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AGENCIA ESTATAL DE INVESTIGACIÓN

The Dawn of Nuclear Supremacy:

First Bounds on Ultralight Dark Matter from the Thorium Isomer Transition

Eric Madge (IFT-UAM/CSIC)

Implications of the laser excitation of the Th-229 nucleus for dark matter searches

Fuchs, Kirk, **EM**, Paranjape, Peik, Perez, Ratzinger, Tiedau; arXiv:2407.15924 [hep-ph]

Introduction

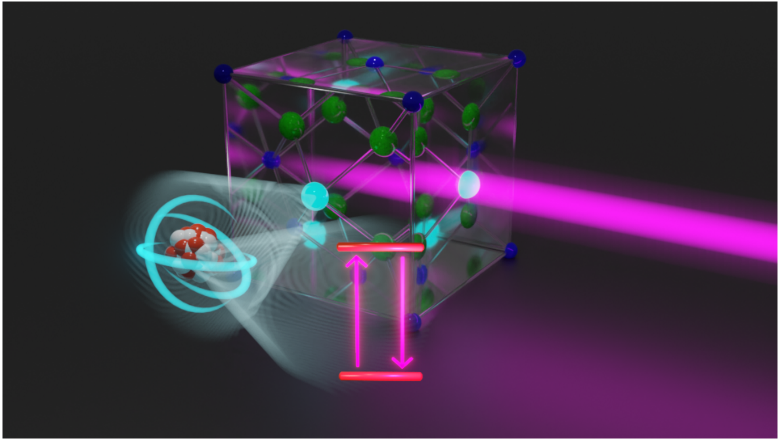
first laser excitation of ^{229m}Th in crystals:

- CaF_2: Tiedau et al., PRL 132 (2024)

  $f = 2020.409(7)$ THz

- $LiSrAlF_6$: Elwell et al., PRL 133 (2024)

  $f = 2020.4073(5)$ THz



credit: TU Wien/PTB

$\Longrightarrow$ breakthrough on the path towards ^{229m}Th $\to$ ^{229}Th nuclear clock

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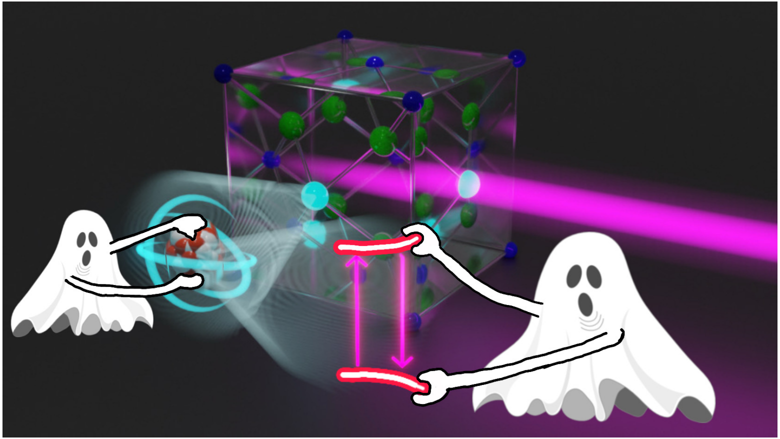

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Excitation spectrum can aready be used to probe ultralight dark matter!

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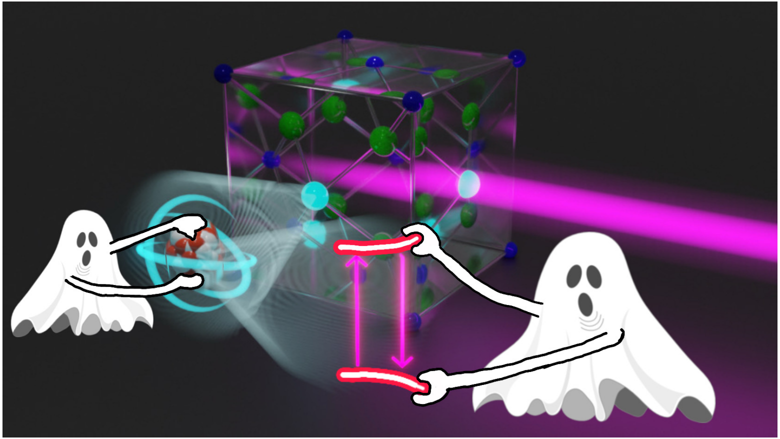

