Light Dark Matter Search with AURIGA

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We present a search for a new scalar particle, called moduli, performed using the cryogenic resonant-mass gravitational wave detector AURIGA. This particle may give a significant contribution to the Dark Matter (DM) in our Universe. DM clusters under the galaxies gravitational effect, forming the so called galactic halo. The interaction of ordinary matter with a DM halo composed by moduli causes the oscillation of solids with a frequency equal to the mass of the DM particle. In particular, the putative signal would appear as a narrow peak ($\triangle f \sim 1\,\text{mHz}$) in the sensitive band of AURIGA, some 100 Hz at about 1 kHz. We used high quality data, selected out of an acquisition of years of continuous running. The search sets upper limits at 95% $C.L.$ on the moduli coupling to matter $d_i \lesssim 10^{-5}$ around moduli masses $m_\Phi = 3.6 \cdot 10^{-12}\,\text{eV}$.

1 Light Dark Matter and matter effects

Scalar fields, Φ, often arise in theories like the String Theory (known as moduli), with mass values, m_Φ, depending on the assumed model. They are good Dark Matter (DM) candidates, within the contest of the standard DM model with an energy density of $\rho_{DM} = 0.3\,\text{GeV/cm}^3$, if they are heavier than $m_\Phi \simeq 10^{-22}\,\text{eV}$. Moreover, this scalar field can be described with a classical wave if it is lighter than $m_\Phi \simeq 0.1\,\text{eV}$ [1]:

$$\Phi(\mathbf{x}, t) = \Phi_0 \cos(m_\Phi t - m_\Phi \mathbf{v} \cdot \mathbf{x}) + O(\mathbf{v}^2). \tag{1}$$

Moduli interact with ordinary matter, in particular with electrons and electromagnetic field:

$$\mathcal{L} \supset \sqrt{4\pi \mathrm{G_N}}\Phi \left[d_{m_e} m_e \bar{e} e - \frac{d_e}{4} F_{\mu\nu} F^{\mu\nu} \right], \tag{2}$$

where G_N is the Newton's constant, d_{m_e} and d_e are the dimensionless coupling to the electron and electromagnetic field, respectively (expressed as a fraction of the gravitational strength). As shown in eq. 2, the effect of moduli can be absorbed by the fine structure constant, α, and electron mass m_e:

$$\alpha(\mathbf{x}, t) = \alpha \left(1 + d_e \sqrt{4\pi G_N} \Phi(\mathbf{x}, t) \right), \tag{3}$$

$$m_e(\mathbf{x}, t) = m_e \left(1 + d_{m_e} \sqrt{4\pi G_N} \Phi(\mathbf{x}, t) \right). \tag{4}$$

Taking into account eq. 1, relations 3 and 4 imply an oscillation of the fine structure constant and of the electron mass around their physical values. As a consequence, also the atom's size,

$a_0 \sim 1/\alpha m_e$, oscillates, with a deformation (strain) with respect the nominal value given by:

$$h \equiv \frac{\delta a_0}{a_0} = -\left(d_e + d_{m_e}\right)\sqrt{4\pi G_N}\,\Phi(\mathbf{x}, t). \tag{5}$$

This effect of moduli on ordinary matter, leads us to the following conclusion: supposing we have a cylindrical body of length L_c; its fundamental mode can be modeled as an oscillator made of two masses connected by a spring of effective length $L_s \sim L_c$; it can be shown that given eq. 5 the effect of moduli is an external force acting on the oscillator, with an expression similar to that of a tidal force produced by a gravitational wave on a resonant detector [1]. This behaviour suggests an experimental method to search for such a moduli field, exploiting same apparatus and analysis techniques employed for gravitational wave signals.

2 Auriga detector

We searched for moduli by analyzing the data of the resonant mass gravitational wave detector AURIGA [2]. Located at INFN National Laboratory of Legnaro (Italy), AURIGA represents the state-of-art in the class of gravitational wave cryogenic resonant-mass detectors. The detector can be modeled by 3 coupled resonators, with nearly the same resonant frequency $f_R \simeq 900\,\mathrm{Hz}$: the core is a cylindrical bar made of an aluminium alloy, which would resonate under the effect of moduli with the right mass range; the mechanical energy of the bar is amplified by a mashroom-shaped resonator, attached to one of the bar's faces, acting also as a transducer, converting the mechanical resonance to an electrical current; the transducer efficiency is further increased by placing the resonance frequency of an electrical LC circuit close to the mechanical resonance frequencies. The electrical signal is detected by a sensitive SQUID amplifier. AURIGA is operated at cryogenic temperatures, with $T = 4.5\,\mathrm{K}$. The system is in thermal equilibrium, thus its fluctuations are described by the Fluctuation-Dissipation theorem. This allows us to model the detector noise with good precision. In particular the detector sensitivity set by the thermal noise is $h = 2 \cdot 10^{-21}\, 1/\sqrt{\mathrm{Hz}}$, within a factor of 2, over a bandwidth of $\triangle f \simeq 100\,\mathrm{Hz}$ centered around $f = 900\,\mathrm{Hz}$.

