Jet Propulsion Laboratory
California Institute of Technology

Searching for dark matter with atomic clocks in space

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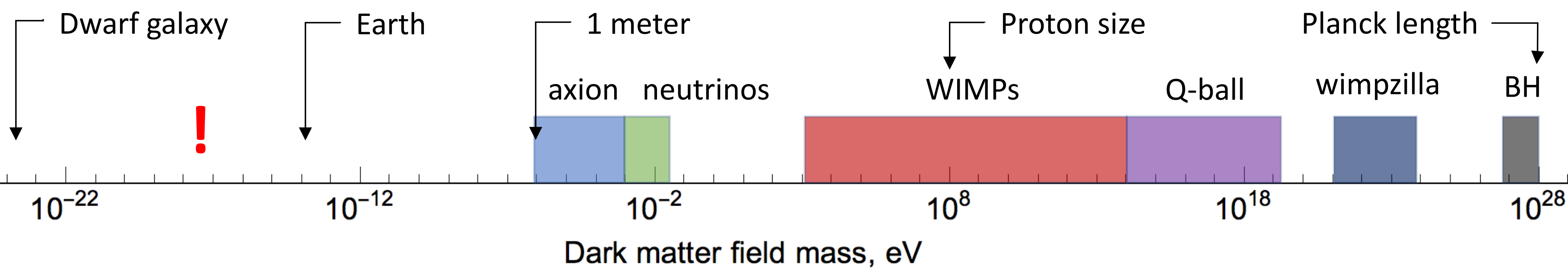
arXiv:1705.05833
(to appear in Phys. Rev. D)

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Motivation

- No direct detection of the dark matter to date, while having an overwhelming amount of indirect observations. Importance: 27% of energy content of the Universe, 85% of the mass content.
- Vast range of unexplored masses (about 80%) of the total span 10^{-24} eV - 10^{28} eV. WIMPs are typically tested above GeV and axions above μeV scale.
- Light bosons predicted by nearly every new theory beyond the Standard Model.
- Specifically for the clock stability studies: able to show high-frequency signals and make easier to identify different types of noise.



Brief theory (dark matter)

Action of the theory and interaction Lagrangian:

$$S = \int d^4x \sqrt{-g} \left\{ \frac{R}{16\pi G} + \frac{1}{2} g_{\mu\nu} \partial^\mu \phi \partial^\nu \phi - V(\phi) + \mathcal{L}_{SM} + \mathcal{L}_{int}^{(n)} \right\},$$

$$\mathcal{L}_{int}^{(n)} = \phi^n \left[\frac{1}{4e^2 \Lambda_{\gamma,n}^n} F_{\mu\nu} F^{\mu\nu} - \frac{\beta_{YM}}{2 g_{YM} \Lambda_{g,n}^n} G_{\mu\nu} G^{\mu\nu} - \sum_{f=e,u,d} \left(\frac{1}{\Lambda_{f,n}^n} + \frac{\gamma_{m_f}}{\Lambda_{g,n}^n} \right) m_f \bar{\psi}_f \psi_f \right]$$

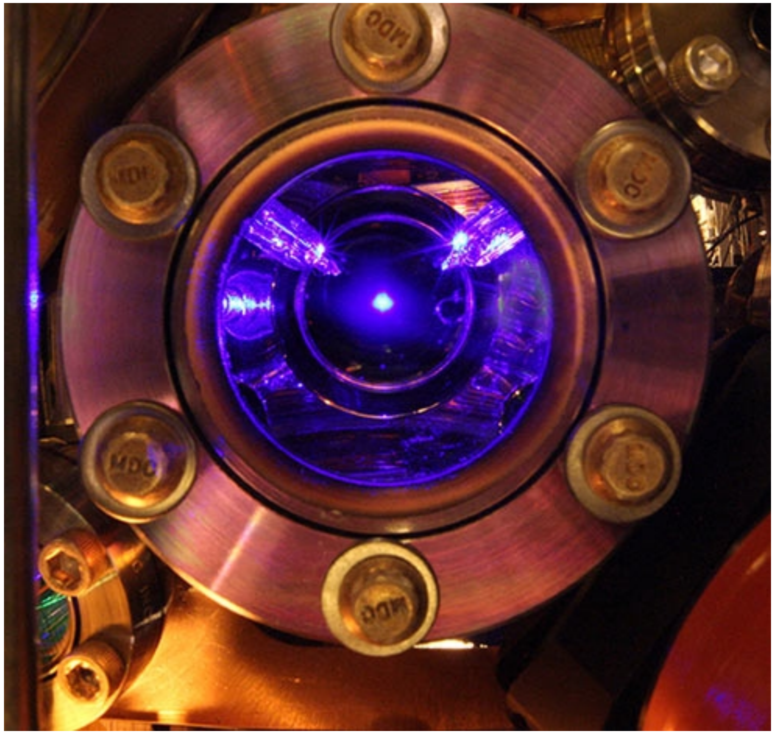
Presence of dark matter can induce a change in the fundamental constants:

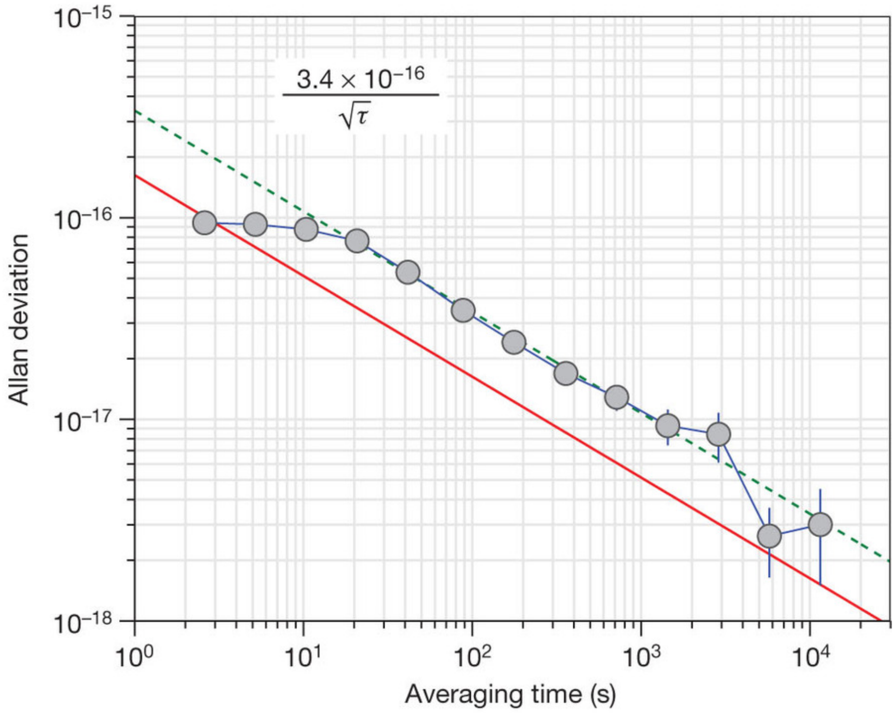
$$\frac{\delta\alpha}{\alpha} = \left(\frac{\phi}{\Lambda_{\gamma,n}} \right)^n, \qquad \frac{\delta m_f}{m_f} = \left(\frac{\phi}{\Lambda_{f,n}} \right)^n, \qquad \frac{\delta \Lambda_{QCD}}{\Lambda_{QCD}} = \left(\frac{\phi}{\Lambda_{g,n}} \right)^n,$$

Clock response is due to the change in the atomic transition frequency:

$$\nu = \text{const} \cdot R_\infty \cdot \alpha^{K_\alpha} \left(\frac{m_q}{\Lambda_{QCD}} \right)^{K_{q\Lambda}} \left(\frac{m_e}{\Lambda_{QCD}} \right)^{K_{e\Lambda}}$$

Example of an atomic clock (^{87}Sr@ JILA)





Source: "An optical lattice clock with accuracy and stability at the 10^{-18} level", B. J. Bloom at al., Nature 506, 71–75 (2014)

Brief theory (clock stability analysis)

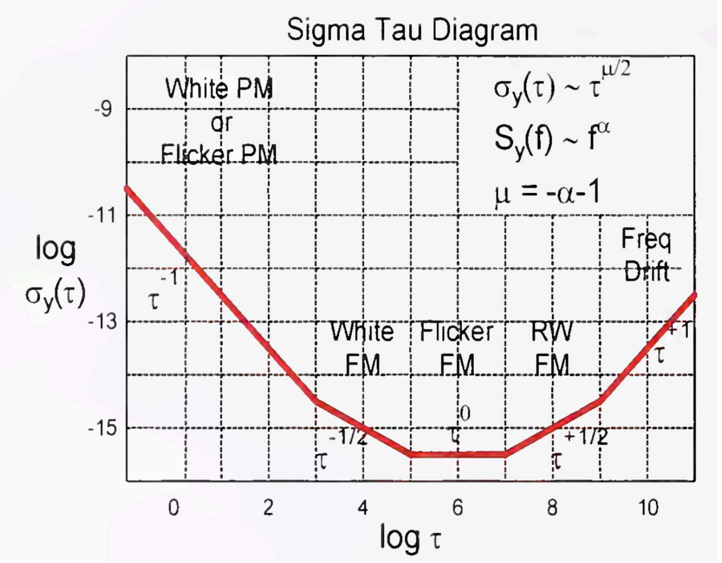
Average fractional frequency deviation:

$$\bar{y}(t) = \frac{1}{\tau}\int_{t-\tau}^{t} y(t')\,dt' \quad \Leftarrow \quad y(t) = dx(t)/dt, \quad x(t) = \frac{\varphi_1(t)}{2\pi\nu_1} - \frac{\varphi_2(t)}{2\pi\nu_2}$$

Allan variance (continuous version):

$$\sigma_y^2(\tau) = \frac{1}{2}\lim_{T\to\infty}\frac{1}{T}\int_0^T \left[\bar{y}(t+\tau) - \bar{y}(t)\right]^2 dt$$

Regime of our interest: $\sigma_y(\tau) = \sigma_0/\sqrt{\tau}$



W.J. Riley,
"Handbook of frequency stability analysis"

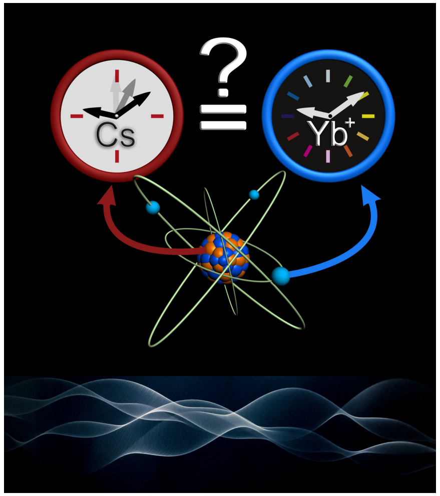
Species	^{133}Cs	^{199}Hg$^+$	^{199}Hg	^{27}Al$^+$	^{87}Sr	^{162}Dy	^{164}Dy	^{229}Th
States	hyperfine	$5d^9 6s^2\,{}^2D_{\frac{5}{2}}$	$6s6p\,{}^3P_0$	$3s3p\,{}^3P_0$	$5s5p\,{}^3P_0$	$4f^9 5d^2 6s$	$4f^{10} 5d6s$	nuclear
	hyperfine	$5d^{10} 6s\,{}^2S_{\frac{1}{2}}$	$6s^2\,{}^1S_0$	$3s^2\,{}^1S_0$	$5s^2\,{}^1S_0$	$4f^{10} 5d6s$	$4f^9 5d^2 6s$	nuclear
K_α	2.83	-3.19	0.81	0.008	0.06	8.5×10^6	-2.6×10^6	10^4(?)
$\sigma_0(10^{-16}\mathrm{Hz}^{-1/2})$	10^3	28	1.8	28	3.1	4×10^7	1×10^8	10(?)

General idea of the measurement

Compare two clocks of different type or spatially separated;
Investigate the two dark matter configurations: dark matter waves or topological defects.