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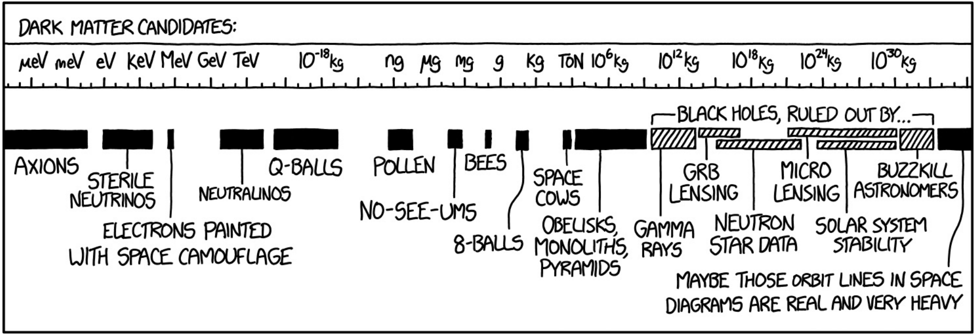
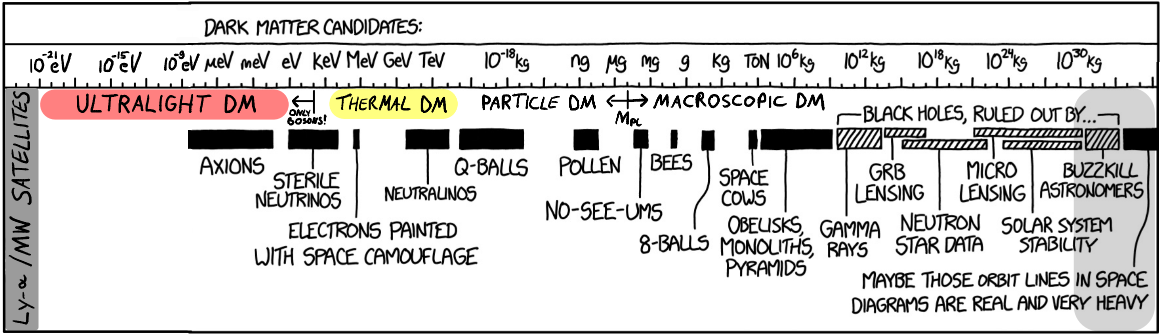
Ultralight Dark Matter



credit: https://xkcd.com/

Ultralight Dark Matter



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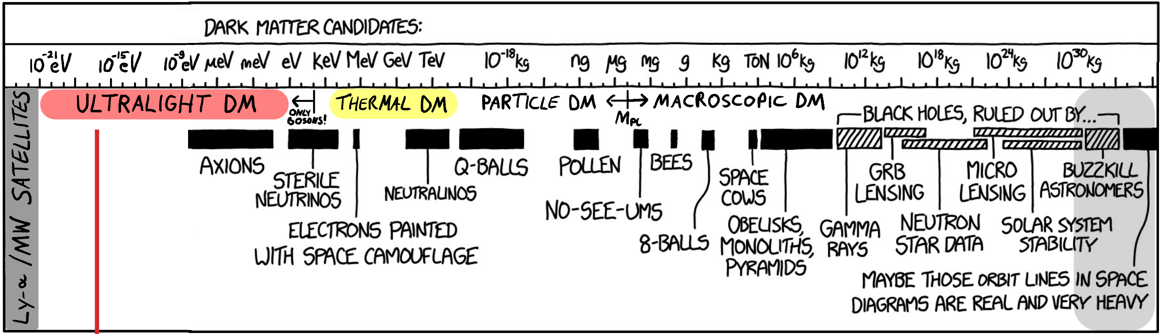

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- behaves like classical field

$$\langle N \rangle \sim n\lambda_{\rm dB}^3 \sim \frac{\rho}{m}(mv)^{-3} \gg 1 \qquad \Longrightarrow \qquad m_{\rm DM} \lesssim 1\,\text{eV}$$

- oscillates coherently $\left(\tau_{\rm coh} \sim \frac{2\pi}{mv^2} \sim 10^6\,\text{oscillations}\right)$

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi^2 = 0 \qquad \Longrightarrow \qquad \phi(t) \sim a^{-\frac{3}{2}}\cos(mt+\delta)$$

Nuclear-Coupled Dark Matter

- scalar ϕ: $$\mathcal{L} \supset -\underbrace{\frac{\beta_s}{2\, g_s}\sqrt{4\pi G_N}}_{\kappa}\, d_g\, \phi\, G^a_{\mu\nu} G^{a\,\mu\nu}$$

$$\Longrightarrow \qquad \Lambda_{\rm QCD} = \Lambda^{(0)}_{\rm QCD}\,(1 + \kappa\, d_g\, \phi)$$

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$$\Longrightarrow \qquad m_\pi^2 \sim m_\pi^{2\,(0)} \left(1 - \frac{m_u \, m_d}{4\,(m_u + m_d)^2} \frac{a^2}{f_a^2}\right)$$

