Light DM search with AURIGA

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Contents

Light Dark Matter

- moduli (ϕ): scalar fields from string theory;
- mass values, m_ϕ, model dependent;
- good dark matter (DM) candidate:
  - Standard Halo Model assumed with $\rho_{DM} = 300\, MeV/cm^3$ and Maxwell-Boltzmann velocity distribution;
  - heavier than $m_\phi \simeq 10^{-22}\, eV$;
  - classical wave description: lighter than $m_\phi \simeq 0.1\, eV$:

$$\phi(\mathbf{x}, t) = \phi_0 cos(m_\phi t - m_\phi \mathbf{v} \cdot \mathbf{x}) + O(\mathbf{v}^2)$$

Reference: A. Arvanitaki, S. Dimopoulos, K. V. Tilburg, Phys. Rev. Lett. 116, 031102 (2016);

Light Dark Matter

Interaction of moduli with ordinary matter:

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

effects of moduli can be absorbed by the fine structure constant (α) and electron mass (m_e):

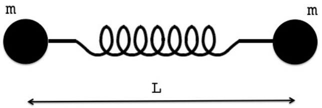
$$\alpha(\mathbf{x}, t) = \alpha(1 + d_e \sqrt{4\pi G_N}\phi(\mathbf{x}, t))$$

$$m_e(\mathbf{x}, t) = m_e(1 + d_{m_e} \sqrt{4\pi G_N}\phi(\mathbf{x}, t))$$

Consequence: oscillation of the atom's size ($a_0 = 1/\alpha m_e$) in a body of length L:

$$h \equiv \frac{\delta L}{L} = -(d_e + d_{m_e})\sqrt{4\pi G_N}\phi(\mathbf{x}, t)$$

Effects on an oscillator



The equation of motion is given by:

$$\ddot{x} + \frac{\omega}{Q}\dot{x} + \omega^2(x - L) = F_{ext} + F_{th}$$

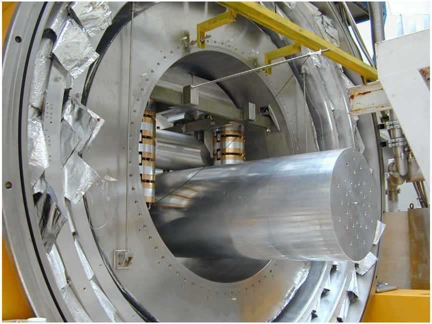
Rewriting: $\xi = x - L$ (displacement) $\Rightarrow$ $\ddot{x} = \ddot{\xi} + \delta L = \ddot{\xi} + \ddot{h}L$:

$$\ddot{\xi} + \frac{\omega}{Q}\dot{\xi} + \omega^2\xi = -\ddot{h}L + F_{ext} + F_{th}$$

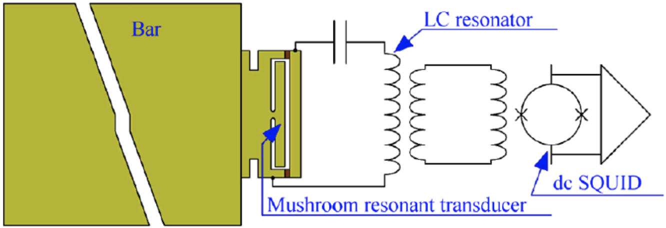
similar to the one of gravitational wave antenna subject to GW tidal force.

Antenna

Searching for moduli can be performed exploiting the same experimental apparatus (AURIGA @ LNL) and same analysis techniques as for the search of GW signals.



AURIGA detector: read-out scheme

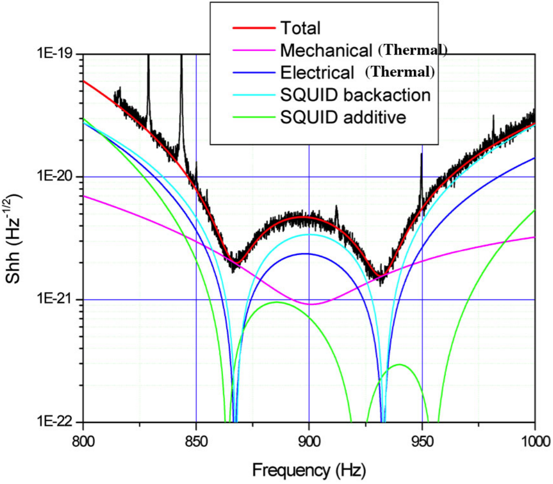


System components: 3 coupled resonators (nearly same $f_R \sim 900\,Hz$):

1. cylindrical bar (aluminium alloy);
2. mashroom-shaped resonator;
3. electrical LC circuit;

Operated at cryogenic temperature: $T = 4.5\,K$;

