects allows to put constraints in terms of the remaining particle physics parameters σv and $m_{\rm DM}$. Beside these targeted searches are wide-field survey searches for DM subhalos that provide constrains either on the subhalo formation scenario such as the case for DM spikes around intermediate mass black holes (IMBHs), or on particle physics parameters.

1.2 Dwarf galaxy satellites of the Milky Way

dSphs are believed to be among the most DM-dominated objects in the universe and are believed to have a reduced astrophysical background since these objects have little or no recent star

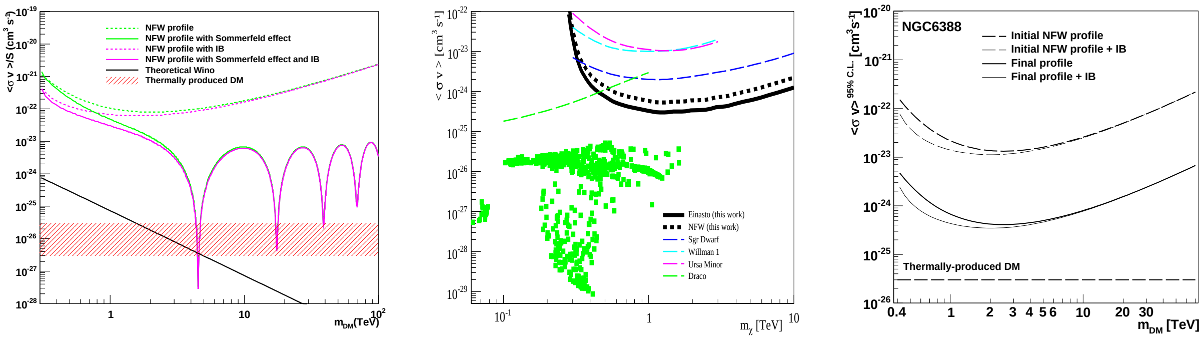

Figure 1: Exclusion limits on the velocity-weighted annihilation cross section σv versus the DM mass towards Sculptor dSph (left), the inner part of the Galactic halo (center) and the galactic globular cluster NGC 6388 (right). The DM halo modeling is described for each target in Refs. [3,5,6], respectively.

formation activity. Nearby dwarf galaxies in the Local Group have already been observed with H.E.S.S. No significant γ-ray signal has been detected and constraints have been derived towards Sagittarius, Canis Major, Sculptor and Carina [1,2,3]. The left-hand side plot of Fig. 1 shows the 95% C. L. exclusion limits on σv towards Sculptor for a NFW halo profile. The strongest constraints lie at the level of 10^{-23} cm^{3}s^{-1} for DM masses around 2 TeV. The predicted γ-ray flux can be enhanced by astrophysical and particle physics effects. Assuming that the DM mean velocity inside the halo is the same as for the stars, the *Sommerfeld* effect can substantially boost the annihilation cross section since it is particularly effective when the relative velocity between the DM particles is sufficiently low. The effect is shown on Fig. 1 for wino DM annihilating purely through the Z boson. A series of resonances allows the exclusion for specific DM masses at the level of $\sigma v \sim 10^{-26}$ cm^{3}s^{-1}. For dSphs, the effect of DM subhalos in the host halo is found of the order of a few percents on the astrophysical factor [3].

1.3 The Galactic halo

The Galactic Center has attracted significant interests due to the expected high DM concentration. The inner 10 pc of the Milky Way is however a very crowded region and standard astrophysical TeV emitters, *i.e.* the supermassive black hole Sgr A* or the pulsar wind nebula G359.95-0.04, can easily account for the strong TeV signal detected by H.E.S.S. [4]. To avoid large standard γ-ray signals and simultaneously an expectedly large DM concentration, DM searches can be efficiently carried out in an annulus around the Galactic Center [5]. Constraints on σv lie at $\sim 10^{-25}$ cm^{3}s^{-1} assuming an Einasto profile (Fig. 1). These are the strongest DM constraints obtained so far with IACTs.