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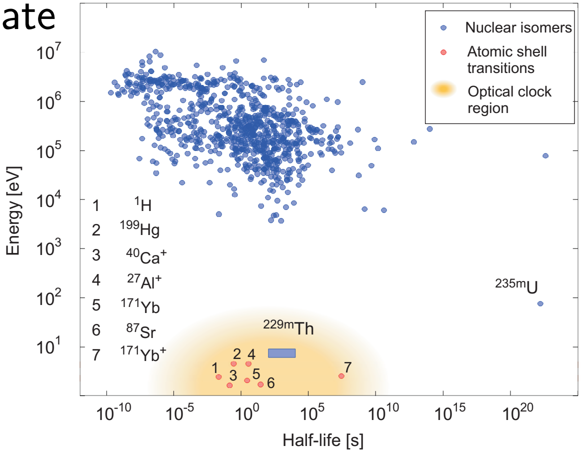
$\implies$ oscillations in ^{229}Th frequency:

$$\frac{\Delta f_{\mathrm{Th}}}{f_{\mathrm{Th}}} \propto d_g\,\phi \propto \cos(m_\phi t) \qquad \text{or} \qquad \frac{\Delta f_{\mathrm{Th}}}{f_{\mathrm{Th}}} \propto \frac{a^2}{f_a^2} \propto \cos(2\,m_a t)$$

^{229}Th as a Nuclear Clock Candidate

^{229m}Th $\rightarrow$ ^{229}Th isomer transition:

- lifetime: $\tau \approx 30\,\text{min}$
- energy: $\omega = 8.36\,\text{eV} \quad (2020\,\text{THz})$



[credit: von der Wense et al., Nature 544 (2016)]

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$$\omega = \Delta E_{\text{nuc}} + \Delta E_C$$

nuclear energy
$\rightarrow \ \propto \Lambda_{\text{QCD}}$
$\rightarrow \ \sim \mathcal{O}(\text{MeV})$

Coulomb energy
$\rightarrow \ \propto \alpha_{\text{EM}}$
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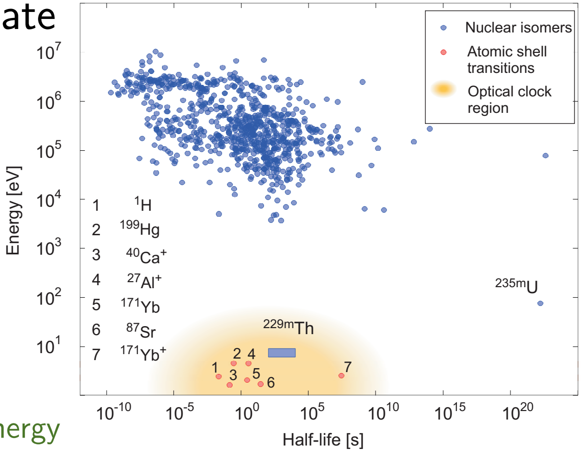

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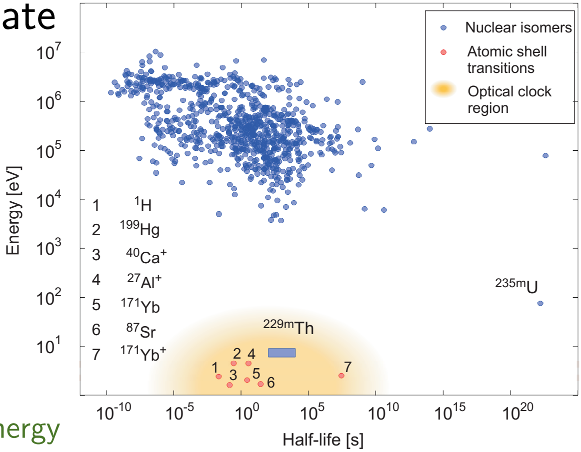

