Jet Propulsion Laboratory
California Institute of Technology

Searching for dark matter with atomic clocks in space

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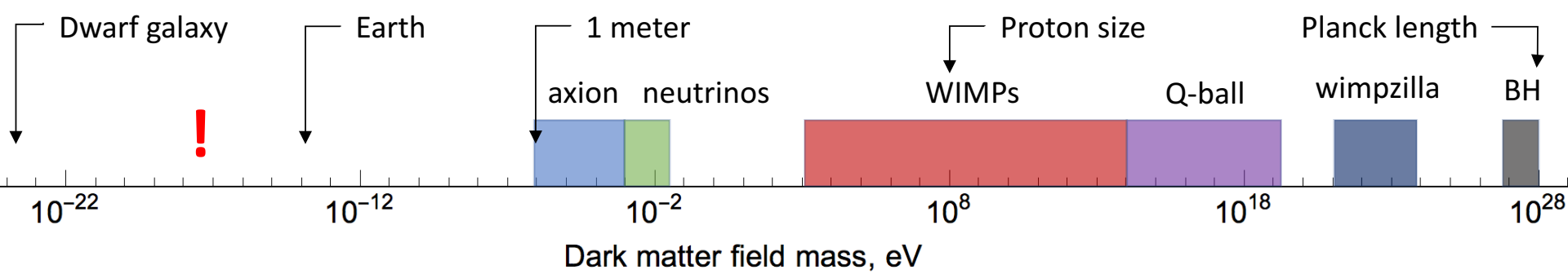
Motivation

- 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:

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

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

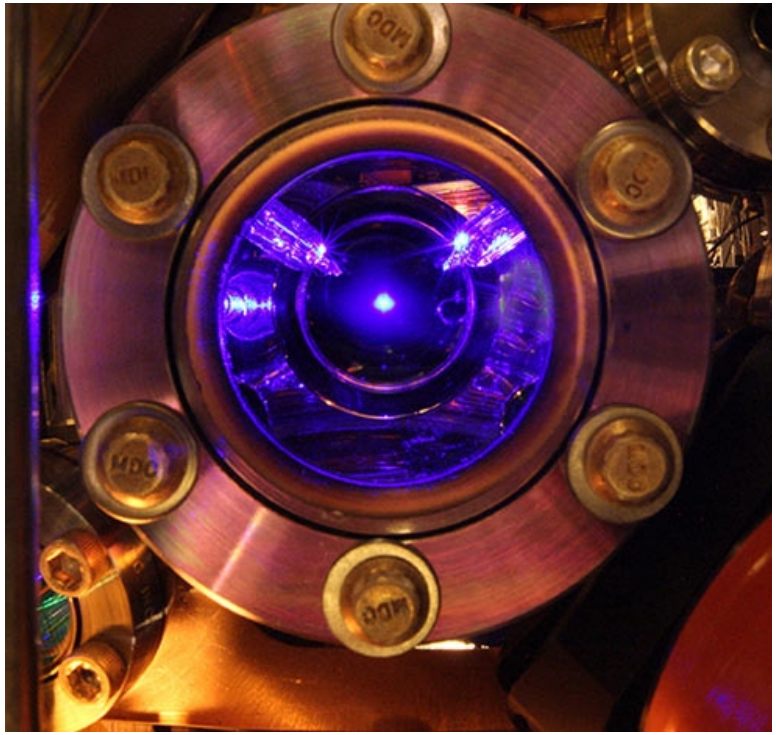
Presence of dark matter can induce a change in the fundamental constants:

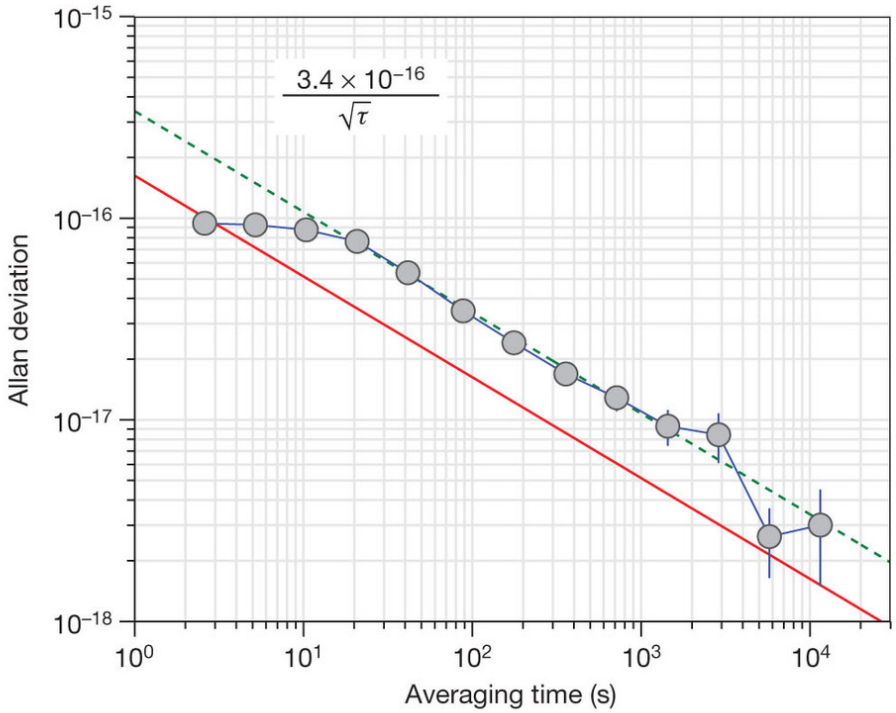
$$\frac{\delta\alpha}{\alpha} = \left(\frac{\phi}{\Lambda_{\gamma,n}}\right)^n, \qquad \frac{\delta m_f}{m_f} = \left(\frac{\phi}{\Lambda_{f,n}}\right)^n, \qquad \frac{\delta\Lambda_{QCD}}{\Lambda_{QCD}} = \left(\frac{\phi}{\Lambda_{g,n}}\right)^n,$$