AURIGA detector: sensitivity



- detector in thermal equilibrium: its fluctuations are described by the Fluctuation-Dissipation theorem
- sensitivity (set by thermal noise) within factor 2:

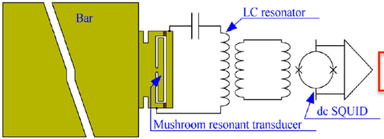
$$h \simeq 2 \cdot 10^{-21}\, 1/\sqrt{Hz}$$

over a bandwidth of:

$$\triangle f \simeq 100\ Hz$$

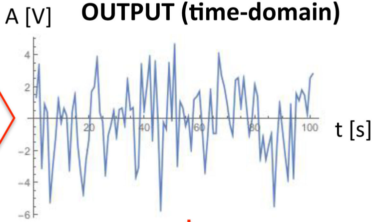
Analysis Workflow

AURIGA DETECTOR

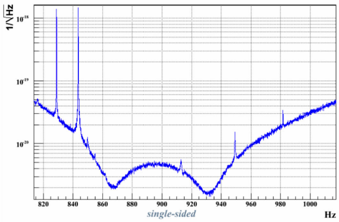


READOUT

OUTPUT (time-domain)



Power Spectrum (FFT) + Transfer Function

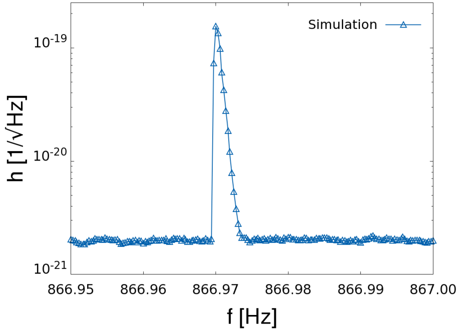


Measured strain of the AURIGA bar:

- thermal noise of a system in thermodynamic equilibrium;

Signal characterization

SIGNAL SIMULATION



f_ϕ [Hz]	$(d_{m_e} + d_e)$	σ_{noise} [$1/\sqrt{Hz}$]
~ 867	$5 \cdot 10^{-4}$	$2 \cdot 10^{-21}$

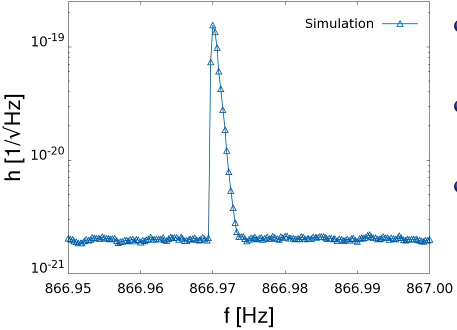
DM moduli model: stochastic process with Maxwell-Boltzmann distribution. Maximum approximately:

$$h_0 \simeq \frac{1.5 \cdot 10^{-16} (d_{m_e} + d_e)}{\left(\frac{1}{3} f_\phi \left\langle v^2 \right\rangle\right)^{\frac{3}{4}} f_\phi}$$

- f_ϕ moduli frequency;
- $\left\langle v^2 \right\rangle \sim 10^{-6}$, DM halo squared velocity;
- Bandwidth: $\triangle f \sim 1\, mHz$;

Power spectrum (PWS) estimation

SIGNAL SIMULATION

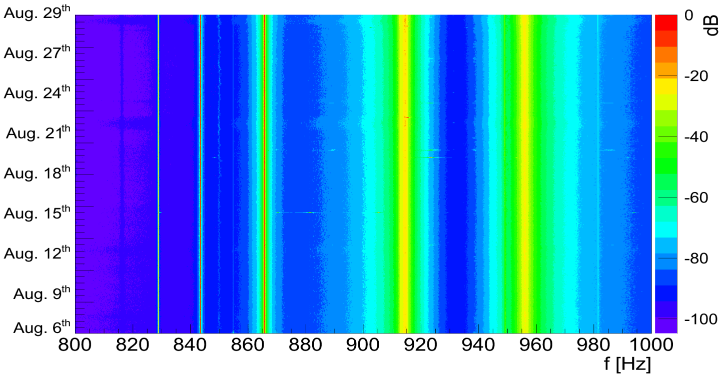


- proper spectrum resolution: N PWSs computed on 1h long data-streams;
- reduce noise standard deviation: the N PWSs are averaged;
- few weeks of data to reach sensitivity plateau: standard deviation of signal fluctuation $\sim N^{-1/4}$;

- Bandwidth: $\triangle f \sim 1\,mHz$;

