Jet Propulsion Laboratory
California Institute of Technology

Searching for dark matter with atomic clocks in space

Tigran Kalaydzhyan

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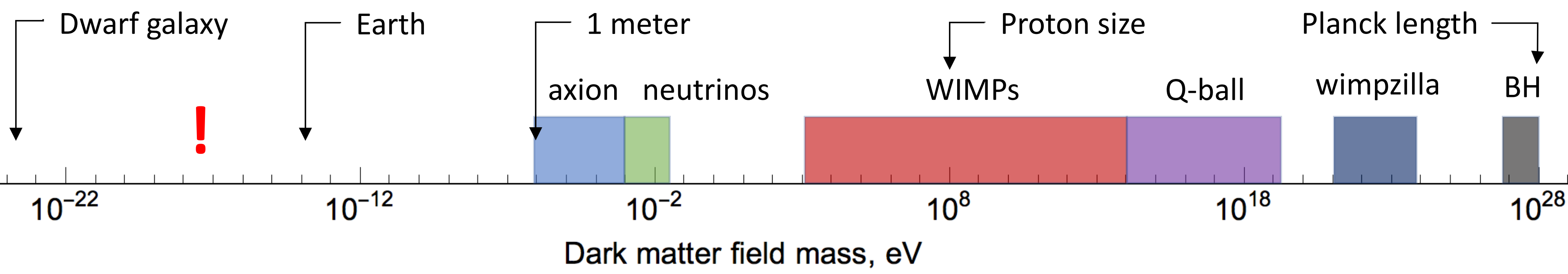
Motivation

- 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:

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

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

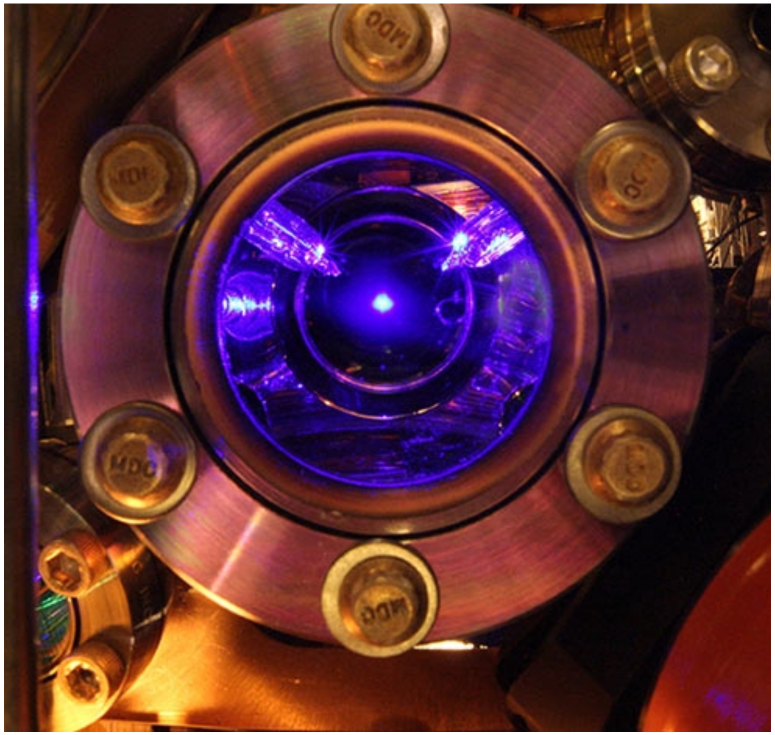
Presence of dark matter can induce a change in the fundamental constants:

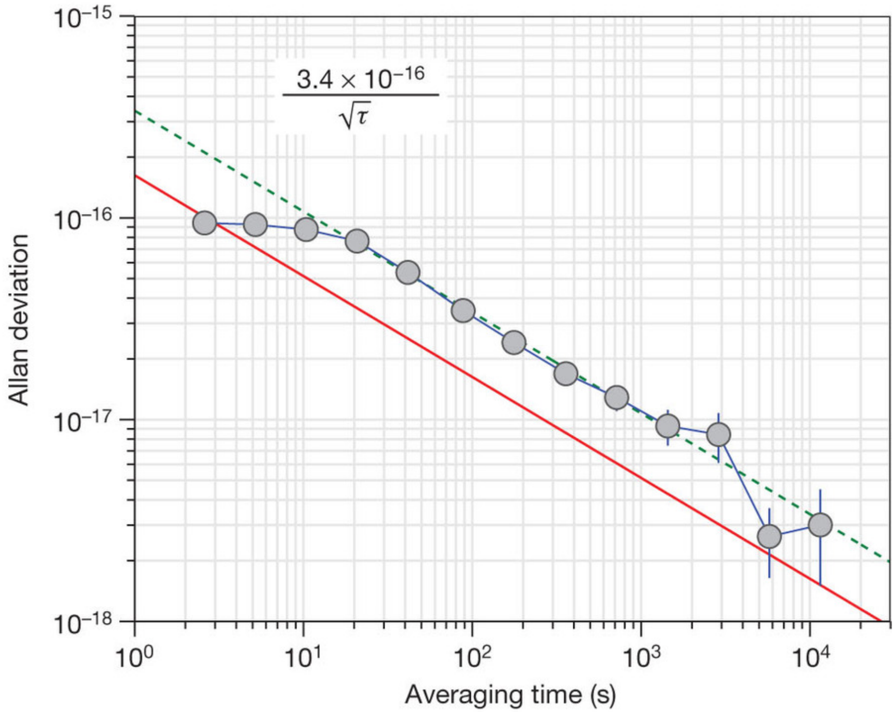
$$\frac{\delta\alpha}{\alpha} = \left(\frac{\phi}{\Lambda_{\gamma,n}} \right)^n, \qquad \frac{\delta m_f}{m_f} = \left(\frac{\phi}{\Lambda_{f,n}} \right)^n, \qquad \frac{\delta \Lambda_{QCD}}{\Lambda_{QCD}} = \left(\frac{\phi}{\Lambda_{g,n}} \right)^n,$$

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)

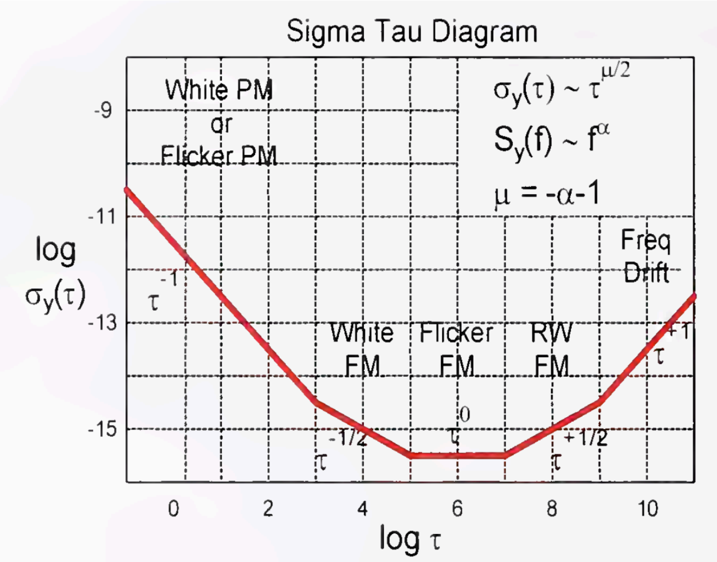
Brief theory (clocks)

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):

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



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

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

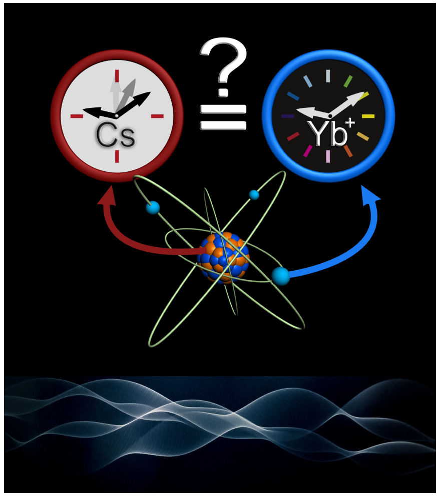
Species	^{133}Cs	^{199}Hg$^+$	^{199}Hg	^{27}Al$^+$	^{87}Sr	^{162}Dy	^{164}Dy	^{229}Th
States	hyperfine	$5d^96s^2\,{}^2D_{\frac{5}{2}}$	$6s6p\,{}^3P_0$	$3s3p\,{}^3P_0$	$5s5p\,{}^3P_0$	$4f^95d^26s$	$4f^{10}5d6s$	nuclear
	hyperfine	$5d^{10}6s\,{}^2S_{\frac{1}{2}}$	$6s^2\,{}^1S_0$	$3s^2\,{}^1S_0$	$5s^2\,{}^1S_0$	$4f^{10}5d6s$	$4f^95d^26s$	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 assuming either of the two dark matter configurations: dark matter waves or topological defects.

