Searching for the Annual Modulation of Dark Matter signal with the GENIUS-TF experiment.

C. Tomei\textsuperscript{1}, A. Dietz, I. Krivosheina, H.V. Klapdor-Kleingrothaus

\textit{Max-Planck-Institut für Kernphysik, PO 10 39 80, D-69029 Heidelberg, Germany}

\textsuperscript{1}On leave from Università degli Studi de L’Aquila, Italy

Abstract

The annual modulation of the recoil spectrum observed in an underground detector is well known as the main signature of a possible WIMP signal.

The GENIUS-TF experiment, under construction in the Gran Sasso National Laboratory, can search for the annual modulation of the Dark Matter signal using 40 kg of naked-Ge detectors in liquid nitrogen. Starting from a set of data simulated under the hypothesis of modulation and using different methods, we show the potential of GENIUS-TF for extracting the modulated signal and the expected WIMP mass and WIMP cross section.

1 Introduction

It is generally assumed that our galaxy is embedded in a halo of dark matter particles (WIMPs) with energy density $\rho \approx 0.3 \text{ GeV/cm}^3$ and velocities distributed according to a Maxwellian distribution with parameter $v_0$ (defined
as $\sqrt{\left(\frac{2}{3}\right) v_{\text{rms}}} \) and cut-off velocity equal to the escape velocity in the Galaxy ($v_{\text{esc}} \simeq 650 \text{ km/s}$).

The recoil spectrum produced by WIMP-nucleus scattering in a target detector is expected to show the so-called annual modulation effect, due to the Earth’s motion around the sun [1]. Along the year, the Earth’s velocity with respect to the galactic reference frame ($v_E$) varies according to a cosinus law. It is customary to express the Earth’s velocity in units of the parameter $v_0$ defined above. The adimensional quantity $\eta = v_E/v_0$ shows the following time-dependence:

$$\eta(t) = \eta_0 + \Delta \eta \cos(\omega(t - t_0)), \quad (1)$$

where the amplitude of the modulated component ($\Delta \eta \simeq 0.07$) is small compared to the annual average $\eta_0 \simeq 1.05$. The period and phase of the cosinus function are known to be $\omega = 2\pi/T$ ($T = 1 \text{ year}$) and $t_0 \simeq 2^{nd} \text{ June}$.

In this framework, the expected countrate of WIMP interactions can be written (first order Taylor approximation):

$$S = S_0 + S_m \cos(\omega(t - t_0)) \quad (2)$$

where $S_0 = S_k[\eta_0]$ is the time-independent part and $S_m = \frac{\partial S_k}{\partial \eta} \bigg|_{\eta_0} \Delta \eta$ is the amplitude of the modulated signal.

Both $S_0$ and $S_m$ depend on the WIMP mass $m_W$ and on the WIMP cross section on proton $\sigma_p$, as well as on many astrophysical parameters ($v_0$, $v_{\text{esc}}$, $\rho$) and some properties of the target material.

A calculation of the expected count rate $R$ from WIMP interactions in a germanium detector as a function of the recoil energy $E_R$ can be performed following the formula given in ref.[4]:

$$\frac{dR}{dE_R} = \rho \frac{N \sigma_{\text{Ge}}}{m_{m_W}^2 \text{rad}(m_{\text{Ge}}, m_W) v_0} \frac{g(\eta, E_R)}{\eta} F^2(E_R) \quad (3)$$

where:

$$g(\eta, E_R) = \begin{cases} 
\text{erf}(\xi + \eta) - \text{erf}(\xi - \eta) - \frac{4}{\sqrt{\pi}} e^{-z^2} & \text{if } \xi \leq z - \eta \\
\text{erf}(z) - \text{erf}(\xi - \eta) - \frac{2}{\sqrt{\pi}} (z + \eta - \xi) e^{-z^2} & \text{if } z - \eta \leq \xi \leq z + \eta \\
0 & \text{if } \xi \geq z + \eta 
\end{cases}$$
and the variables $\xi$, $\eta$ and $z$ are listed in Table 1 together with the values of the parameters used in the calculation. The WIMP cross section on germanium $\sigma_{\text{Ge}}$ can be easily related to the correspondant cross section on proton; in the case of spin-independent interaction (SI), the conversion formula is (see [4] and [7]):

$$\sigma_{\text{Ge}} = \frac{m^2_{\text{red}}(m_{\text{Ge}}, m_W)}{m^2_{\text{red}}(p, m_W)} c \sigma_p$$

(4)

where $m^2_{\text{red}}$ is the reduced mass and $c = A^2$.