1. Waves with frequency

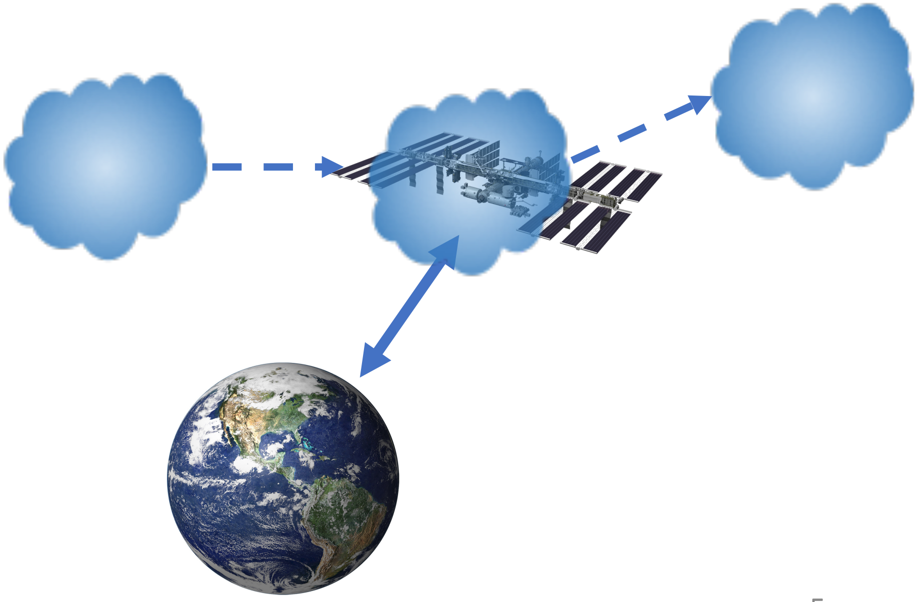
$$f = m_\phi/(2\pi)$$



Images: Phys.org, http://danielpalacios.info

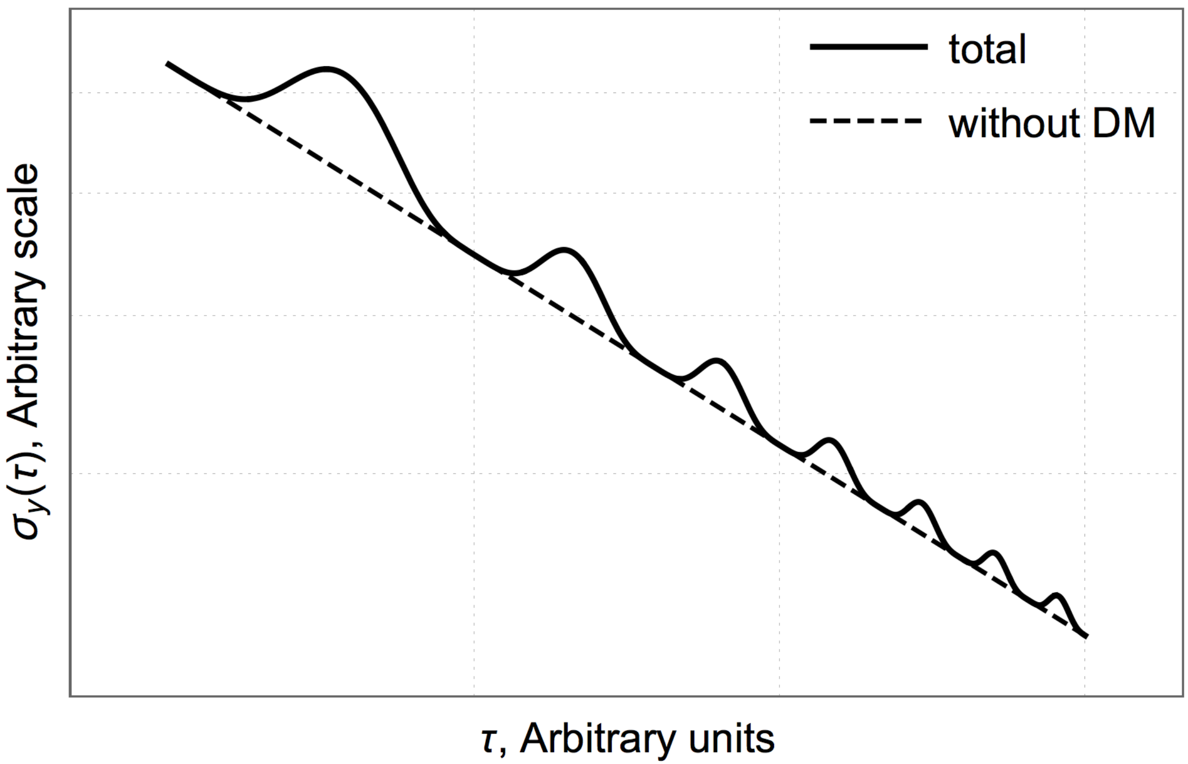
2. Clumps of dark matter of size

$$d \sim \hbar/(m_\phi c)$$



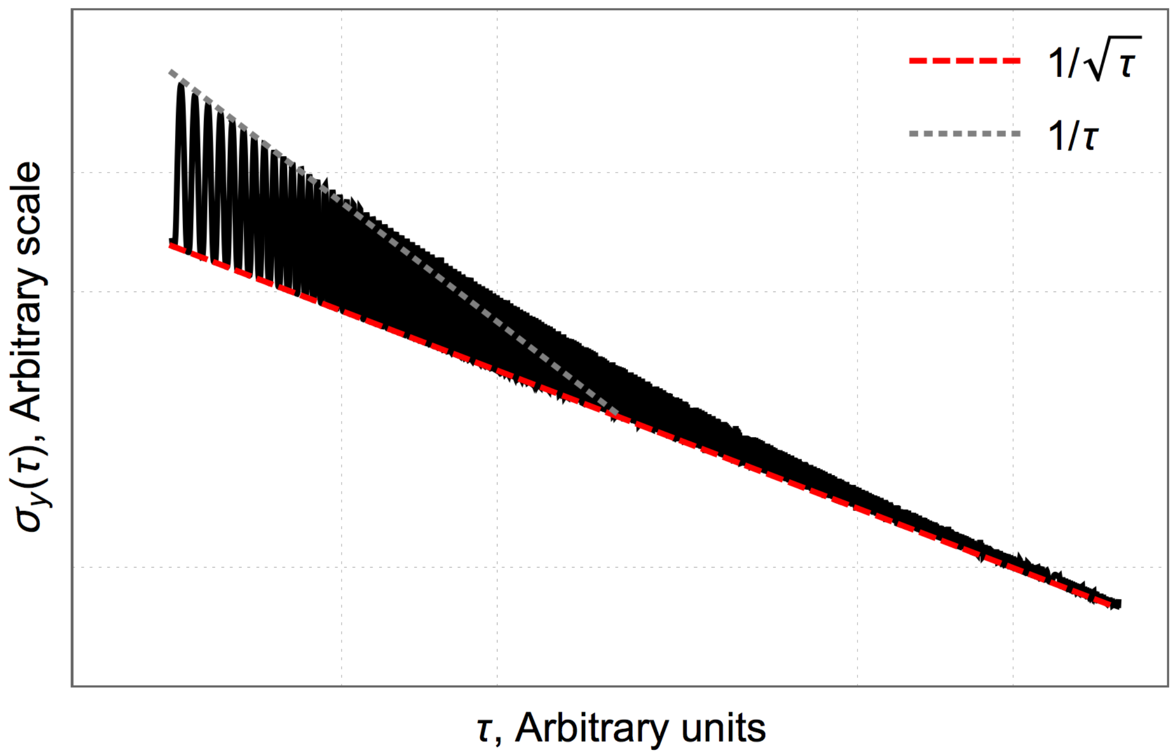
Anomalies in the stability plots

- Dark matter wave with a period within the range of the averaging times (example: 1s – 1000s)