1. Waves with frequency

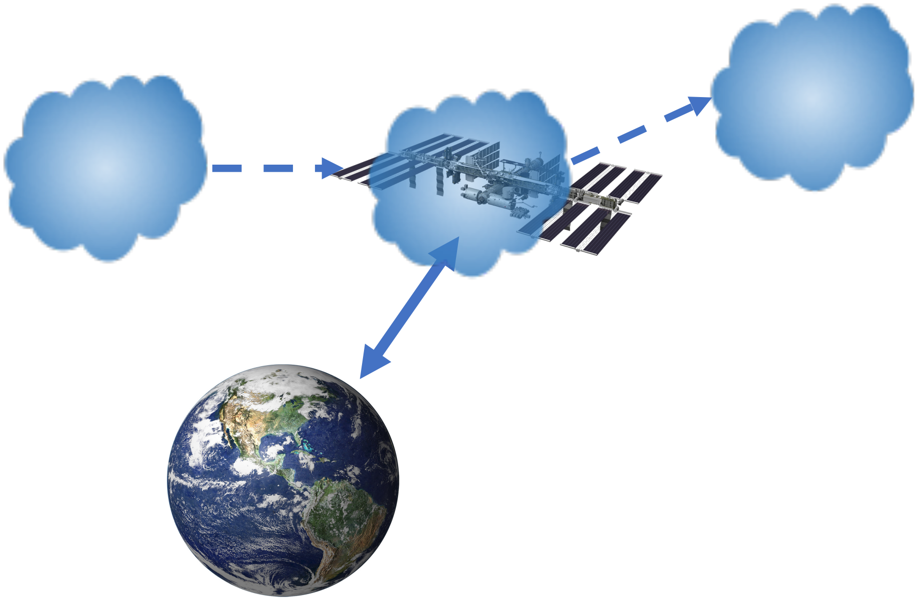
$$f = m_\phi/(2\pi)$$



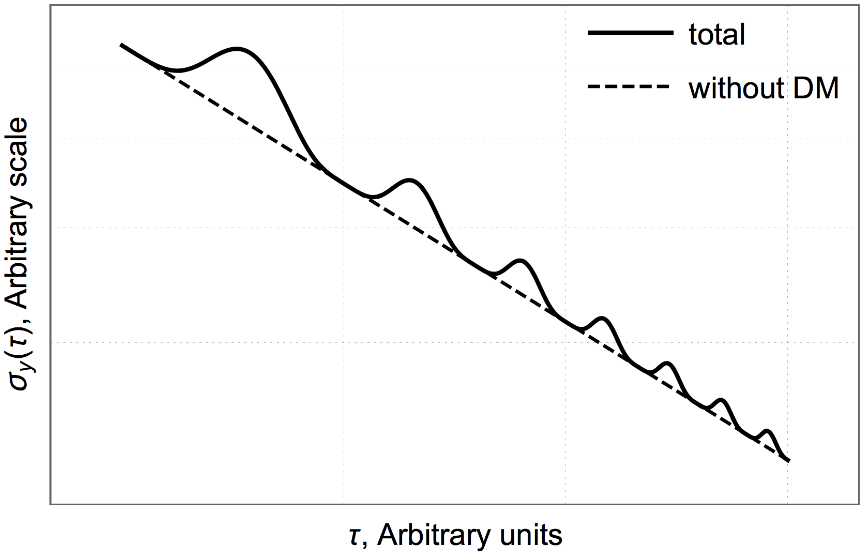
Images: Phys.org, http://danielpalacios.info