Table 1
Relevant astrophysical and detector parameters: their expressions and the values used in the present work.

| Parameter | Value |
|-----------|-------|
| $v_E$     | 232 km/s |
| $v_{\text{esc}}$ | 600 km/s |
| $v_0$     | 220 km/s |
| $\rho$    | 0.3 GeV/cm$^3$ |
| $M_{\text{Ge}}$ | 72.59 (uma) |

For the nuclear form factor $F^2(E_R)$, necessary to take into account the finite size of the nucleus, we use a Besselian approximation (see again ref. [4]).

Using formula (3) and its derivative with respect to the quantity $\eta$, we can calculate the expected value of $S_0$ and $S_m$ (units of counts/kg keV day) in our GENIUS-TF experiment for different values of the WIMP mass and cross section, as a function of the energy released in the detector.

The spectra in fig. 1 have been calculated for WIMP masses running from 40 to 100 GeV (in steps of 20 GeV) and for a cross section on germanium of $\sigma_{\text{Ge}} = 10^{-34}$ cm$^2$ (assuming a WIMP mass of 40 GeV this corresponds to $\sigma_p = 2.63 \times 10^{-5}$ pb).

A suitable conversion law for germanium (see [6]) is used to convert the recoil energy of the nucleus ($E_R$) into the visible energy actually released in the detector.

As we can see from fig. 1a, the time-independent component of the signal $S_0$ is exponentially decreasing with the energy masses. The amplitude of the modulated signal $S_m$ (fig. 1b) is only a small fraction of the total signal (note the different scale of the pictures) and moreover its contribution to the total signal $S$ can be not only positive but also negative or zero.

Due to the small entity of the annual modulation effect, a sufficiently high
exposure and a great stability of the experimental conditions over the time are required in order to detect the presence of a possible modulation in a set of experimental data. It is important to point out that two different analyses can be performed: a model-independent analysis, in which only the presence of the modulation is looked for in the data and a model-dependent analysis, where, assuming a complete model framework, one allows (or excludes) a region in the space of the parameters $m_W$ and $\sigma_p$. Therefore, if a modulation signature is discovered in the experimental data, it is possible to extract informations on the WIMP relevant quantities only in the framework of a given model (for example: spin-independent WIMP-nucleon interactions, non-rotating halo, Maxwellian distribution of WIMP’s velocity and so on).

So far, the DAMA experiment has reported results on 4 annual cycles of observation [3] and claims for a positive evidence of the annual modulation effect. In a model independent analysis, the probability of an unmodulated behaviour of the experimental rate is $4 \cdot 10^{-4}$. In the framework of spin-independent (SI) WIMP-matter scattering, the best fit values for the WIMP mass and cross section from the DAMA experiment are $m_W = (43^{+12}_{-9})$ GeV and $\sigma_p = (5.4 \pm 1.0) \cdot 10^{-6}$ pb, where $\rho = 0.3$ GeV·cm$^3$ and $v_0 = 220$ km/s have been assumed.

Since in the present work we have used these values of WIMP mass and cross section for our simulation, we were careful to work in the same framework of ref. [3] and we have used the same values for all the astrophysical parameters (see Table 1).

2 The GENIUS-TF experiment

The GENIUS-TF [8] experiment is born as a test facility for the GENIUS [9] project. It is at present under installation at the Gran Sasso National Laboratory (LNGS) and it is designed to test experimentally some features for the feasibility of the GENIUS experiment.