1.4 Galactic globular clusters

Under the assumption that globular clusters (GCs) formed in DM halos, DM could still be present in these baryon-dominated environments. Astrophysical processes can substantially influence the initial DM profile during the evolution of the GC: the adiabatic contraction of DM by baryons, the adiabatic growth of a black hole in the DM halo, and the kinetic heating of DM by stars. From H.E.S.S. observations, no signal is found towards NGC 6388 and M15 [6]. Starting from an initial NFW profile, the final DM distribution has been carefully modeled [6]. 95% C.L. constraints on σv of a few 10^{-25} cm^{3}s^{-1} towards NGC 6388 have been derived (Fig. 1).

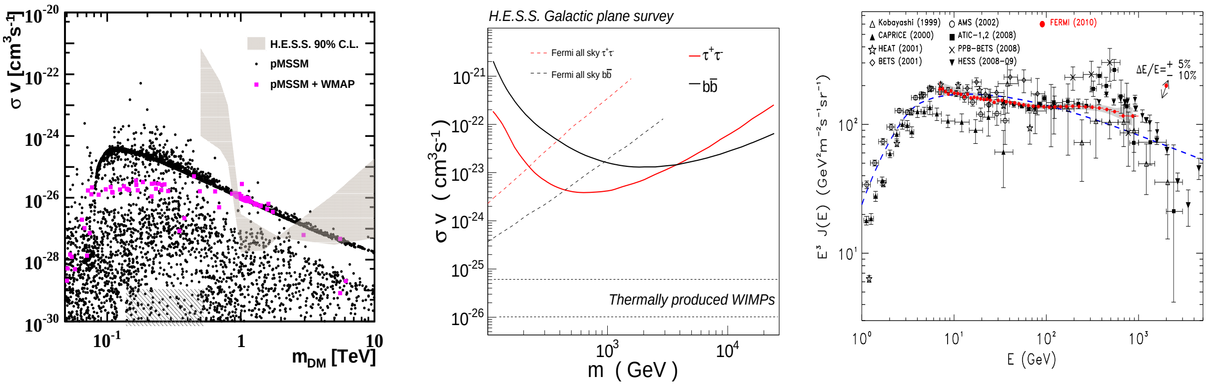

Figure 2: Exclusion limits on the velocity-weighted annihilation cross section σv versus the DM mass in the case of DM spikes around IMBHs (left) and DM subhalos in the Galactic halo predicted by the Via Lactea-II N-body simulations (centre). Right: Measurements on the cosmic-ray electron spectrum by Fermi LAT for 1 year of observations and H.E.S.S. along with other recent high-energy results.

1.5 Wide field-of-view searches

The large field of view obtained with the HE.S.S. Galactic plane survey allows for the first time for IACTs to search for DM substructures whose position is not known *a priori*. Searches towards DM spikes around IMBHs believed to populate the Galactic halo have been conducted by H.E.S.S. Strong constraints on scenarios with $\sim 10^5$ M$_\odot$ black holes have been obtained for TeV DM masses [7]. These constraints challenge the entire γ-ray production scenario around IMBHs (Fig. 2) of $\sim 10^5$ M$_\odot$. The same field of view has been used to test the more conventional CDM subhalo scenario as obtained by the cosmological N-body simulation Via Lactea II [8]. The constraints lie at the level of 10^{-23} cm^{3}s^{-1}, well complementing the limits obtained by Fermi [9].

1.6 Cosmic-ray electron searches

Recent results on cosmic-ray electron spectrum have been interpreted in terms of DM. A prominent peak around 800 GeV have been found by ATIC, which has further been excluded by H.E.S.S. [10,11] and Fermi [12,13] measurements, as seen on Fig. 2. The DM interpretation requires annihilations preferentially into leptons to avoid an overproduction of antiprotons and thus be in tension with PAMELA measurements. Although the DM interpretation is plausible, a more prosaic explanation is the presence of local electron sources such as nearby pulsars or supernovæ.