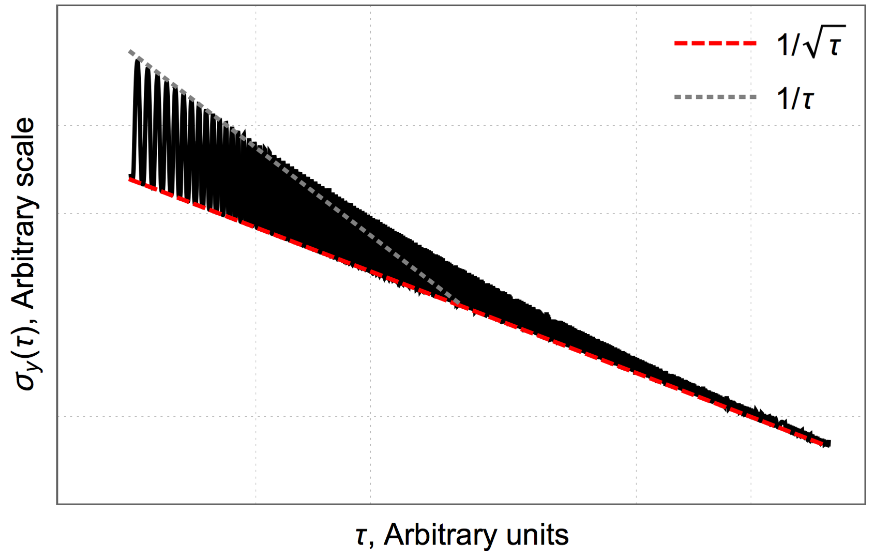
2. Clumps of dark matter of size

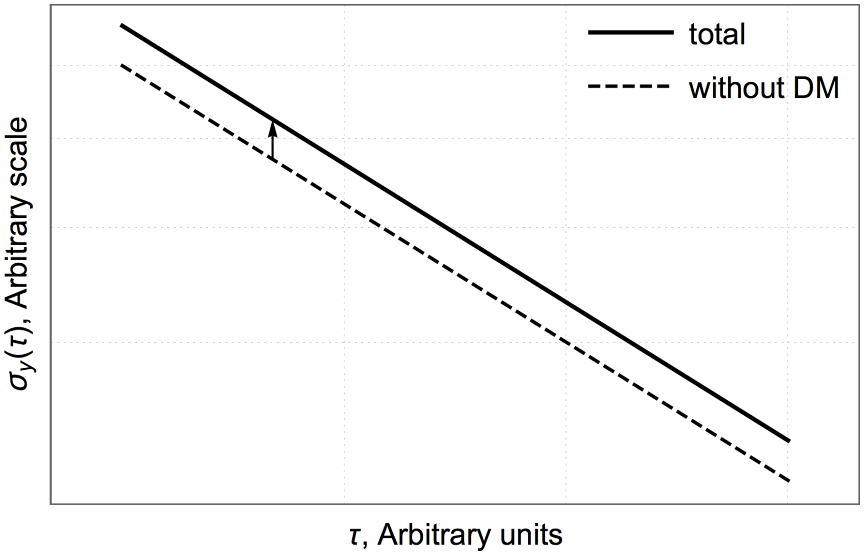
$$d \sim \hbar/(m_\phi c)$$