GENIUS-TF consists of 14 natural Ge crystals (40 kg) operated in a volume of 0.064 m$^3$ ultra-pure liquid nitrogen. The liquid nitrogen is housed by a steel vessel (0.5 mm thick) inside a (0.9 m × 0.9 m × 0.9 m) box of polystyrene foam, with a 5 cm thick inner shield of high purity Ge bricks. Outside the foam box there will be 10 cm of low-level copper, 30 cm of lead and 15 cm of borated polyethylene as shield against the natural radioactivity of the environment.

The general layout of the experiment is shown in fig. 2. The Ge crystals are positioned in two layers on a holder system made of high molecular polyethylene. The signal and high voltage contacts of the crystals are established trying to
minimize the amount of material nearby the detectors, and made of stainless steel (about 3 g). Further details on the setup are described in the GENIUS-TF proposal [8].

Concerning the background, the aim of GENIUS-TF is to reach a level of 2 - 4 counts/(kg y keV) in the energy region below 50 keV (corresponding to about 200 keV nuclear recoil energy). This value is one order of magnitude lower than the actual background of the Heidelberg-Moscow experiment and two orders of magnitude higher than the final goal of GENIUS. Careful simulations of the background, show that the level of counts mentioned above can be reached ([10], [11]). These simulations have been performed taking into account all possible sources of background (natural decay chains, cosmogenic activation by cosmic rays, anthropogenic radionuclides, contribution of neutrons and muons) and assuming standard values for the radioactive contaminations of different materials in the experimental setup.

In the following we assume that the background level for the experiment in the region below 50 keV is \( b = 0.01 \text{ counts/(kg keV day)} \) (corresponding to 4 counts/(kg keV y)).

With this level of background and a detector mass of 40 kg, GENIUS Test Facility can have a physics program of its own in the domain of WIMP search through the annual modulation effect.

It has been already shown [7] that the region of interest for the WIMP mass and cross section indicated by the DAMA experiment is within reach of many future experiments looking for the annual modulation signature.

In the specific case of a germanium detector with a background level of 0.01 counts/(kg keV day) (the same that we assume for our GENIUS-TF) one can fully enter the DAMA region with exposures ranging from 10 to 100 kg·year depending on the energy threshold of the experiment (see fig. 1 and 2 of [7]). Such exposures are achievable by the GENIUS-TF experiment within few years of measurement.

In this work we follow a different approach from [7]; assumed a WIMP of a mass \( m_W \) and cross section \( \sigma_p \) in a given theoretical framework, we simulate a set of experimental countrates and we show which methods can be used in the GENIUS-TF experiment to extract the presence of the annual modulation and the values of the parameters \( m_W \) and \( \sigma_p \).

3 Simulation of experimental data

To analize the potential of GENIUS-TF in searching for the annual modulation effect, we have simulated a set of experimental count rates, as they would be
recorded in our detector under the hypothesis of a WIMP with a given mass and cross section and in the framework of a given model, in the following way.

Let $N_{ij}$ be the number of counts detected in the $i$-th time bin and in the $j$-th energy bin; if there is no WIMP signal we have:

\[
\langle N_{ij} \rangle = b_j M \Delta T_i \Delta E_j
\]  

(5)

where $b_j$ is the expected background in the $j$-th energy bin (as usual in units of counts/keV kg days), $M$ is the detector mass in kg, $\Delta T_i$ the amplitude of the time bin in days and $\Delta E_i$ the amplitude of the energy bin in keV.

If, instead, we assume that WIMPs are contributing to the signal recorded in the detector, equation (5) becomes:

\[
\langle N_{ij} \rangle = [b_j + S_{0,j} + S_{m,j} \cos \omega(t_i - t_0)] M \Delta T_i \Delta E_j.
\]  

(6)

As already mentioned before, we will assume $b_j$ to be constant and equal to 0.01 counts/keV kg days, while for $S_{0,j}$ and $S_{m,j}$ we take the values calculated according to (3) for the corresponding energy bin. Here and in the following we assume $\Delta T_i = 1$ day and $\Delta E_i = 1$ keV.