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

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

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:

$$\bar{y}(t) = \frac{1}{\tau}\int_{t-\tau}^{t} y(t')\,dt'$$

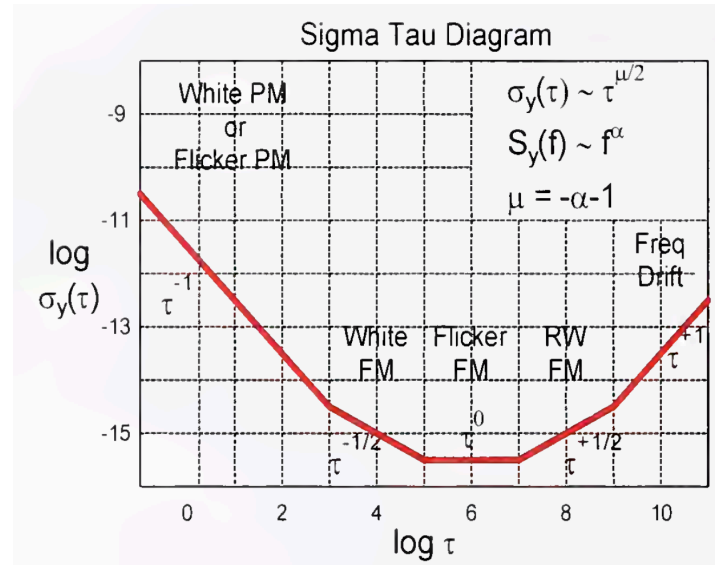
$$y(t) = dx(t)/dt,$$

$$x(t) = \frac{\varphi_1(t)}{2\pi\nu_1} - \frac{\varphi_2(t)}{2\pi\nu_2}$$

Allan variance (continuous version):

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

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



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

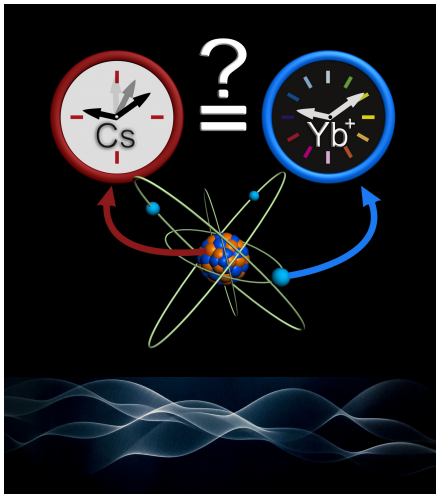
Species	^{133}Cs	^{199}Hg$^+$	^{199}Hg	^{27}Al$^+$	^{87}Sr	^{162}Dy	^{164}Dy	^{229}Th
States	hyperfine	$5d^9 6s^2\,{}^2D_{\frac{5}{2}}$	$6s6p\,{}^3P_0$	$3s3p\,{}^3P_0$	$5s5p\,{}^3P_0$	$4f^9 5d^2 6s$	$4f^{10}5d6s$	nuclear
	hyperfine	$5d^{10}6s\,{}^2S_{\frac{1}{2}}$	$6s^2\,{}^1S_0$	$3s^2\,{}^1S_0$	$5s^2\,{}^1S_0$	$4f^{10}5d6s$	$4f^9 5d^2 6s$	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