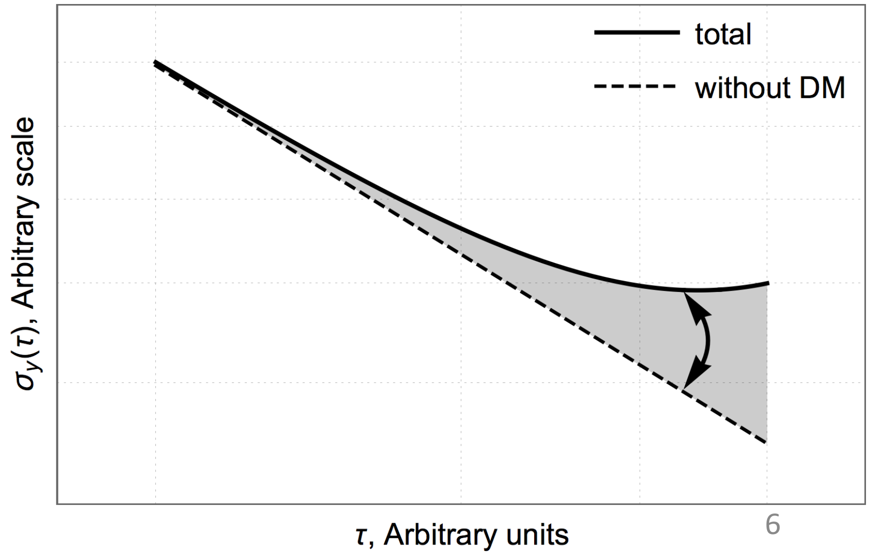


Anomalies in the stability plots

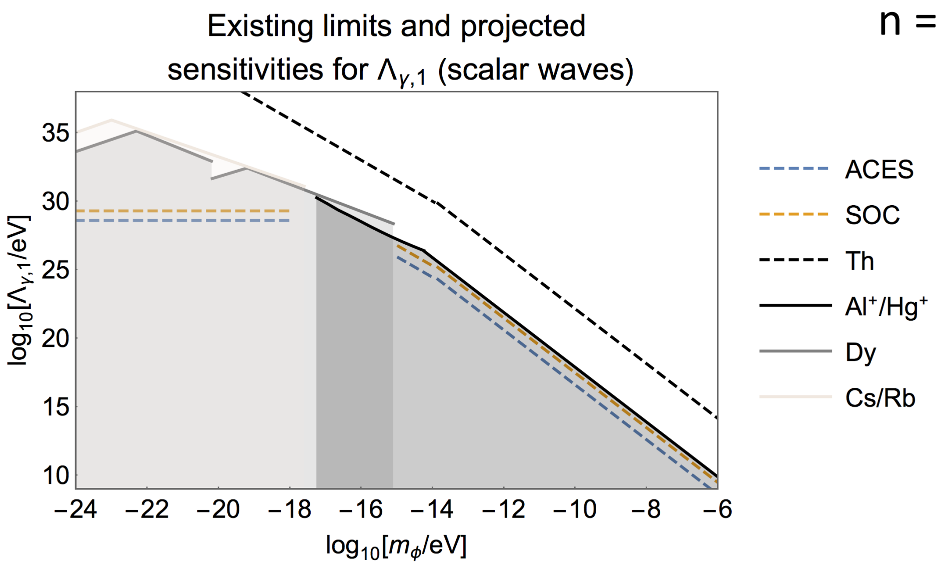




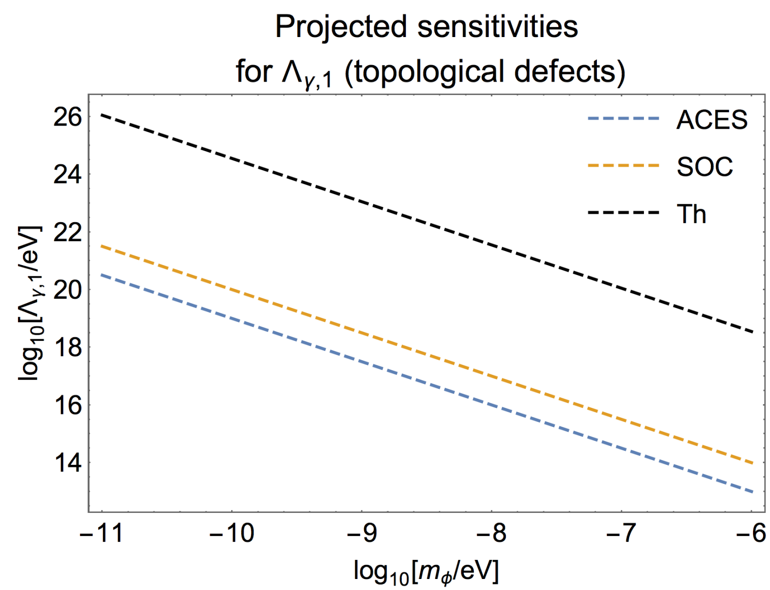




n = 1:

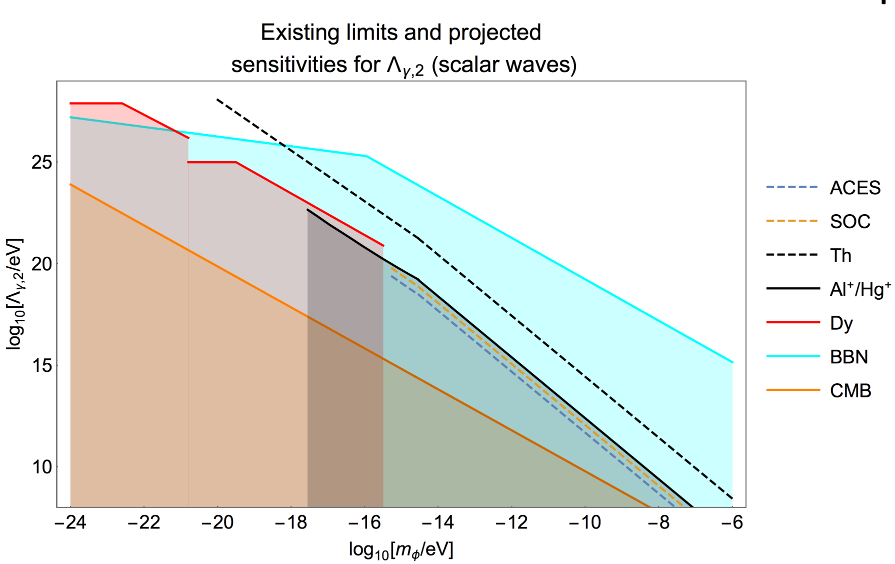


Existing limits and projected sensitivities for $\Lambda_{\gamma,1}$ (scalar waves)
ACES
SOC
Th
Al^+/Hg^+
Dy
Cs/Rb
$\log_{10}[\Lambda_{\gamma,1}/\mathrm{eV}]$
$\log_{10}[m_\phi/\mathrm{eV}]$

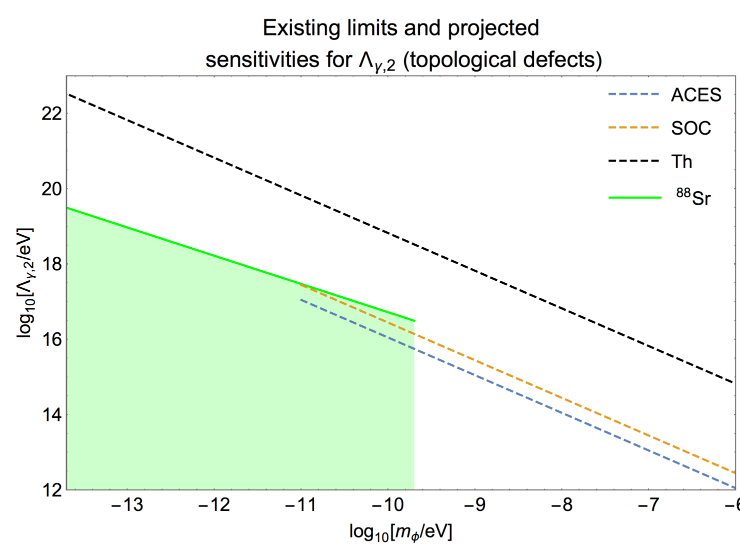


Projected sensitivities for $\Lambda_{\gamma,1}$ (topological defects)
ACES
SOC
Th
$\log_{10}[\Lambda_{\gamma,1}/\mathrm{eV}]$
$\log_{10}[m_\phi/\mathrm{eV}]$

n = 2:

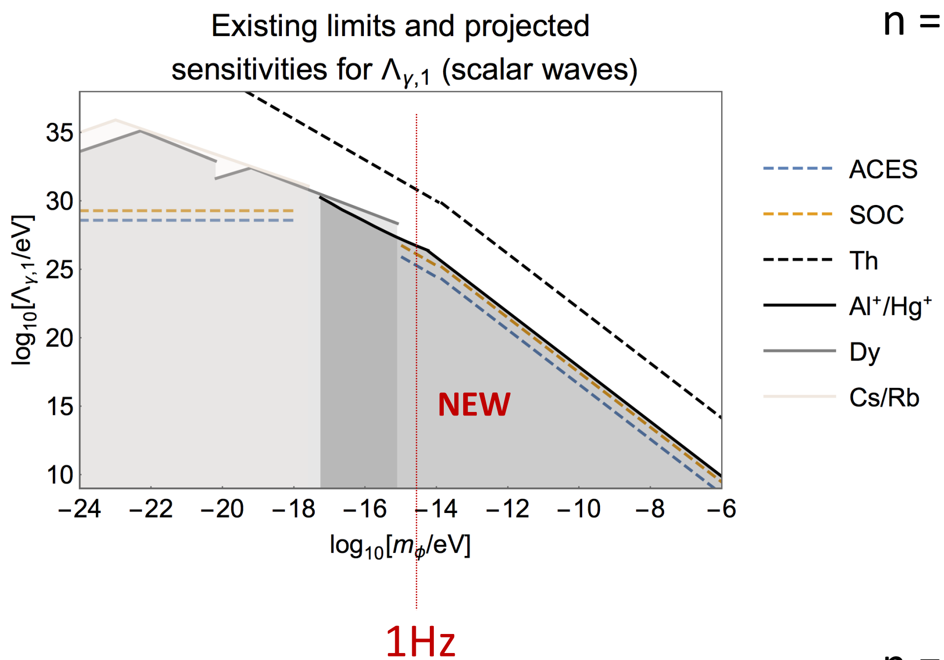


Existing limits and projected sensitivities for $\Lambda_{\gamma,2}$ (scalar waves)
ACES
SOC
Th
Al^+/Hg^+
Dy
BBN
CMB
$\log_{10}[\Lambda_{\gamma,2}/\mathrm{eV}]$
$\log_{10}[m_\phi/\mathrm{eV}]$