- Co-located or spatially separated clocks of different type
- Anomaly: primary bump at τ similar to the period of oscillation, secondary bumps at larger τ



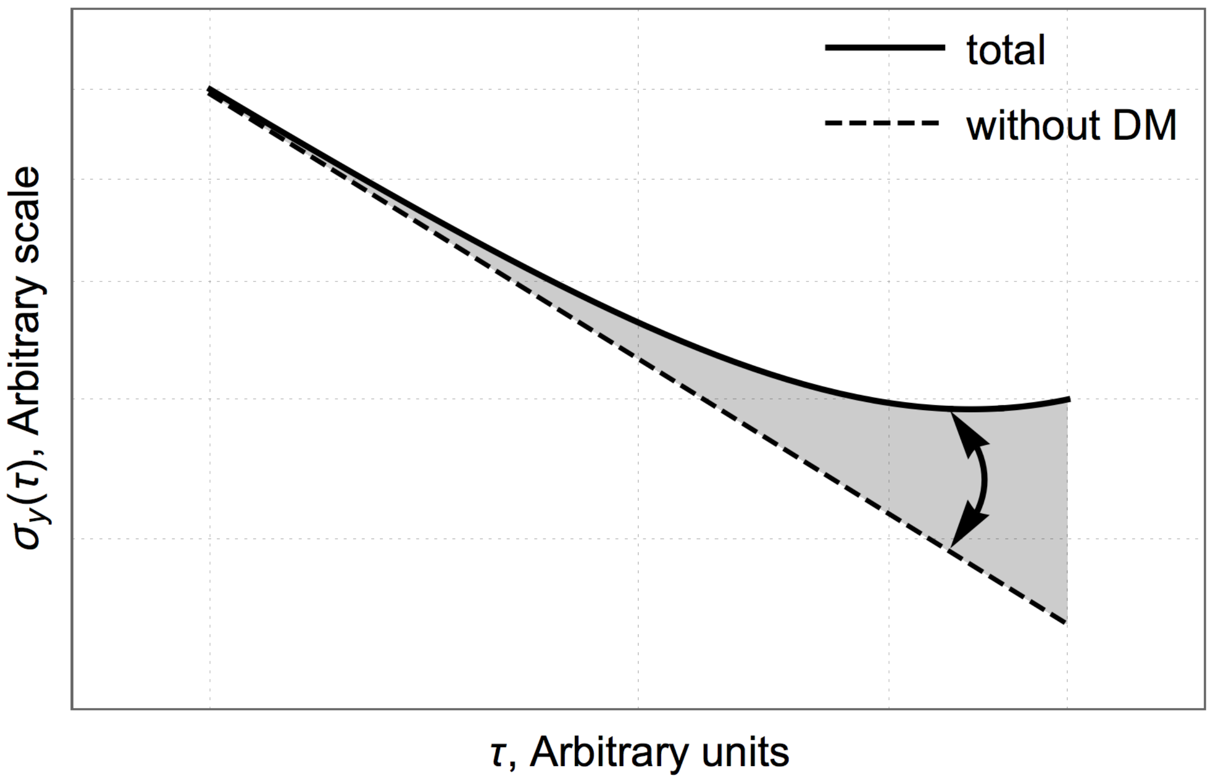
Anomalies in the stability plots

- Dark matter wave with a period much smaller than the clock loop time (example: 1ms)
- Co-located or spatially separated clocks of different type
- Anomaly: train at small τ with $1/\tau$ envelope. Aliasing effect!