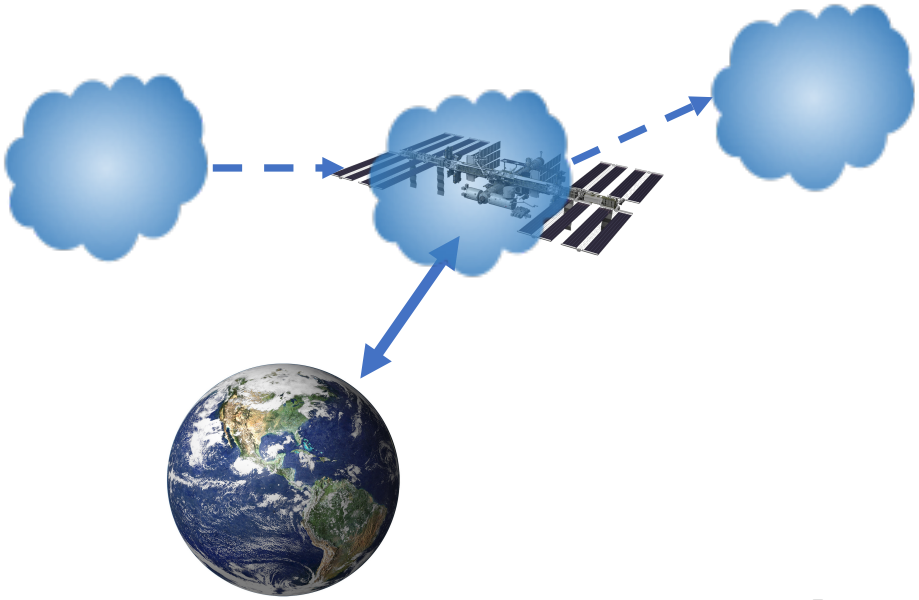
$$f = m_\phi/(2\pi)$$



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

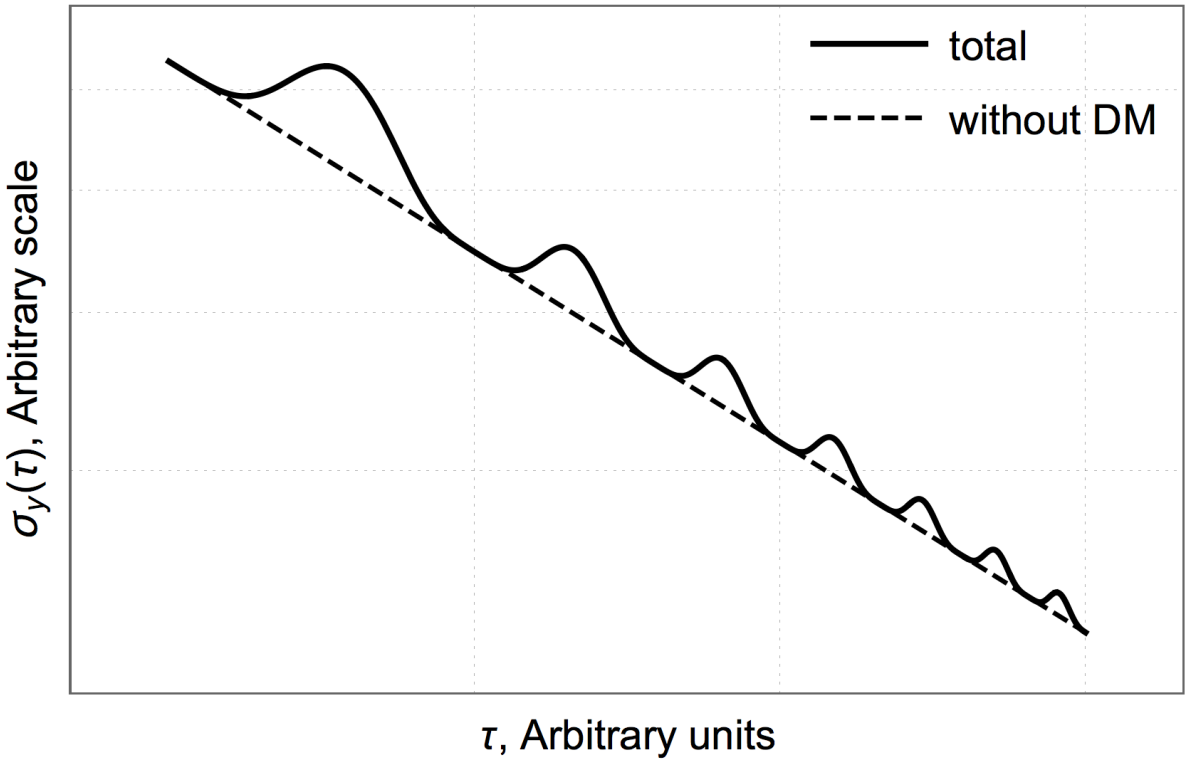
2. Clumps of dark matter of size

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