2 Lorentz invariance violation studies

Lorentz invariance is a fundamental symmetry in modern physics. It is however crucial to further improve the verification of its validity. Several models in the context of quantum gravity predict a possible energy-dependence of the speed of light, believed to appear at energies of the order of the Planck energy ($E_P = 1.22 \times 10^{19}$ GeV). For cosmological sources such as active galaxies, this minuscule effect can add up to measurable photon-energy dependent time lags. For energies much smaller than the Planck energy, the energy dependence of the speed of light can be parameterized in a model-independent way [14], up to the second order in energy, as

$$c' = c\left(1 + \xi\frac{E}{E_{\rm P}} + \zeta\frac{E^2}{E_{\rm P}^2}\right), \qquad (2)$$

where ξ and ζ are free parameters. For IACTs, distant AGNs are well-suited sources since they are transient and bright sources in TeV γ-rays. Complementary approaches using GRBs allow

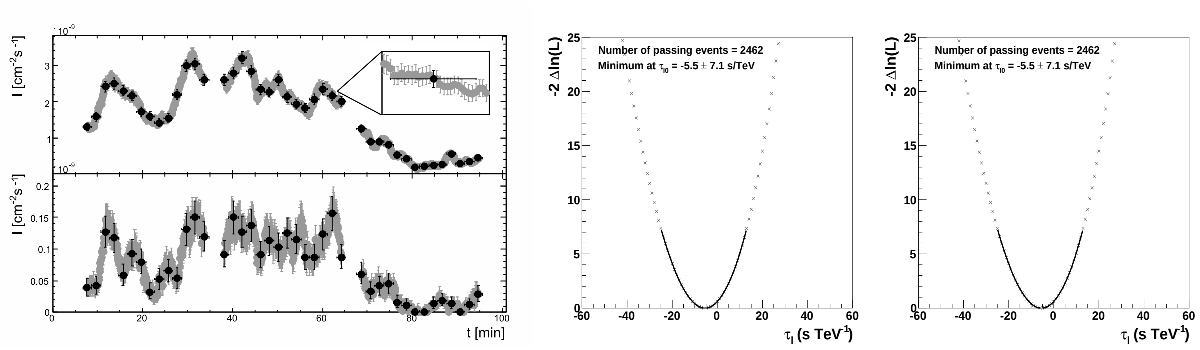

Figure 3: Left: Black points show the integral flux VHE light curves measured from the PKS 2155-304 flare by H.E.S.S. between 200-800 GeV (upper panel) and >800 GeV (lower panel), binned in two-minute time intervals. Gray points show the oversampled light curve, for which the two-minute bins are shifted in units of five seconds. The inlay in the upper panel illustrates this in a zoom, where the horizontal error bar shows the duration of the bin in the original light curve. Right: -2Δln(L) as a function of the injected time-lag τ when the measured light curve is fitted in 0.25-0.28 TeV and the likelihood is computed in 0.3-4.0 TeV for the linear and quadratic terms.

to probe different energy ranges and levels of variability. The VHE exceptional flare of the active galaxy PKS 2155-304 (z=0.116) detected by H.E.S.S. in 2006 has been used to look for possible energy dependence of the dispersion relation of VHE photons. The event statistics on the flare data amounts to about 10^5 γ rays in 1.5 hour after analysis cuts. The light curve shows fast variability ($\sim$200 s) as seen on Fig. 3, and covers an energy range of a few TeV with no significant spectral variabilty. The measurement of a possible energy lag in two energy bands shows no significant delay. This results in 95% C.L. limits on the linear term of $|\xi|^{-1}E_{\rm P} > 7.2 \times 10^{17}$ GeV and on the quadratic term of $|\zeta|^{-1/2}E_{\rm P} > 1.4 \times 10^9$ GeV [15]. Improved constraints have been obtained using an event-by-event method using a likelihood fit [16] (see Fig. 3). 95% C.L. limits reach $|\xi|^{-1}E_{\rm P} > 2.1 \times 10^{18}$ GeV and $|\zeta|^{-1/2}E_{\rm P} > 0.6 \times 10^{11}$ GeV. These are the best constraints to date with AGNs. The detection by Fermi of a 31 GeV photon from GRB 090510 put the strongest constraints on the linear term so far, at several times the Planck energy [17].

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