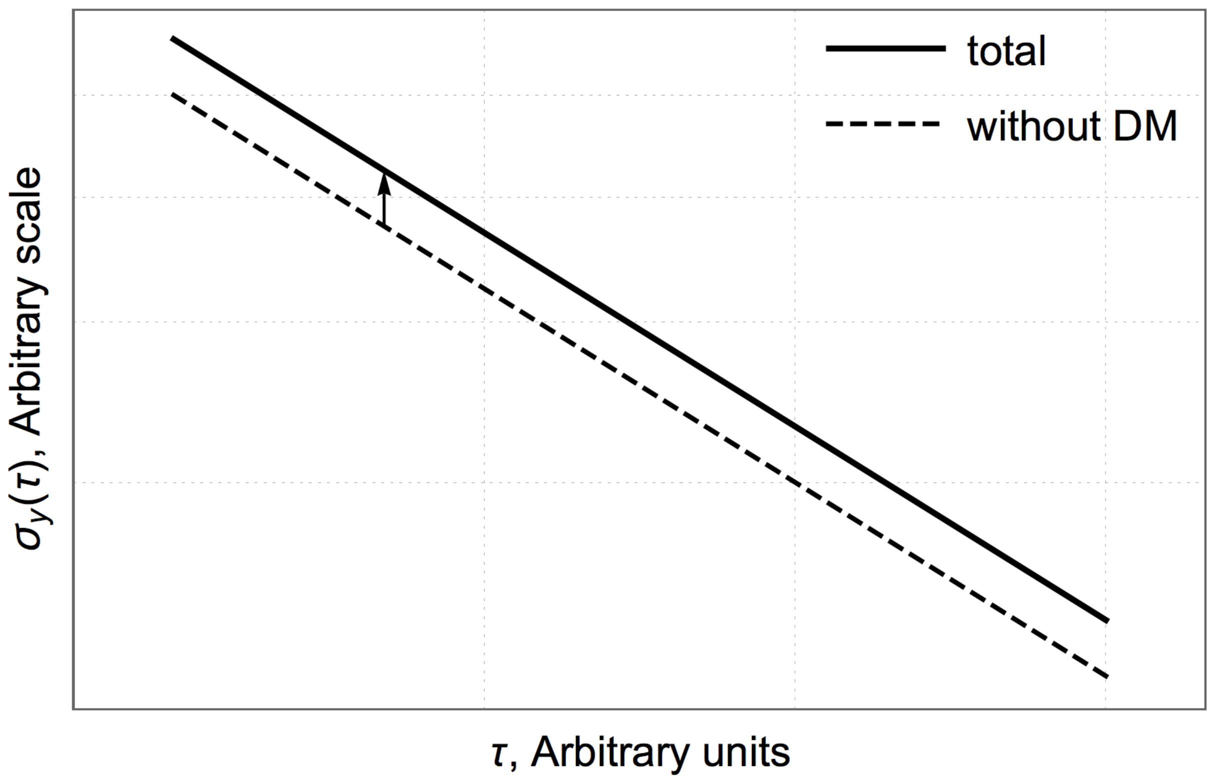
Anomalies in the stability plots

- Dark matter wave with a period much larger than a single clock comparison session (example: several days)
- Co-located or spatially separated clocks of different type
- Anomaly: periodic wiggle at large τ from session to session

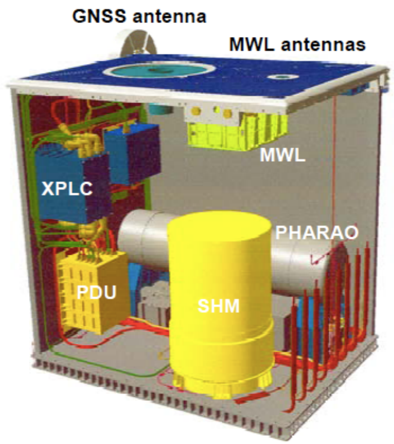


Anomalies in the stability plots

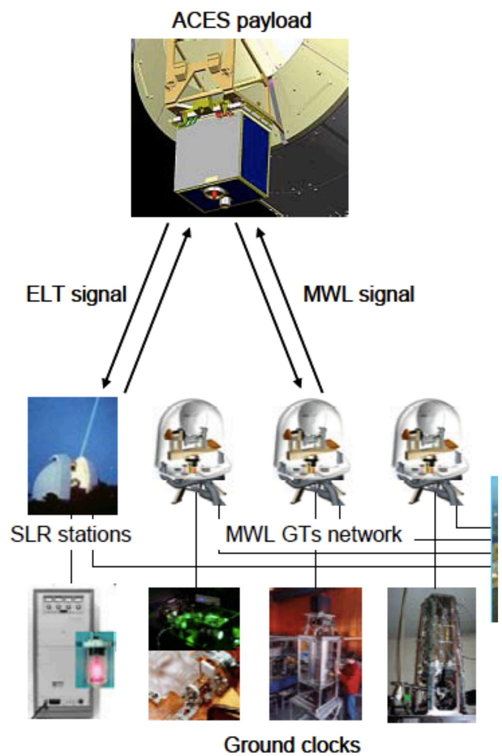
- Topological Dark Matter objects of size d ≈ ħ/(mc)
- Spatially separated clocks of identical or different type
- Anomaly: shift in the position of the Allan deviation curve



ACES mission configuration



Cs clock and
space hydrogen
Maser onboard



~ 300 s overpass time between space clocks and ground clocks separated by time-varying distances,

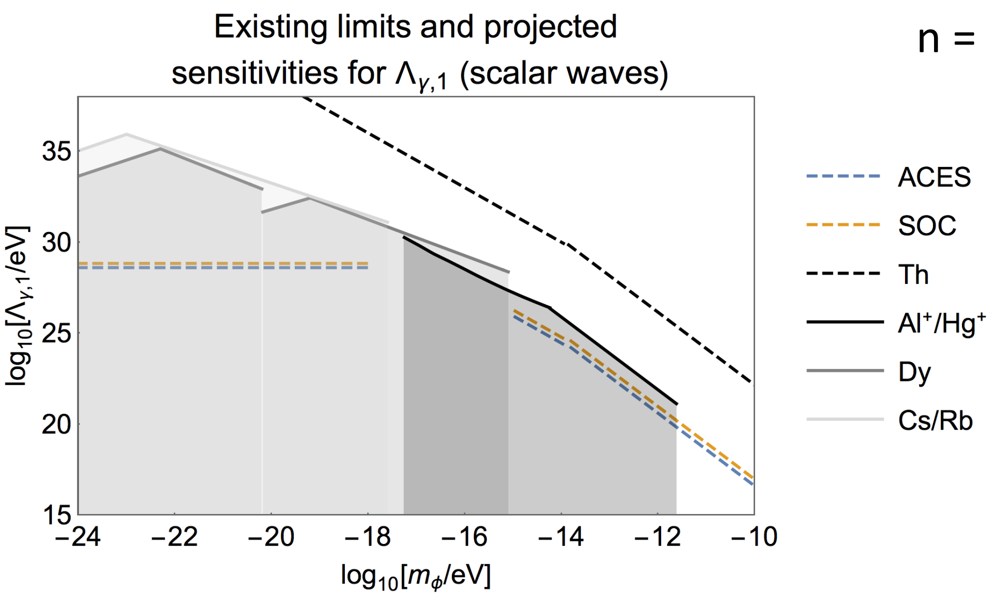
and common view ground clock comparisons