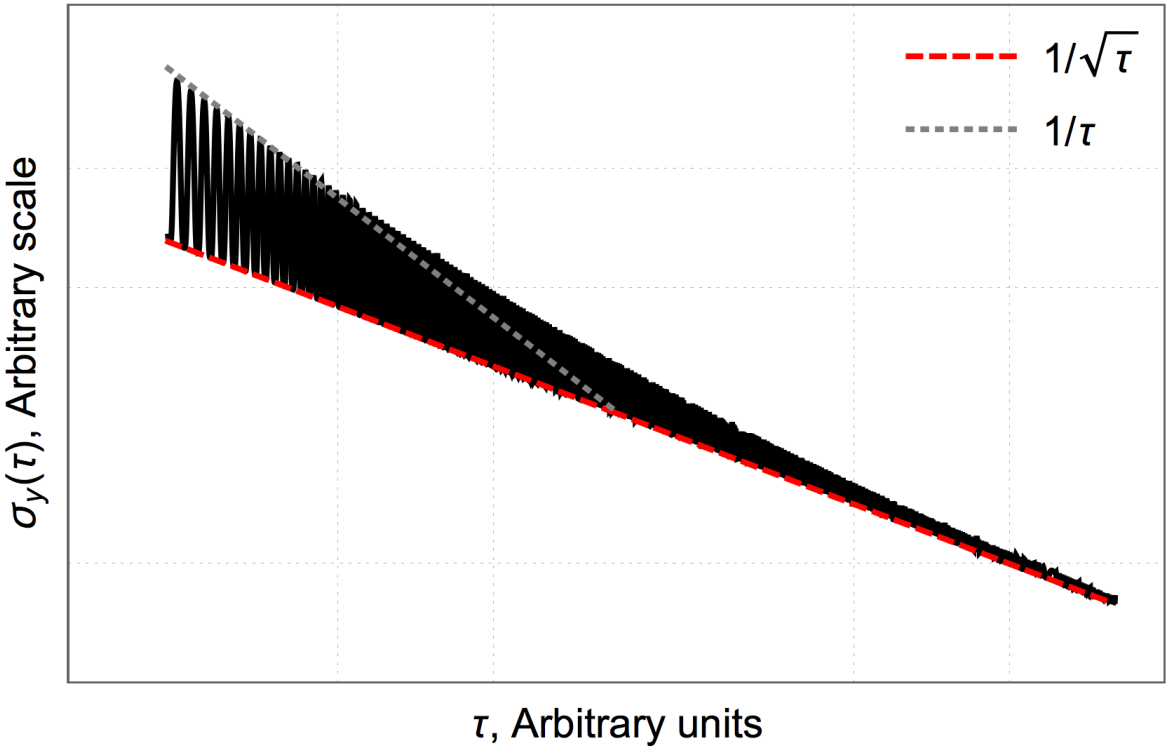
Anomalies in the stability plots

- 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



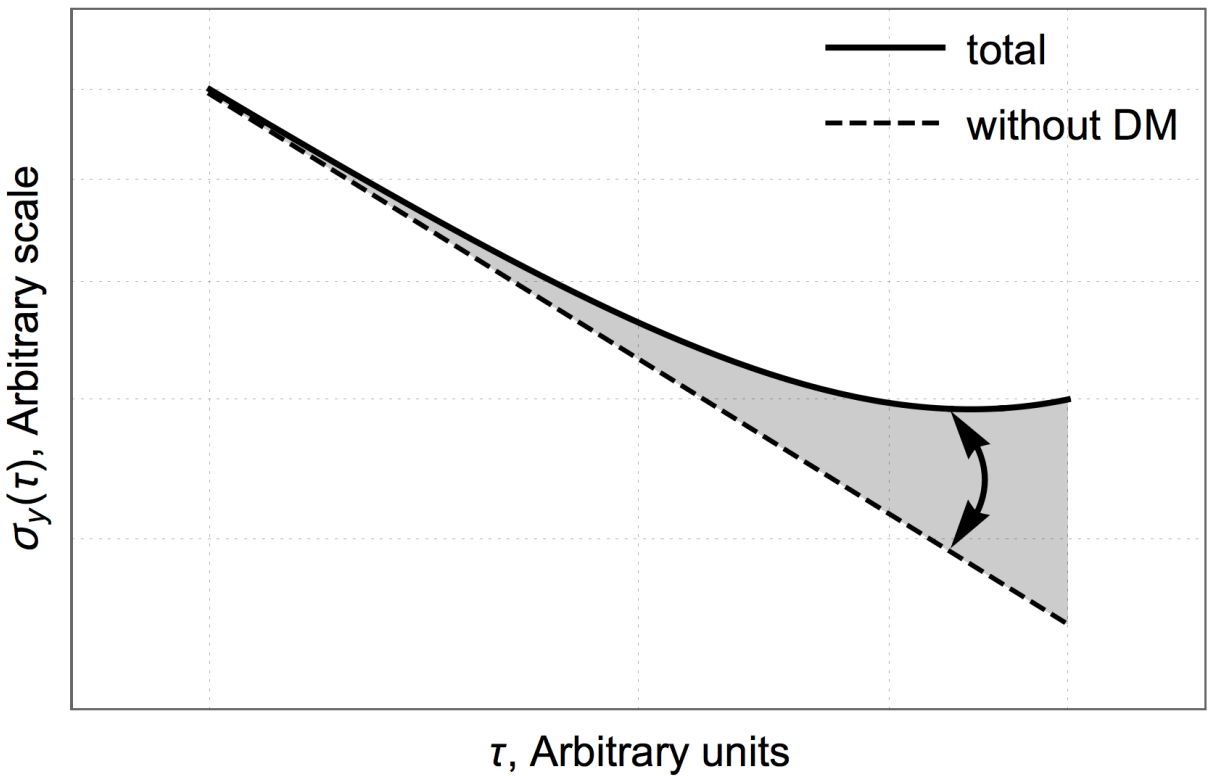
Anomalies in the stability plots

- 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!