If $N_{ij}$ is a Poisson-distributed random variable with mean $\mu_{ij}$ given by eq. (6), we can obtain the desired count rates calculating for each time and energy interval the value of $\mu_{ij}$ and then randomly extracting $N_{ij}$ from the Poisson distribution: $P(N, \mu_{ij}) = e^{-\mu_{ij}} \frac{\mu_{ij}^N}{N!}$.

Such a simulation has been performed for the energy-interval (0, 50) keV, for this is the region where a possible signal should be searched for [7]. For the WIMP mass $m_W$ we have chosen values around the best-fit result of the DAMA experiment (40, 50, 60 GeV) since we wanted first of all to understand the potential of GENIUS-TF for testing the region of parameters allowed, at the moment, by the DAMA experiment. We have also assumed a cross section on proton of $5.4 \cdot 10^{-6}$ pb, corresponding to the best-fit value of the DAMA analysis for $v_0 = 220$ km/s.

4 Modulation analysis

The way to extract the modulated signal, with the proper period and phase, from a set of experimental data has been discussed by many authors in the literature ([2], [3], [7], [12]-[14]). In the present work we will apply 3 different methods: first we try to identify, at a certain confidence level, the presence of the modulation in our data, then we apply the maximum likelihood method to find out the values of the WIMP’s relevant parameters.
4.1 The modulation significance

Following [2] and defining $S_i$ the number of counts collected in the i-th day of observation integrated over a given energy interval

$$S_i = \sum_{j=E_i}^{E_f} N_{ij},$$

we can project out the modulated component of the data through the variable $r$, called modulation significance:

$$r = \frac{\sum_i 2 \cos \omega (t_i - t_0) S_i}{\sqrt{2} \sum_i S_i}$$ \hspace{1cm} (7)

If no modulation is present in the data the variable $r$ is expected to be nearly Gaussian distributed with zero mean and unit variance. On the contrary, for experimental data modulated according to (2), the mean value of $r$ will be no longer zero, but it will increase with the collected statistics. At the same time the distribution of the variable $s$:

$$s = \frac{\sum_i 2 \sin \omega (t_i - t_0) S_i}{\sqrt{2} \sum_i S_i}$$ \hspace{1cm} (8)

orthogonal to $r$, will be unaffected by the presence of a modulation.

Once a value $r_0$ of $r$ has been measured in an experiment, one can exclude the absence of the annual modulation (with the correct period and phase) at a confidence level given by:

$$C.L. = \frac{1}{2} + \frac{1}{\sqrt{2}} \text{erf} \left[ \frac{r_0}{\sqrt{2}} \right]$$ \hspace{1cm} (9)

The choice of the energy interval $(E_i, E_f)$ where we integrate the signal is important. It is well known that one should avoid the so-called cross-over region, i.e. the region where the differential spectra of June (maximum) and December (minimum) cross. Integrating over this region could hide a possible signal. The cross-over energy $(E_C)$ depends on the WIMP mass and on the $v_0$ parameter; in case of Ge detectors $E_C$ usually lies between 1 and 30 keV [13]. In fig. 3 we have explicitly calculated its value as a function of the WIMP mass assuming as usual $v_0 = 220$ km/s. The result is in agreement with [13].

In fig. (4) we report the distributions of the values for the estimators $r$ and $s$ that would be measured in $10^3$ experiments like GENIUS-TF after two years of measurement, in the case of a WIMP with mass of 40 GeV and $\sigma_p = 5.4 \cdot 10^{-6}$ pb.
As it is easy to see, the distribution of the variable \( s \) is the expected Gaussian centered around zero and with unit variance, while the \( r \) distribution is shifted to higher values of the variable, indicating the presence of the modulation. The distribution of the variable \( r \) under the same assumptions but without assuming the modulation (only background) is shown in fig. (5), again compared to the distribution under the hypothesis of modulation and, as expected, it shows no sign of a deviation from the zero mean.

For our purposes is interesting to consider the distribution for the modulated data-set. Measuring a value of \( r \) equal to the mean value of the distribution in fig. (4) will allow us to reject the hypothesis of no modulation with a confidence level \( C.L. = 0.99\% \).