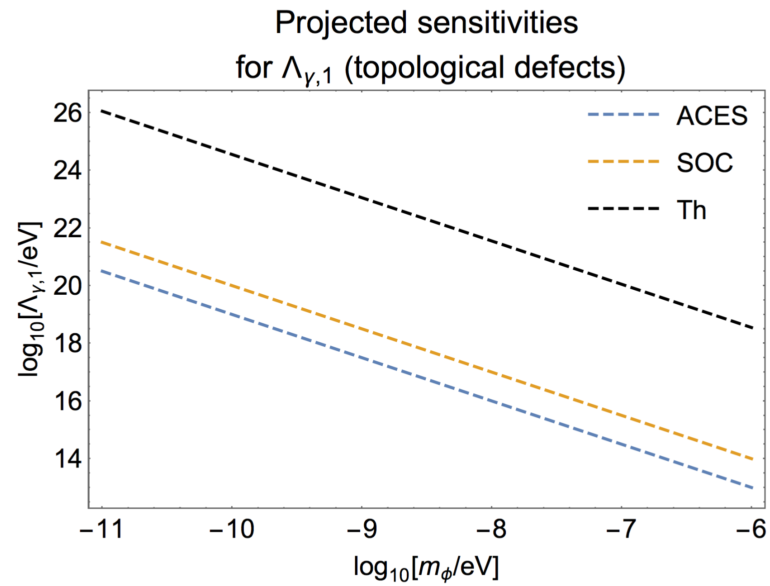


Existing limits and projected sensitivities for $\Lambda_{\gamma,2}$ (topological defects)
ACES
SOC
Th
^{88}Sr
$\log_{10}[\Lambda_{\gamma,2}/\mathrm{eV}]$
$\log_{10}[m_\phi/\mathrm{eV}]$

n = 1:

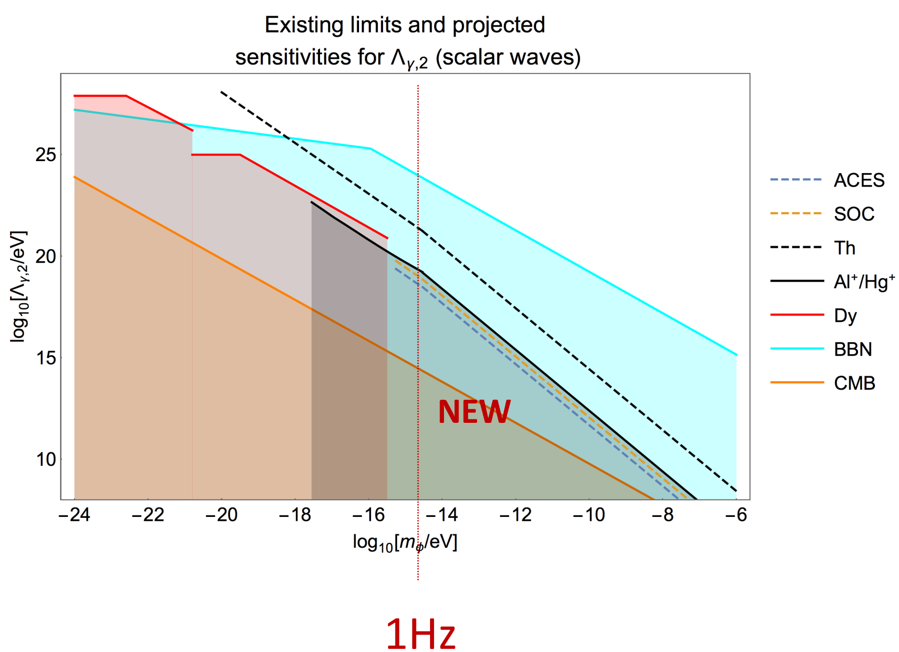


Existing limits and projected sensitivities for $\Lambda_{\gamma,1}$ (scalar waves)
$\log_{10}[\Lambda_{\gamma,1}/eV]$
$\log_{10}[m_\phi/eV]$
NEW
ACES
SOC
Th
Al^+/Hg^+
Dy
Cs/Rb
1Hz