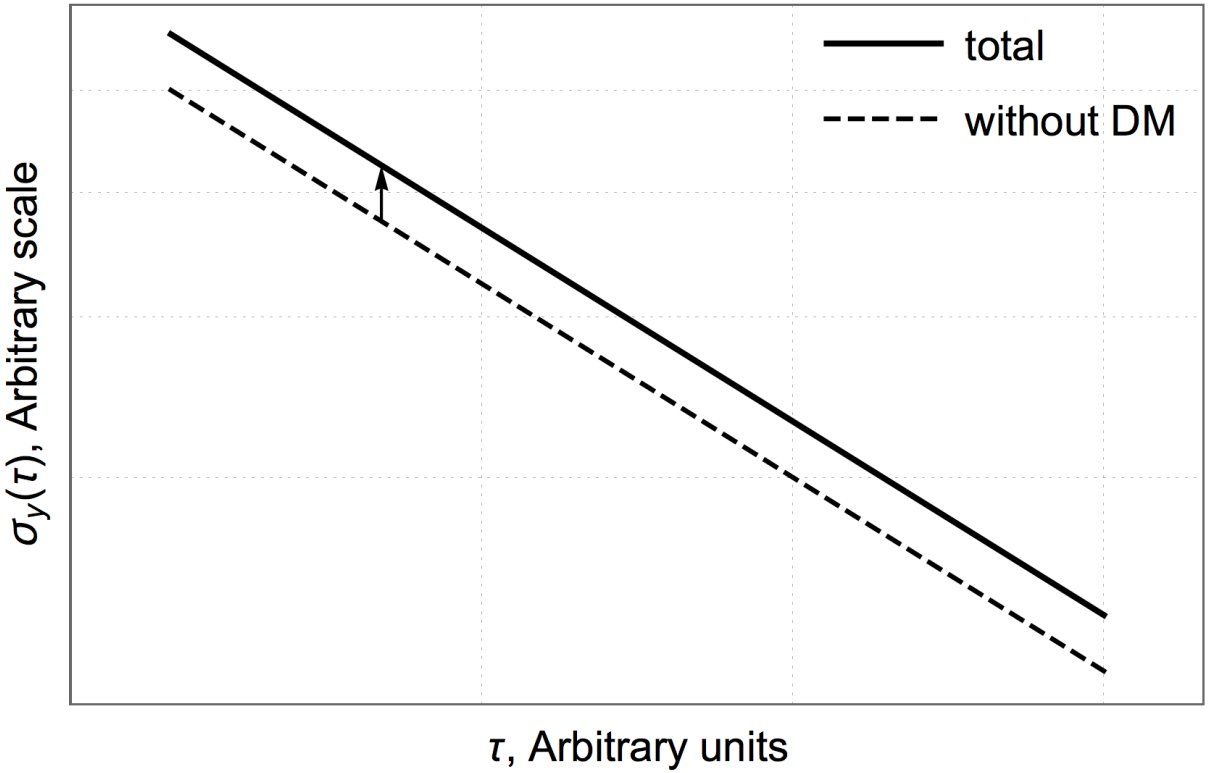
Anomalies in the stability plots

- 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

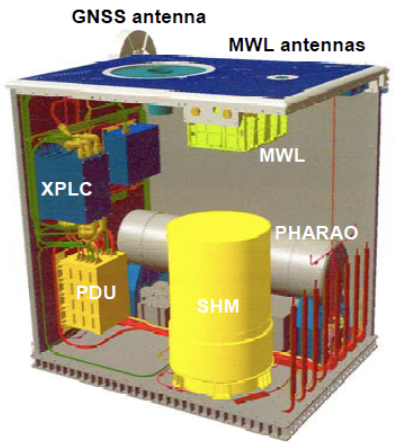


Anomalies in the stability plots

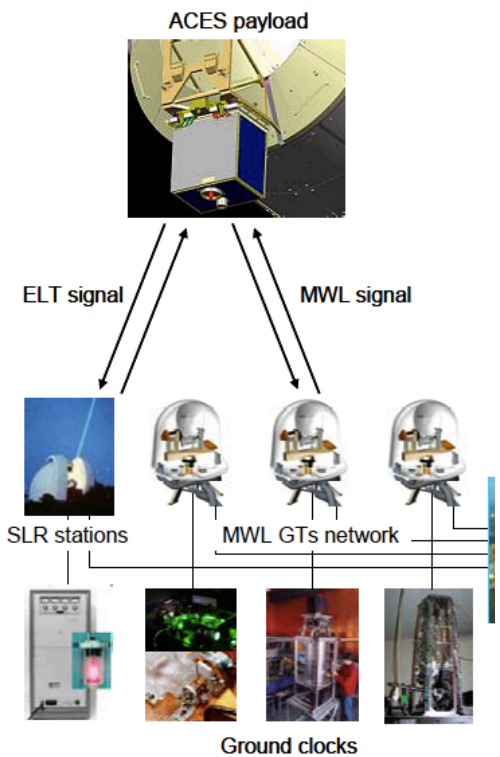
- Topological Dark Matter objects of size d ≈ ħ/(mc)
- Spatially separated clocks of identical or different type
- Anomaly: shift in the position of the Allan deviation curve