Dataset and data quality

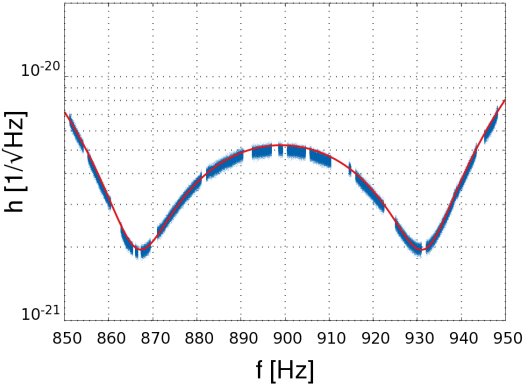
Dataset considered for analysis: August 2015 data. Time-frequency view:



- stable detector conditions: constant mode frequency and shape;
- energetic background events (spikes at fixed time): cut-off by RMS requirement (86% detector duty-cicle);

Measured PWS

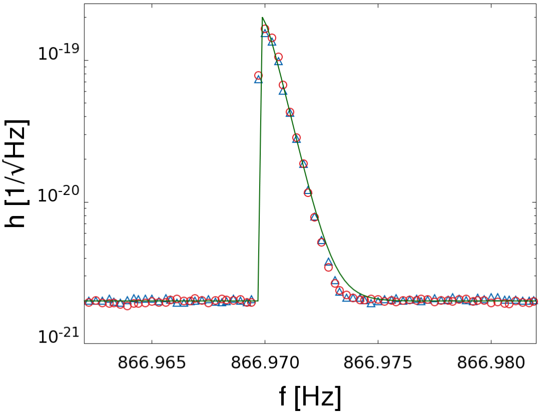
Spectrum of the measured bar relative deformation compared to theory prediction:



- one-sided power spectrum;
- from $N = 400$ averaged power spectrums;
- good agreement with prediction ($\sigma_{Th} \sim 5 - 10\,\%$);
- spurious peaks discarded;

Test: signal injection

Comparison: full simulation vs signal injection

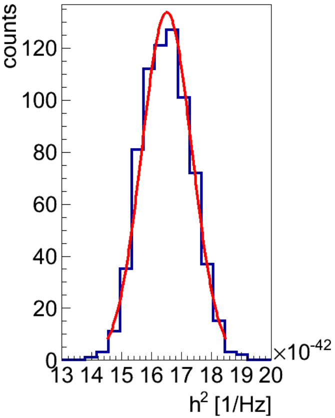


Signal parameters	
f_ϕ [Hz]	$(d_{m_e} + d_e)$
~ 867	$5 \cdot 10^{-4}$

- signal well reconstructed;
- no reduction due to RMS cut;

Statistical analysis

Bins' spectrum statistic

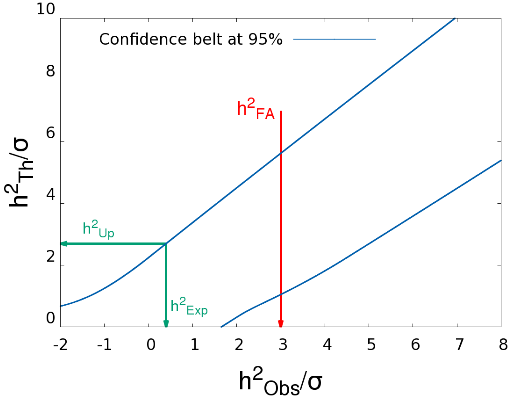


f [Hz]	$\langle h^2 \rangle$ [$\frac{1}{Hz}$]	σ_{h^2} [$\frac{1}{Hz}$]	χ^2/ndf
857	$1.65 \cdot 10^{-41}$	$1.11 \cdot 10^{-42}$	6.3/5

- gaussian PDF describing bin statistics;
- PDF is used to build the confidence belt in the parameter space (h^2_{obs}, h^2_{Th});

Confidence belt

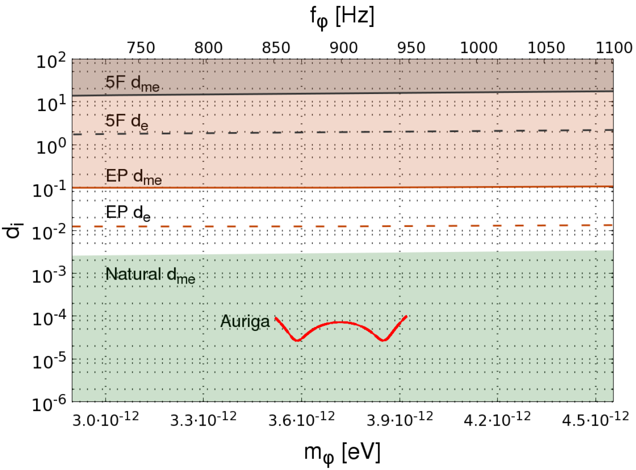
Reference: G. J. Feldman, R. D. Cousin, Phys. Rev. D 57, 3873-38891 (1998).