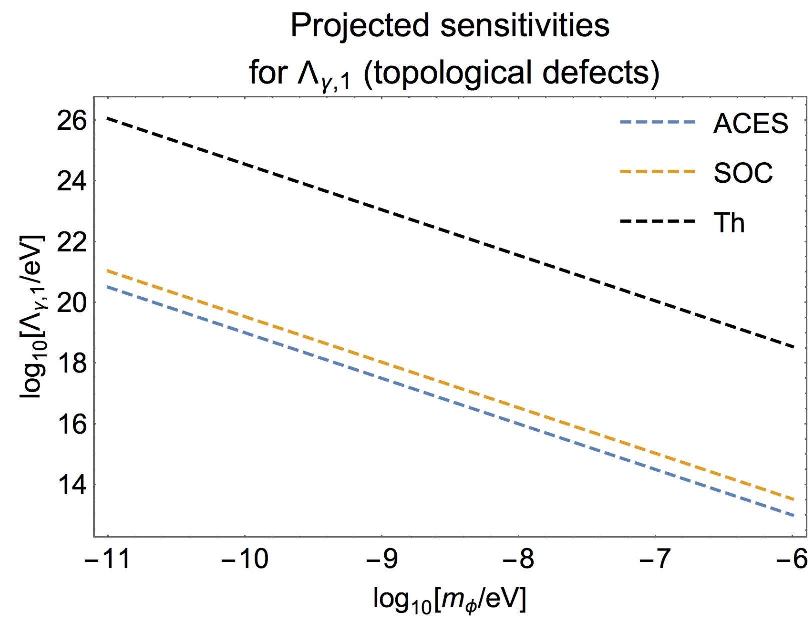
ACES can be used for establishing

[1] new limits for the topological dark matter (e.g., monopoles) in the region of masses 10^{-10} - 10^{-6} eV

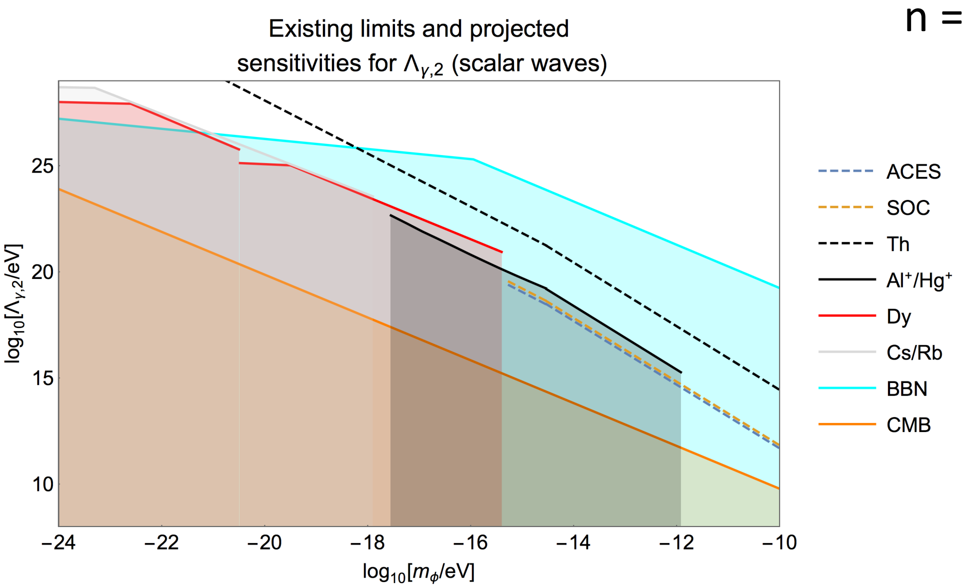
[2] complementary limits on the dark matter wave background in the region of masses 10^{-15}-10^{-10} eV

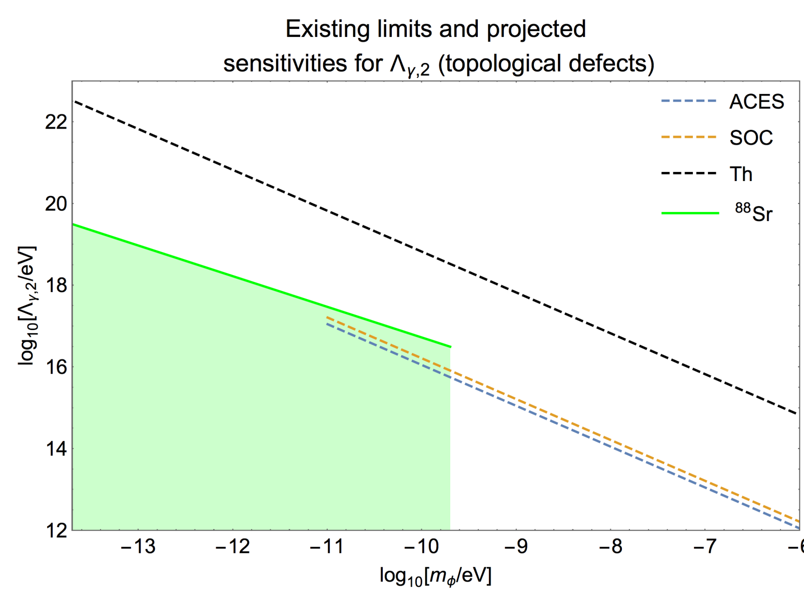
n = 1:


Existing limits and projected sensitivities for $\Lambda_{\gamma,1}$ (scalar waves)
$\log_{10}[\Lambda_{\gamma,1}/\mathrm{eV}]$
$\log_{10}[m_\phi/\mathrm{eV}]$
ACES
SOC
Th
Al^+/Hg^+
Dy
Cs/Rb