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,

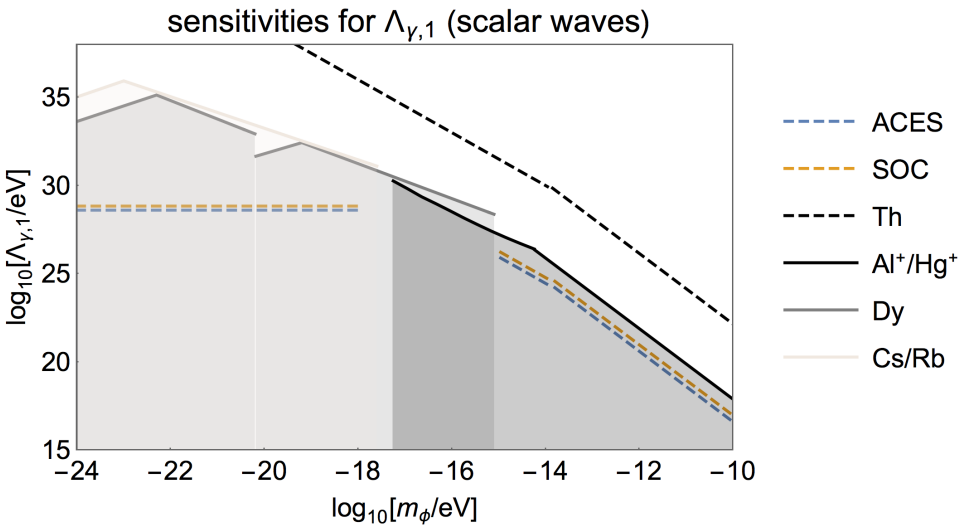
and common view ground
clock comparisons

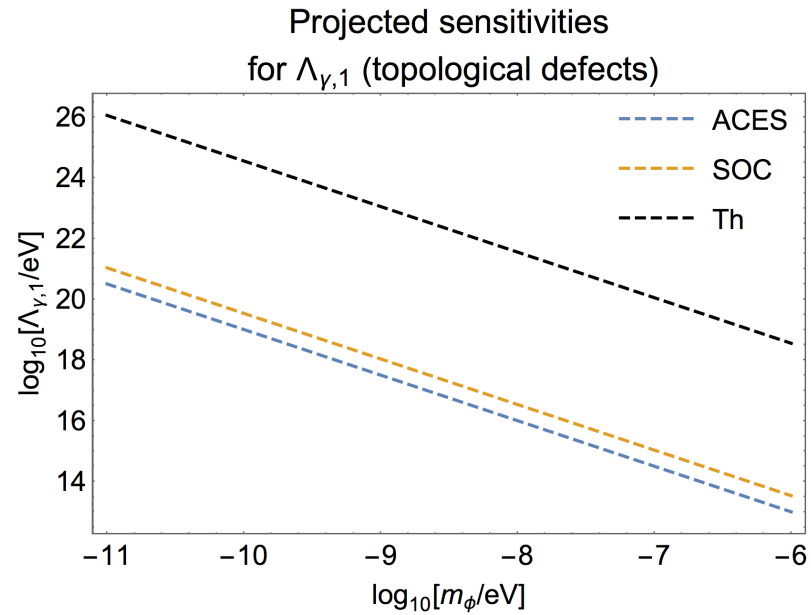
ACES can be used for establishing

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

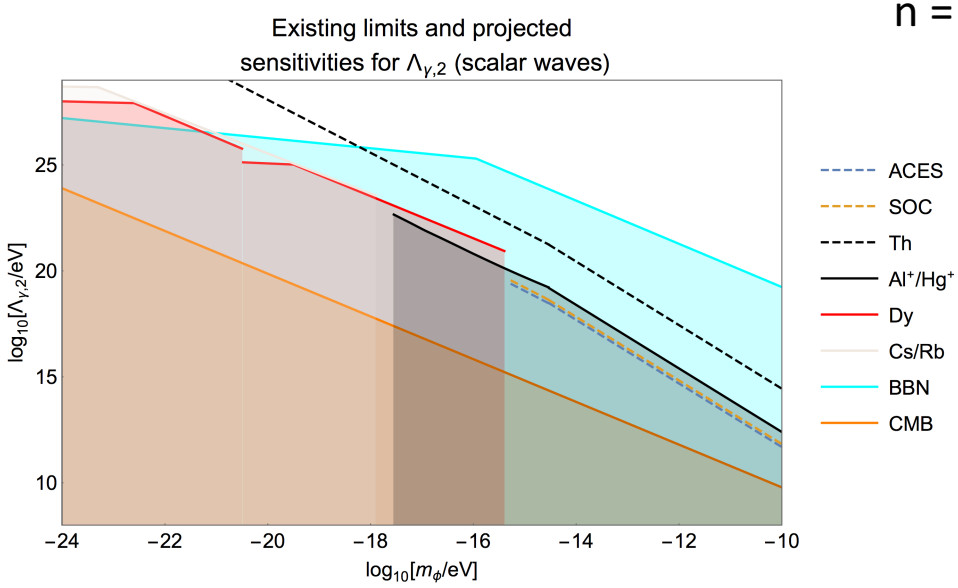
[2] complementary limits on the dark matter wave background in the region of masses 10^{-15}-10^{-10} eV