Obviously, once we set a value for the confidence level \( \alpha \) at which we reject the hypothesis of no modulation, there is still a probability to fail in detecting the modulation at a confidence level \( (1 - \beta) \), depending on the overlap region between the two distributions (see [15]). If for example, referring to fig. (4), we set \( \alpha = 97.5 \) \( (r_0 = 2) \) we will report a positive evidence of the modulation only if the measured value of \( r_0 \) is greater than 2 and this correspond to an error of the second kind \( (1 - \beta) = 35\% \) (integral of the \( r \) distribution on the interval \( (0,2) \)). If we want to have a lower error (for the same value of \( \alpha \)) we should wait until the two distributions are separated enough, as for example in fig. (6), with the same assumptions as in (4) and considering 4 years of measurements. In this case we will fail in detecting the modulation hidden in the data only in a small fraction of the experiments \( (1 - \beta = 8\%) \).

| \( m_W \) | years | \( \langle r \rangle \) | C.L.    |
|----------|-------|----------------|--------|
| 50 GeV   | 2     | 2.60           | 99.2 % |
| 50 GeV   | 4     | 3.74           | 99.9 % |
| 60 GeV   | 2     | 2.36           | 98.8 % |
| 60 GeV   | 4     | 3.37           | 99.9 % |

Table 2
Mean value of the modulation significance \( r \) obtained in \( 10^3 \) simulated experiments for different WIMP masses and measuring time in years. The last column contains the confidence level at which we could exclude the absence of the modulation when a value of \( r \) equal to \( \langle r \rangle \) is measured.

The distribution of \( r \) for the modulated data-set shows no substantial variation when we move the left limit of the energy interval where we integrate the signal \( (E_i) \) from 4 keV to 8 keV. Increasing \( E_i \) above 8 keV, the mean value of the distribution slowly decreases; this is an indication that we are missing part of the signal that, as we recall here, is concentrated in the lower energy bins. For this reason is of primary importance to have a low experimental threshold.
We have repeated the same simulation for different WIMP masses and the same cross section; in tab. (2) we report, for different measuring times, the mean value of the $r$ distribution (for the modulated data-set) together with the corresponding confidence level $\alpha$.

4.2 Extracting the modulated amplitude $S_m$

Calculating the value of the above mentioned estimators $r$ and $s$ is not the only way to discover the modulation hidden in the data. Given our set of experimental data, we can try to extract directly the value of $S_m$, the amplitude of the modulated signal, as a function of the energy.

Following [1], we can write:

$$S_m = \frac{\sum_i 2 \cos \omega (t_i - t_0) S_i}{N}$$

(10)

$$\sigma(S_m) = \frac{\sqrt{\sum_i 2 [\cos \omega (t_i - t_0)]^2 S_i}}{N}$$

(11)

where $N$ is the running time of the experiment and $S_i$ is no more integrated over a broad energy region but in small energy bins (1 or 2 keV). In this way it is possible to measure the amplitude of the modulated signal and its error for each energy bin (of the given size) and moreover, taking small energy bins we avoid the problem of the cross-over energy.

In picture (7) we report a typical result for the amplitude of the modulated signal $S_m$ as calculated using (10) on the simulated data without and with modulation ($m_W = 40$ GeV and $\sigma_p = 5.4 \cdot 10^{-6}$ pb). The energy region between 4 and 50 keV has been divided in 2 keV energy bins and for each one the value of $S_m$ and the corresponding error have been calculated.

By looking at the two pictures (note the different scales on the $y$ axis), we see how the distribution $b$ represents an indication of an annual modulation amplitude $S_m \neq 0$. In the case with modulation (b) all the data points are compatible within the error with the theoretical signal while in the case where no modulation is present (a) the same points are distributed around zero. The big errors are due to the low statistic and become smaller if we increase the measuring time.

Averaging the signal in the region from 4 to 16 keV, we obtain in the case of modulation: $\langle S_m \rangle = 0.0024 \pm 0.0016$ counts/keV day, while in the case of no modulation we have: $\langle S_m \rangle = -0.00034 \pm 0.0006$ counts/keV day, compatible with the hypothesis $S_m = 0$.  