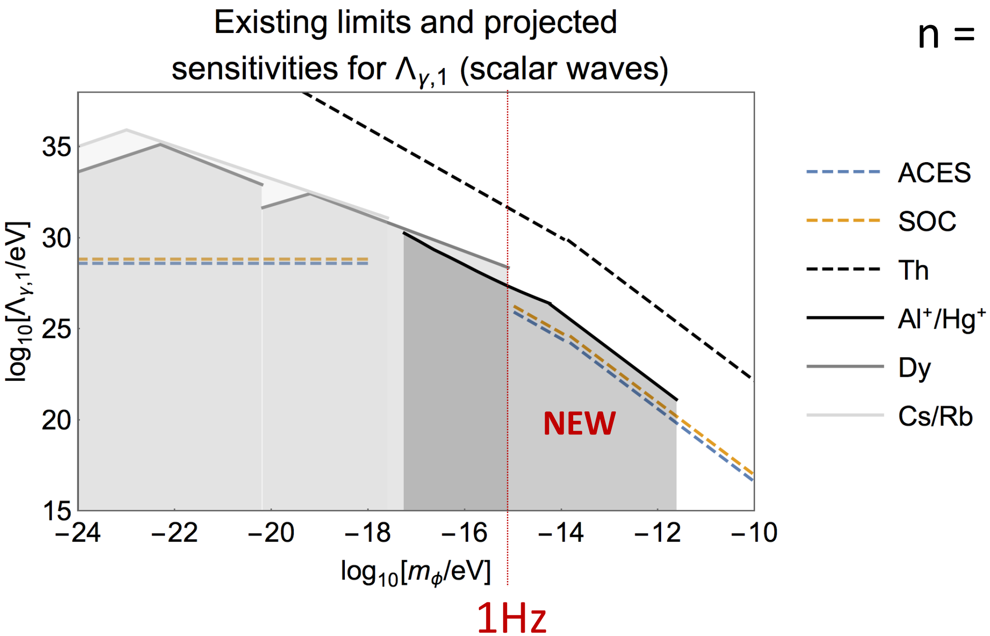

Projected sensitivities for $\Lambda_{\gamma,1}$ (topological defects)
$\log_{10}[\Lambda_{\gamma,1}/\mathrm{eV}]$
$\log_{10}[m_\phi/\mathrm{eV}]$
ACES
SOC
Th

n = 2:

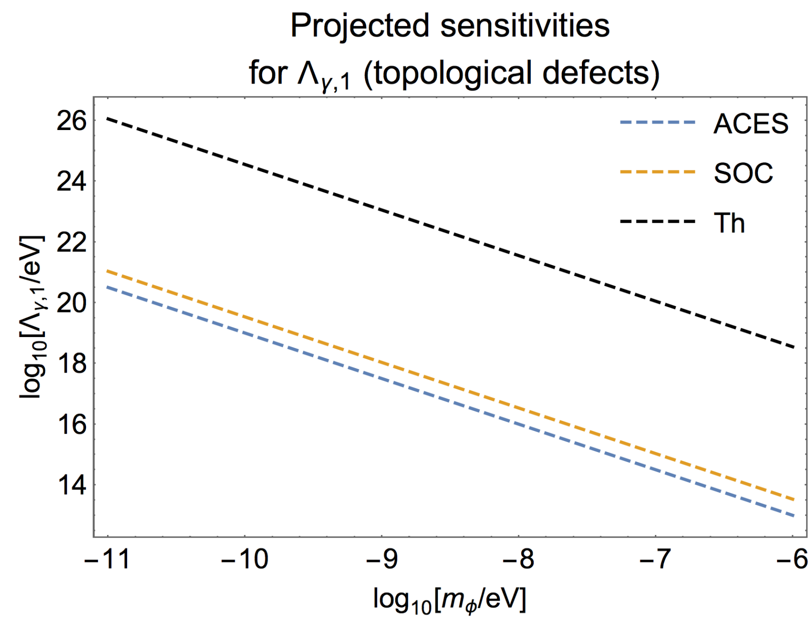

Existing limits and projected sensitivities for $\Lambda_{\gamma,2}$ (scalar waves)
$\log_{10}[\Lambda_{\gamma,2}/\mathrm{eV}]$
$\log_{10}[m_\phi/\mathrm{eV}]$
ACES
SOC
Th
Al^+/Hg^+
Dy
Cs/Rb
BBN
CMB


Existing limits and projected sensitivities for $\Lambda_{\gamma,2}$ (topological defects)
$\log_{10}[\Lambda_{\gamma,2}/\mathrm{eV}]$
$\log_{10}[m_\phi/\mathrm{eV}]$
ACES
SOC
Th
^{88}Sr

n = 1:

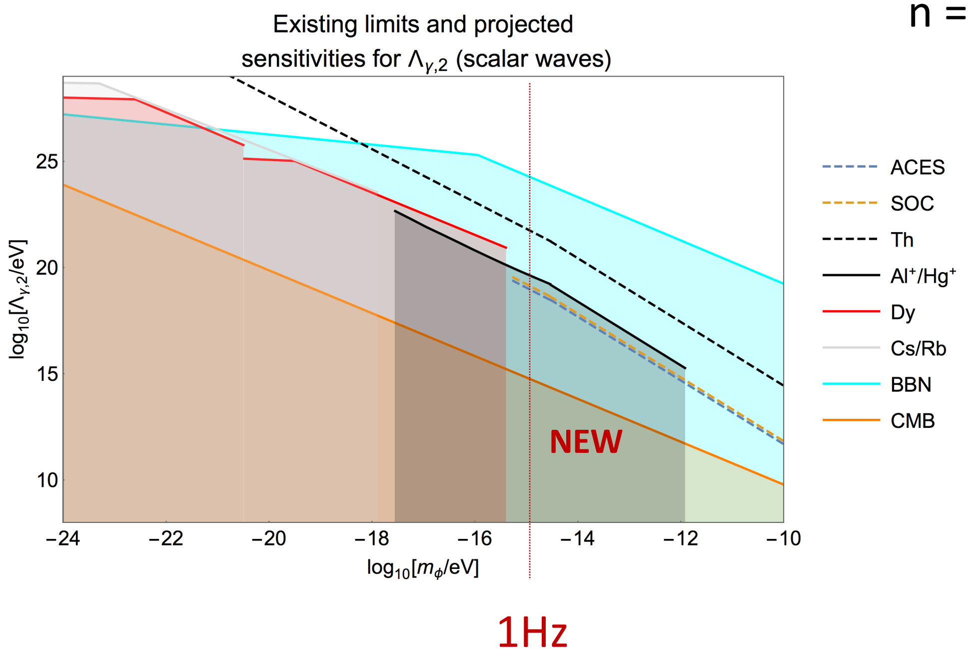


Existing limits and projected sensitivities for $\Lambda_{\gamma,1}$ (scalar waves)
$\log_{10}[\Lambda_{\gamma,1}/\text{eV}]$
$\log_{10}[m_\phi/\text{eV}]$
NEW
1Hz
ACES
SOC
Th
Al^+/Hg^+
Dy
Cs/Rb