- h^2_{FA}: false alarm probability threshold of 3σ from background only hypothesis;
- h^2_{Exp}: observed value (for a given bin);
- h^2_{Up}: upper limit corresponding to experimental value;

Upper Limits

Upper limits on h interpreted as upper limit on the DM couplings to ordinary matter: $h_0 \simeq 1.5 \cdot 10^{-16}(d_{m_e} + d_e)/\left(\frac{1}{3} f_\phi \left\langle v^2 \right\rangle\right)^{\frac{3}{2}} f_\phi$

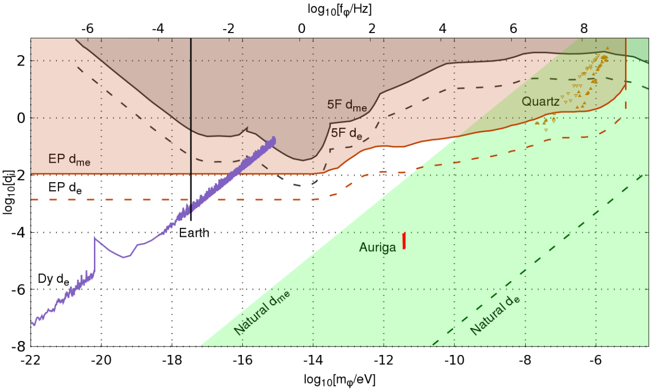


- reached sensitivity on DM couplings: $d_i \simeq 10^{-4}$;
- bandwidth sensitivity: $\triangle f \simeq 100\ Hz$

FIRST TIME EVER!

Upper Limits: wider view

Comparison with other upper limits:



From: A. Arvanitaki, S. Dimopoulos, K. V. Tilburg, Phys. Rev. Lett. 116, 031102 (2016)

- Natural: natural parameter space (theory);
- 5F and EP: fifth force and equivalence principle tests;
- Dy: sensitivity of atomic spectroscopy in dysprosium;
- Earth: low frequency terrestrial seismology;
- Quartz: sensitivity of piezoelectric quartz resonators;

Conclusions

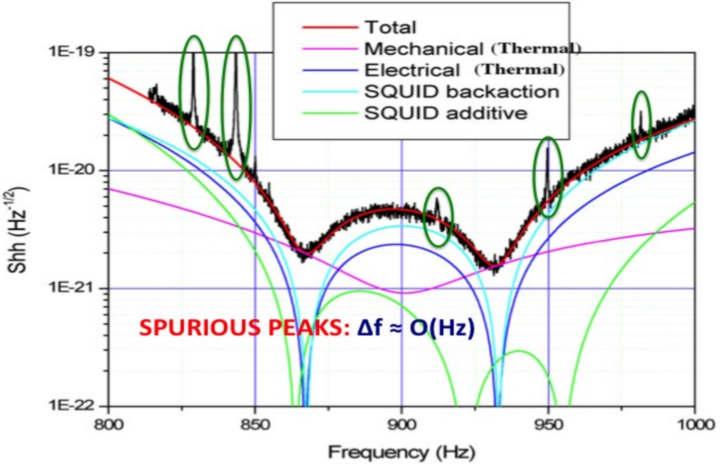
Search for light Dark Matter with AURIGA resonant-mass cryogenic detector:

- light dark matter effects on ordinary matter: microscopic changes of bodies size;
- effects exploited to search for effects on AURIGA detector;
- good sensitivity reached: upper limits on Dark Matter coupling in a physical interesting region of parameter space;

Backup Material

BACKUP MATERIAL

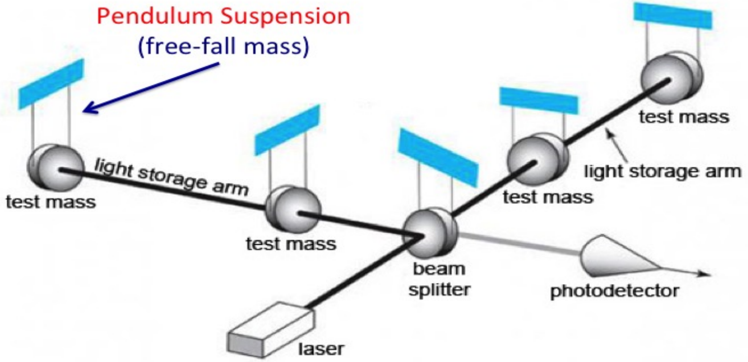
Spurious peaks



Spurious peaks not described by Fluctuation-Dissipation Theorem:

- discarded from the data analysis

Interferometers



Light Dark Matter moduli:

- does not affect distance between mirrors (vacuum);
- effects only on the mirrors size themselves;