9
4.3 The maximum likelihood method

One of the general procedures to treat experimental data when searching for the annual modulation effect is to use the maximum-likelihood method. The likelihood function \( L \) for a set of experimental rates \( N_{ij} \), assuming that they are Poisson-distributed, is:

\[
L = \prod_{ij} e^{-\mu_{ij}} \frac{\mu_{ij}^{N_{ij}}}{N_{ij}!}.
\]

Since \( \mu_{ij} \) depends on the parameters of interest \( m_W \) and \( \sigma_p \), through the expressions of \( S_{0,j} \) and \( S_{m,j} \), it is possible to obtain the best-fit value for the parameters minimizing \( \log L \), or better the function:

\[
y(m_W, \sigma_p) = -2 \log L + \text{const} = \sum_{ij} 2\mu_{ij} - 2N_{ik} \log \mu_{ij} + \text{const}
\]

where the constant contains the components that do not depend on \( m_W \) and \( \sigma_p \). The minimization of \( y(m_W, \sigma_p) \) is not an easy operation: if we want to keep as a free parameter the number of background counts in each energy bin (and here we consider as background the number of counts due to the time-independent component of the signal \( (S_0 + b) \)) we have to deal with many parameters.

The usual procedure is to carry out the minimization in two steps. As a first step we minimize with respect to the time-independent component \( f_j = b_j + S_{0,j} \). During this minimization the condition \( f_j > 0, j = 1, N_{\text{bin}} \) is imposed. As a second step we minimize with respect to \( \sigma_p \) and \( m_W \) requiring, as is usual done:

\[
\begin{align*}
(b_j + S_{0,j}) &= f_j & \text{if } \sigma_p S_{0,j} \leq f_j \\
(b_j + S_{0,j}) &= \sigma_p S_{0,j} & \text{otherwise.}
\end{align*}
\]

We did not impose limits or conditions on the parameters \( \sigma_p \) and \( m_W \) except that both have to be greater than zero.

We have carried out the minimization procedure on the data set simulated under the mentioned hypothesis \( m_W = 40 \) GeV and \( \sigma_p = 5.4 \cdot 10^{-6} \) pb, in the energy range from 5 to 40 GeV. After the first step we obtain the values of the quantity \( f_j = b_j + S_{0,j} \) for each energy bin: we have plotted that result in fig. (8) and this reproduces exactly the curve \( f = b + S_0 \) that we have used in the simulation.

In the second step we obtain the best-fit values for the parameters of interest.
The minimization procedure converged for the selected energy window, giving
the following best-fit values for the fit parameters:

\[ m_W = (39.9 \pm 5.6) \text{ GeV} \]
\[ \sigma_p = (7.0 \pm 1.6) \cdot 10^{-6} \text{ pb} \]  (13)

The value of the WIMP mass is in excellent agreement with the real one used
in the simulation; the value of the cross section, though compatible within 1\( \sigma \) with the true value, shows a lower agreement: this can be due to the fact
that \( m_W \) influences the shape of the WIMP spectrum while \( \sigma_p \) appears only
as a multiplying factor.

We repeated the fitting procedure assuming different values of the energy
threshold of the experiment (3 and 4 keV), finding very little difference from
the given best-fit.

The set of best-fit values (13) corresponds to the 2\( \sigma \) allowed region shown in
fig. (9). This region of the plane \((\sigma_p, m_W)\) has been calculated using:

\[ y(\sigma_p, m_W) - y_{\text{min}} \leq n^2. \]  (14)

with \( n = 2 \) and \( y_{\text{min}} \) being the result of the fitting procedure.

Fig. 9 should be interpreted in this way: if a WIMP exists with the properties
assumed so far, we can point out its presence within two years of measurement
(80 kg \( y \) significance) and give the result in Fig. 9 for the 2\( \sigma \) allowed region
for the relevant parameters.