3 Data analysis

The output from the detector is an electrical signal in time digitized with a frequency of $f_s = 4882.8125\,\mathrm{Hz}$. A calibration procedure [3] is applied on these data to convert them into the strain h of the AURIGA resonant bar length. The power spectrum is computed on the calibrated data, obtaining a measure of the noise of the system in thermal equilibrium. The signal we would expect from moduli is a peak in this power spectrum. The peak would have a characteristic frequency around the moduli mass, $f_\Phi = m_\Phi/2\pi$, and a narrow Maxwell-Boltzmann shape [4]. A simulation of this signal has been performed to study the actual signal bandwidth within the detector sensitive region and to fine-tune the analysis workflow. The simulation takes into account that the detector noise around the moduli peak is white, given the narrow bandwidth of the signal.

The estimated signal bandwidth from simulation is $\triangle f \simeq 1\,\mathrm{mHz}$. Therefore, the analyzed dataset has been split into one hour long data streams and power spectrum computation has been performed on each stream to achieve the proper spectrum resolution. Eventually, the

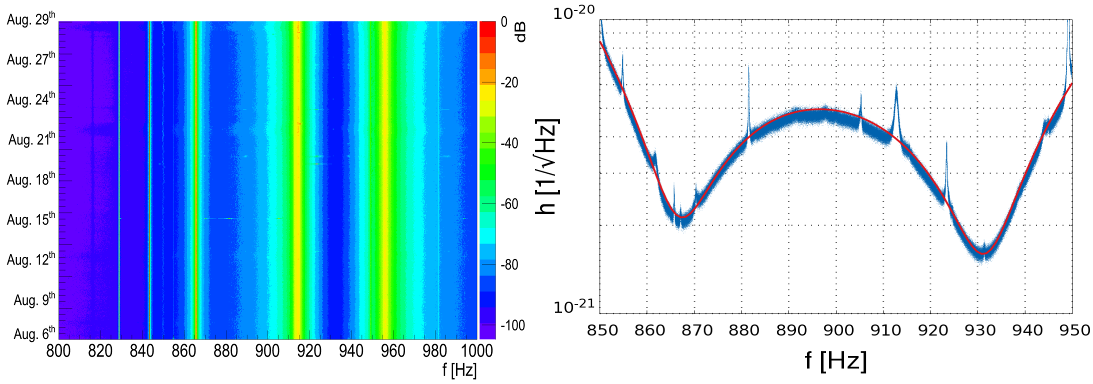

Figure 1: (color online). [left] Evolution of the detector noise spectrum during the data-taking period considered for the analysis. The three main modes of the detector are shown by the yellow-green area. [right] Frequency spectrum of the bar strain computed on AURIGA data (blue curve), compared to the predicted noise power spectrum density by Fluctuation-Dissipation theorem plus noise contribution from the SQUID (red line). Spurious peaks are due to external known sources of background.

one hour long power spectra are averaged to reduce the noise standard deviation and gain sensitivity. Actually, few weeks of data are enough to reach the sensitivity plateau for this kind of signal, which looses its coherence in about one hour and its standard deviation decreases with the number of averages N as $N^{1/4}$. Using the entire dataset acquired by AURIGA (~ 10 years) would improve the sensitivity just by a factor of ~ 3. So that, for this analysis we focused on a dataset corresponding to about one month of data-taking. AURIGA detector has been running in stable conditions during this period: stability of the detector is inferred by the stable frequencies and shape of the three main detector's modes, checked by studying the evolution of the detector power spectrum on the analyzed dataset, shown in fig. 1-left. Spikes in time due to energetic background events could hide a possible signal from moduli and have been removed by excluding data streams which have a large fluctuation in the time domain. This cut still allows to maintain a 86% duty-cicle of the detector. A check is performed to prove we are not throwing away a possible signal from moduli: a simulated moduli signal has been injected into the real dataset and the analysis workflow successfully reconstructs it. Neither a loss nor an attenuation of the signal strength is observed.