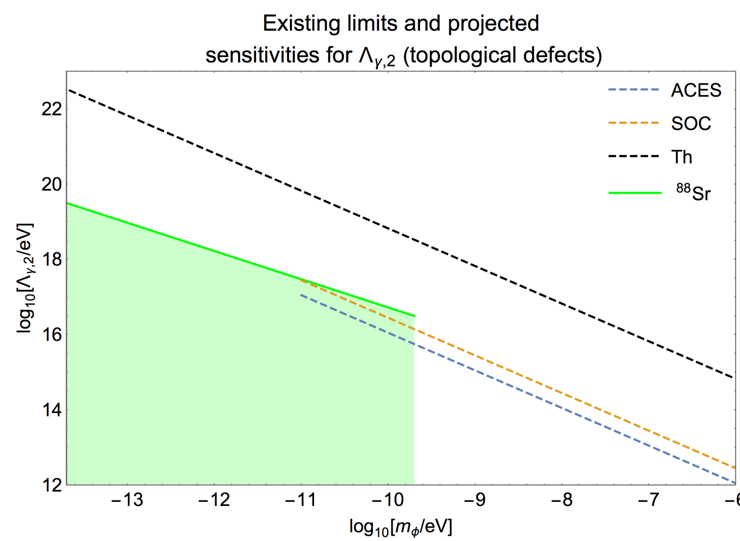


Projected sensitivities for $\Lambda_{\gamma,1}$ (topological defects)
$\log_{10}[\Lambda_{\gamma,1}/eV]$
$\log_{10}[m_\phi/eV]$
ACES
SOC
Th

n = 2:



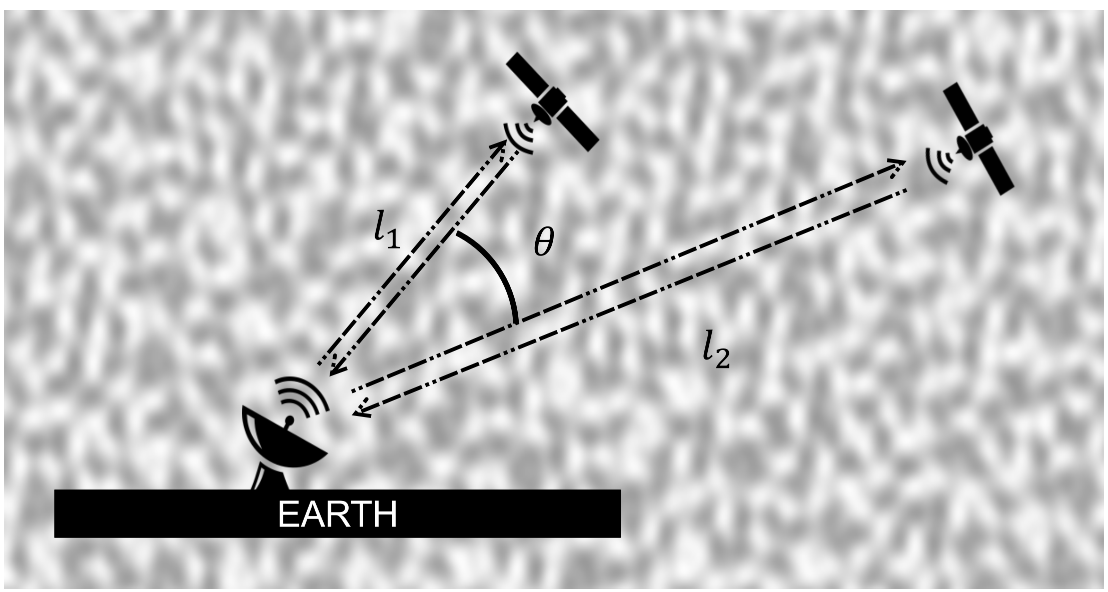
Existing limits and projected sensitivities for $\Lambda_{\gamma,2}$ (scalar waves)
$\log_{10}[\Lambda_{\gamma,2}/eV]$
$\log_{10}[m_\phi/eV]$
NEW
ACES
SOC
Th
Al^+/Hg^+
Dy
BBN
CMB
1Hz



Existing limits and projected sensitivities for $\Lambda_{\gamma,2}$ (topological defects)
$\log_{10}[\Lambda_{\gamma,2}/eV]$
$\log_{10}[m_\phi/eV]$
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.
- Time domain analysis 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.

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