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)
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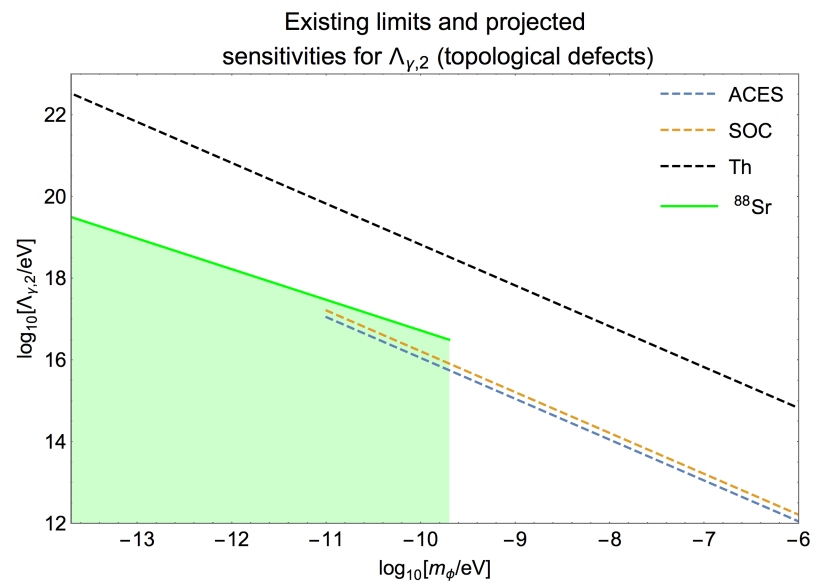
$\log_{10}[m_\phi/\mathrm{eV}]$
ACES
SOC
Th
Al^+/Hg^+
Dy
Cs/Rb
BBN
CMB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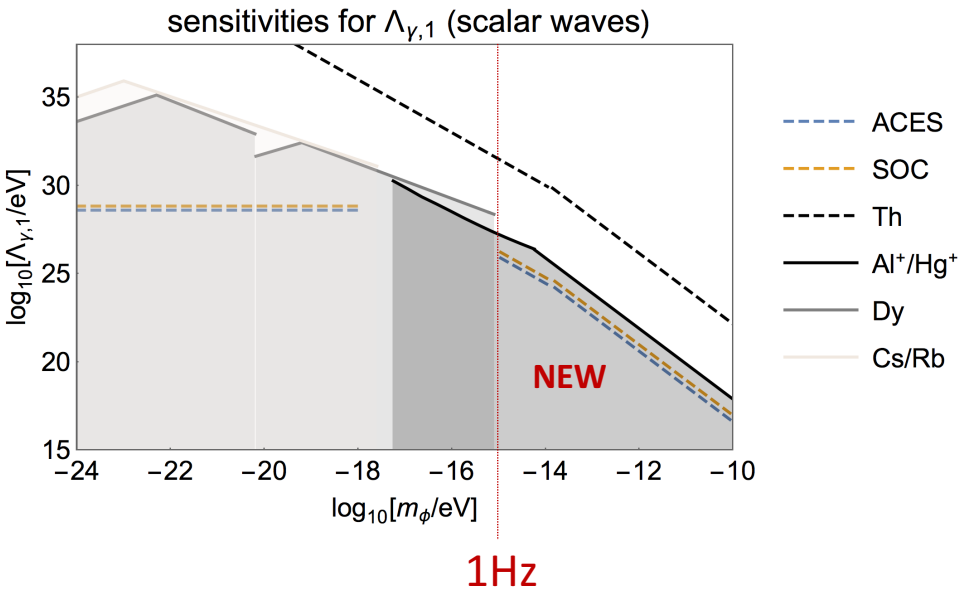
$\log_{10}[m_\phi/\mathrm{eV}]$
ACES
SOC
Th
^{88}Sr