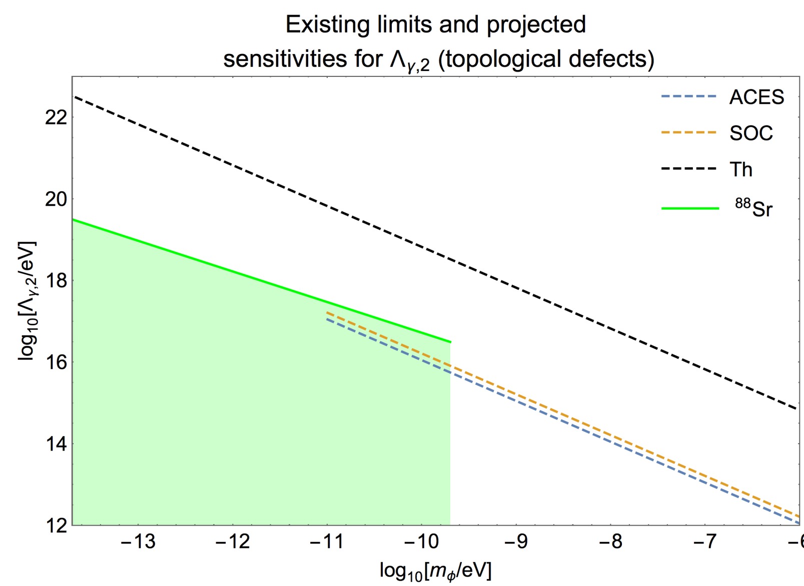


Projected sensitivities for $\Lambda_{\gamma,1}$ (topological defects)
$\log_{10}[\Lambda_{\gamma,1}/\text{eV}]$
$\log_{10}[m_\phi/\text{eV}]$
ACES
SOC
Th

n = 2:



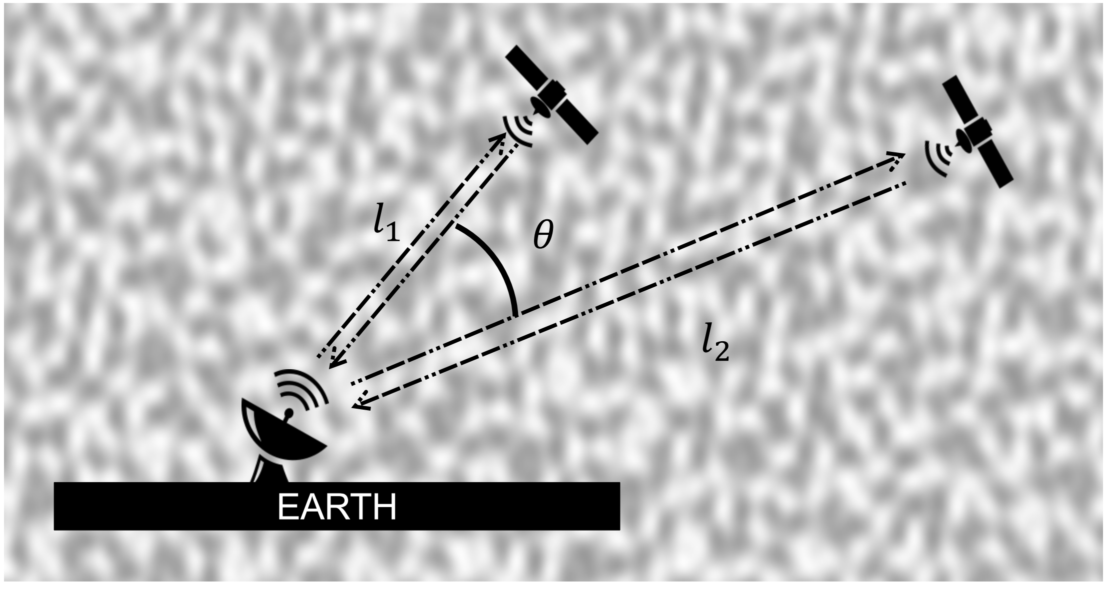
Existing limits and projected sensitivities for $\Lambda_{\gamma,2}$ (scalar waves)
$\log_{10}[\Lambda_{\gamma,2}/\text{eV}]$
$\log_{10}[m_\phi/\text{eV}]$
NEW
1Hz
ACES
SOC
Th
Al^+/Hg^+
Dy
Cs/Rb
BBN
CMB



Existing limits and projected sensitivities for $\Lambda_{\gamma,2}$ (topological defects)
$\log_{10}[\Lambda_{\gamma,2}/\text{eV}]$
$\log_{10}[m_\phi/\text{eV}]$
ACES
SOC
Th
^{88}Sr

Further directions

- Comparing mechanical clocks allows to test larger DM masses (Bohr radius scales with α)
- One can study stochastic backgrounds of various fields (including DM waves) by cross-correlating noises from different atomic sensors: atomic clocks (scalar DM), atom interferometers (vector DM).



Conclusions

- Comparison of ultra-stable atomic clocks provides an opportunity for direct tests of light dark matter.
- Clock stability analysis can be used as a tool and opens access to a new region of parameter space for the DM masses and couplings.
- Existing data for Hg^{+}/Al^{+} comparison puts new limits on the DM coupling in the DM wave background.
- Networks of atomic sensors can be used for the search of the stochastic backgrounds of new fields.

This work has been done under supervision of Dr. Nan Yu within the science study of the ACES collaboration project. We are grateful to Slava Turyshev, Eric Burt, Jason Williams, Dmitry Duev and Andrei Derevianko for useful comments and suggestions.