Conclusions

The annual modulation, due to the motion of the earth with respect to the
galactic halo, is the main signature of a possible WIMP signal. The effect is
supposed to be small, only a few percent of the total Dark Matter signal, and
therefore very difficult to extract. A positive indication of this modulation has
been found over the past five years by the DAMA experiment and it would
be of great importance to look for the same effect with another experiment,
expecially in the region of the WIMP parameter’s space indicated by the
DAMA results.

The GENIUS-TF experiment [8], born as a prototype for the GENIUS project,
is at present under installation at the Gran Sasso National Laboratory. With
a mass of 40 kg and a background of 4 counts/(kg \( y \) keV), GENIUS-TF can
be used to look for Dark Matter, not only through the direct detection of
WIMP-induced nuclear recoils, but also through the annual modulation of the
experimental rate. GENIUS-TF will be - in addition to DAMA [18] - the only
experiment which will be able to probe the annual modulation signature in a foreseeable future. The at present much discussed cryo detector experiments, such as CDMS [19], CRESST [20], EDELWEISS [21] have no chance to do this because the mass projected to be in operation in these experiments is by far too low (see also [17]).

We have developed a set of routines and tools to look for the annual modulation effect with our GENIUS-TF experiment using different analysis methods discussed in the literature. We have analysed data simulated under the hypothesis of modulation, using three different approaches (modulation significance, direct calculation of the modulation amplitude $S_m$ and maximum likelihood fit of the data) and we have shown that the mass and the low background level of GENIUS-TF will allow us to test, within few years of measurements, low WIMP masses and WIMP cross sections in the region of interest indicated by the DAMA experiment. A digital multi-channel spectroscopy system with 100 MHz flash ADC’s for the GENIUS-TF project has been recently developed [16].

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Fig. 1. Expected WIMP rate in Ge for \( m_W = 40, 60, 80, 100 \) GeV (from top to bottom) and \( \sigma_{Ge} = 10^{-34} \) cm\(^2\): a) time-independent component of the signal \( (S_0) \); b) amplitude of the modulated component \( (S_m) \).
Fig. 2. A schematic view of the GENIUS-TF experiment.

Fig. 3. Cross-over energy in Ge as a function of WIMP mass. We assume $v_0 = 220$ km/s.
Fig. 4. Distributions of the estimators $r$ (blue histogram) and $s$ (red histogram) for $10^3$ simulated experiments in the case: $m_W = 40$ GeV and $\sigma_p = 5.4 \cdot 10^{-6}$ pb. The measuring time is 2 years and the energy interval where the signal is integrated is from 4 keV to 50 keV.

Fig. 5. Distributions of the estimator $r$ for $10^3$ simulated experiments in the case of modulated (blue histogram, $m_W = 40$ GeV and $\sigma_p = 5.4 \cdot 10^{-6}$ pb) and unmodulated data (red histogram). The measuring time is 2 years and the energy interval where the signal is integrated is (4-50) keV.
Fig. 6. Distributions of the estimators \( r \) and \( s \) for \( 10^3 \) simulated experiments in the case: \( m_W = 40 \text{ GeV} \) and \( \sigma_p = 5.4 \cdot 10^{-6} \text{ pb} \). The measuring time is 4 years and the energy interval where the signal is integrated is from 4 keV to 50 keV.

Fig. 7. Amplitude of the modulated signal extracted from the simulated data using eqn.(10): a) when no modulation is present in the data; b) when a WIMP is assumed with \( m_W = 40 \text{ GeV} \) and \( \sigma_p = 5.4 \cdot 10^{-6} \text{ pb} \). The full squares in picture (b) represent the theoretical signal for the given WIMP mass and cross section. Both the pictures correspond to a measuring time of 2 years.
Fig. 8. The time-independent component of the signal $f = b + S_0$: what we have simulated (red triangles) and what we obtain in the first step of the minimization procedure (solid histogram).

Fig. 9. Allowed region at $2\sigma$ C.L. corresponding to the best-fit values of (13). The region is calculated using eq. (14) and has to be interpreted as the result that can be given by GENIUS-TF after two years of measurement if a WIMP exists with the properties assumed so far.