n = 1: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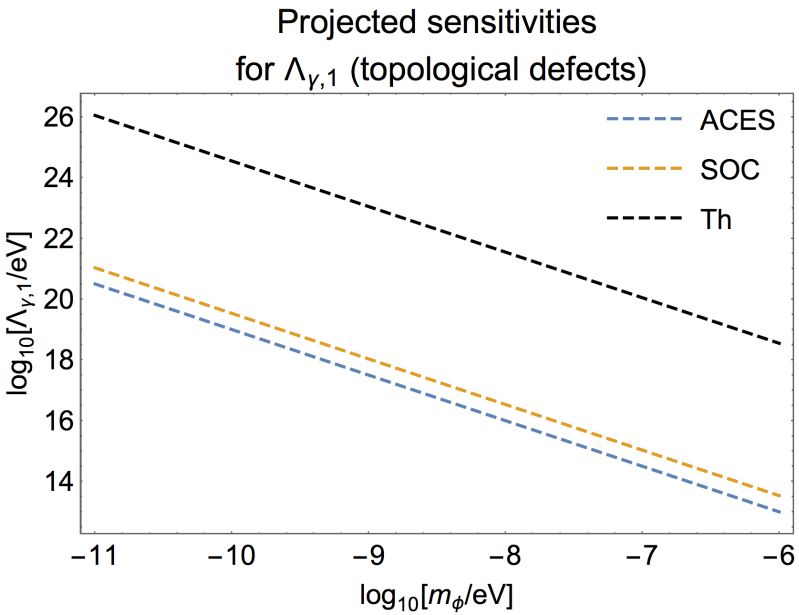
ACES
SOC
Th
Al^+/Hg^+
Dy
Cs/Rb
NEW

1Hz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SOC
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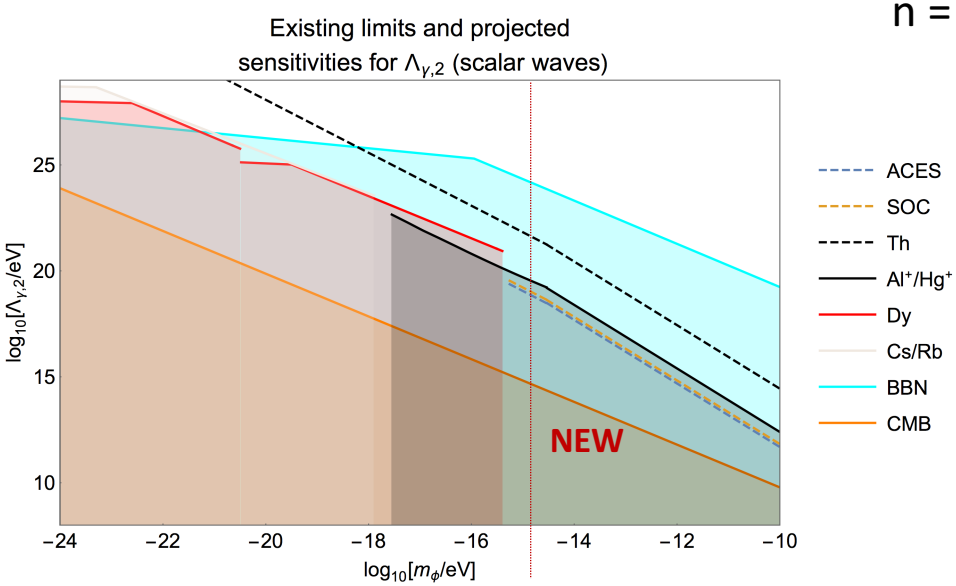
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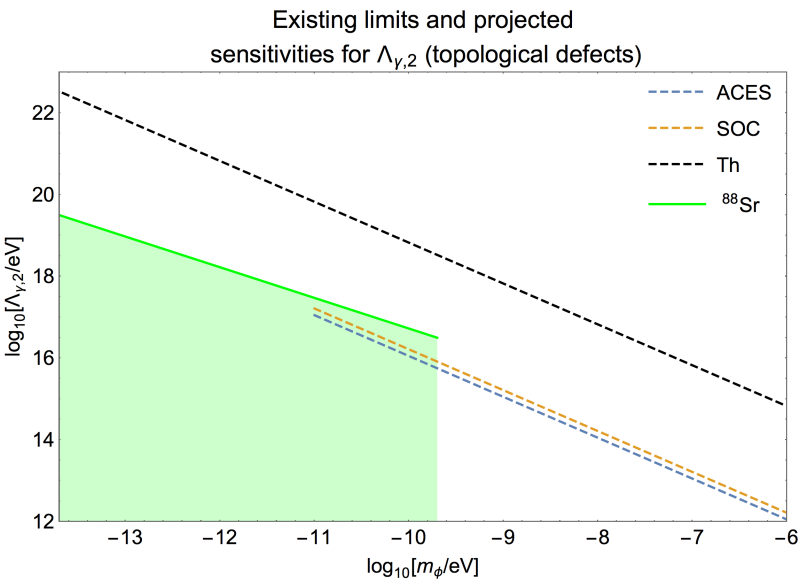
NEW

1Hz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$\log_{10}[m_\phi/\mathrm{eV}]$
ACES
SOC
Th
^{88}Sr

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.

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