The power spectrum of the measured bar strain is shown in fig. 1-right, obtained by averaging N = 400 power spectra from 1 hour long data streams. The comparison to the predicted noise shows a good agreement. The thickness of the data curve is due to the noise variance, reduced by averaging the N power spectra. Spurious peaks in data correspond to associated external sources of noise. We stress that these spurious peaks have shape and width that do not match the expected signal. Data corresponding to spurious peaks have been excluded from the analysis, since we are not able to model the detector response in those regions. Each bin of the power spectrum in fig.1-right has a gaussian distribution: this has been demonstrated by studying the distribution of the bin values and can be understood from statistical reasons, since the power spectrum is the result of averaging a large number ($N = 400$) of single spectra. Consequently, we used a gaussian probability density function to describe the bin statistics and

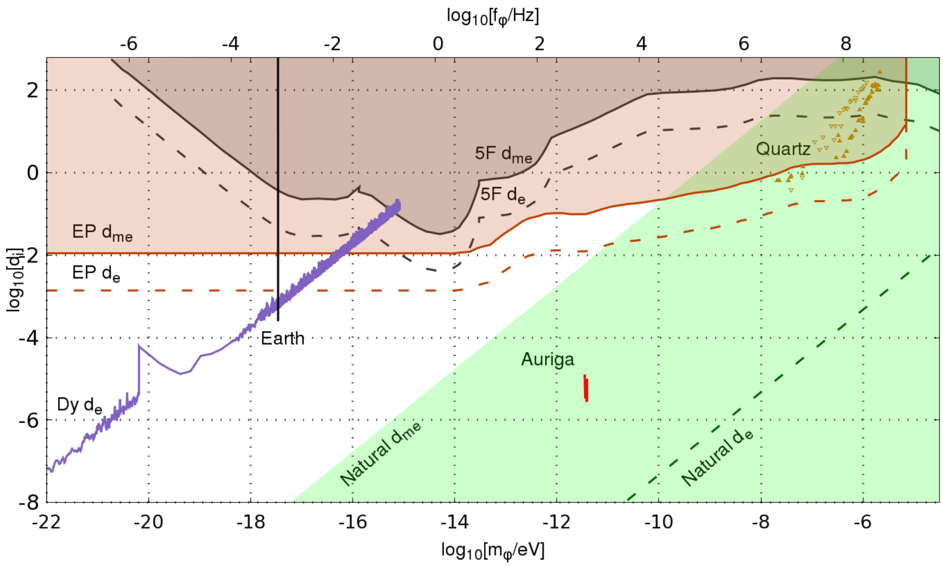

Figure 2: (color online). Upper limits on the coupling of both an electron mass modulus ($d_i = d_{m_e}$) and an electromagnetic gauge modulus ($d_i = d_e$) to ordinary matter (red-curve) obtained from AURIGA data and reported in the moduli parameter space: bottom and top horizontal axes represent the moduli mass m_Φ and corresponding frequency $f_\Phi = m_\Phi/2\pi$, vertical axis represents the moduli coupling values. Depicted green area shows the natural parameter space preferred by theory. Other regions and dashed curves represent 95% $C.L.$: limits on fifth-force tests (5F, gray), equivalence-principle tests (EP, orange), atomic spectroscopy in dysprosium (Dy, purple-line), low frequency terrestrial seismology (Earth, black vertical line) and piezoelectric quartz resonators (Quartz, yellow-triangles).

build a confidence belt by using Feldman and Cousin recipe [5]. The confidence belt provides a confidence interval for the moduli signal strength, given the measured value of h for each bin of the distribution in fig. 1-right. The signal strength is always compatible with zero, thus we set upper limits on the moduli coupling to ordinary matter at 95% confidence level. We improved the upper limit calculation by exploiting the noise curve obtained adding thermal noise prediction from Fluctuation-Dissipation theorem and noise contribution from the SQUID (see fig. 1-right). The curve is fitted to data and upper limits are obtained from the χ^2 distribution. Thus, a more precise estimation of errors from the fit allows us to improve the upper limits. Final upper limits on moduli coupling to ordinary matter are reported in fig. 2. They are better then $d_i \simeq 10^{-5}$ in the sensitive band of AURIGA, $\triangle f = [850, 950]$ Hz, and cover for the first time an interesting physical region of the parameter space, within the natural parameter space for moduli [1].

References

[1] A. Arvanitaki, S. Dimopoulos, K. V. Tilburg, Sound of Dark Matter: Searching for Light Scalars with Resonant-Mass Detectors, Phys. Rev. Lett. **116**, 031102 (2016).

[2] M. Cerdonio, M. Bonaldi, D. Carlesso et al, The ultracryogenic gravitational-wave detector AURIGA, Class. Quantum Grav., 14 (1997) 1491;

[3] A. Vinante, Present performance and future upgrades of the AURIGA capacitive readout, Classical Quantum Gravity 23, S103 (2006).

[4] L. Krauss, J. Moody, F. Wilczek, D. E. Morris, Calculations for cosmic axion detection, Phys. Rev. Lett. 55, 1797 (1985).

[5] G. J. Feldman, R. D. Cousin, A Unied Approach to the Classical Statistical Analysis of Small Signals, Phys. Rev. D 57, 3873-38891 (1998).

[6] Proceeding of the Fifth Young Researchers Workshop “Physics Challenges in the LHC Era” 2016, Frascati Physics Series, Volume LXIII.