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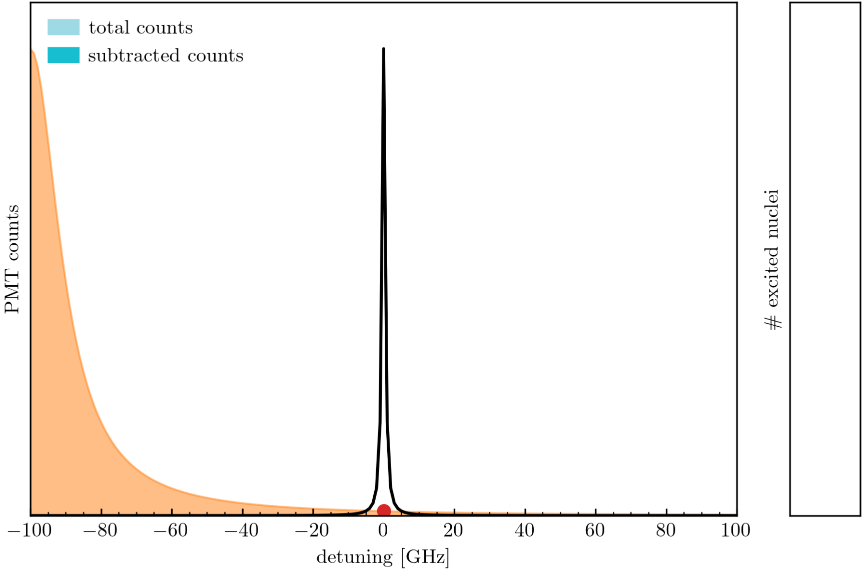
$\implies$ enhanced sensitivity: $$\frac{\Delta f}{f} \sim \frac{\Delta E_{\text{nuc}}}{\omega} \frac{\partial \log \Delta E_{\text{nuc}}}{\partial \log \Lambda_{\text{QCD}}} \frac{\Delta \Lambda_{\text{QCD}}}{\Lambda_{\text{QCD}}} \sim 10^5 \frac{\Delta \Lambda_{\text{QCD}}}{\Lambda_{\text{QCD}}}$$

[Flambaum, PRA 73 (2006); Flambaum, Wiringa, PRC 79 (2009); Fadeev, Berengut, Flambaum, PRA 102 (2020); Caputo et al., arXiv:2407.17526 [hep-ph]]

Excitation Spectrum



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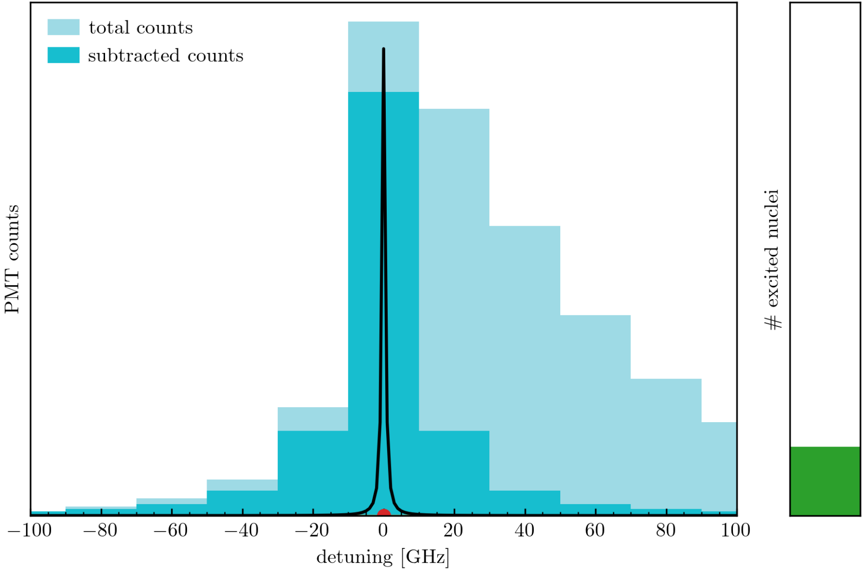

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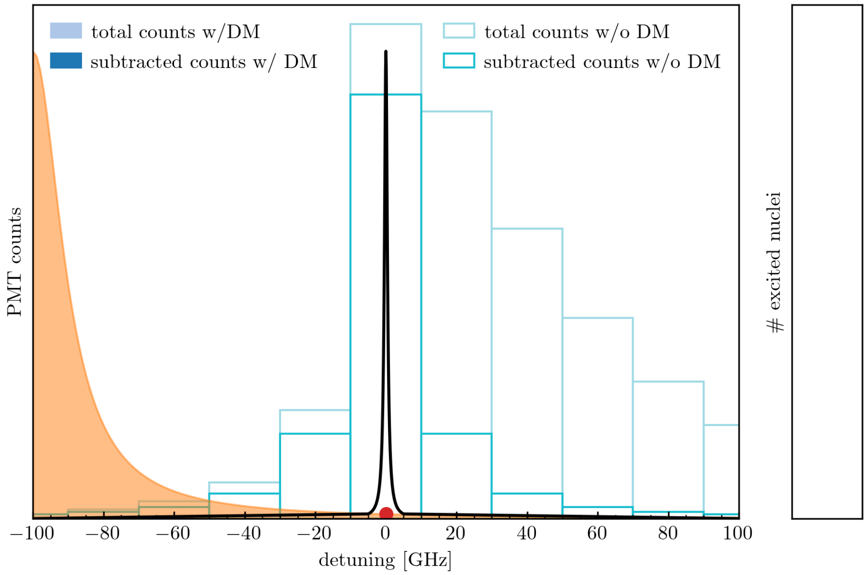

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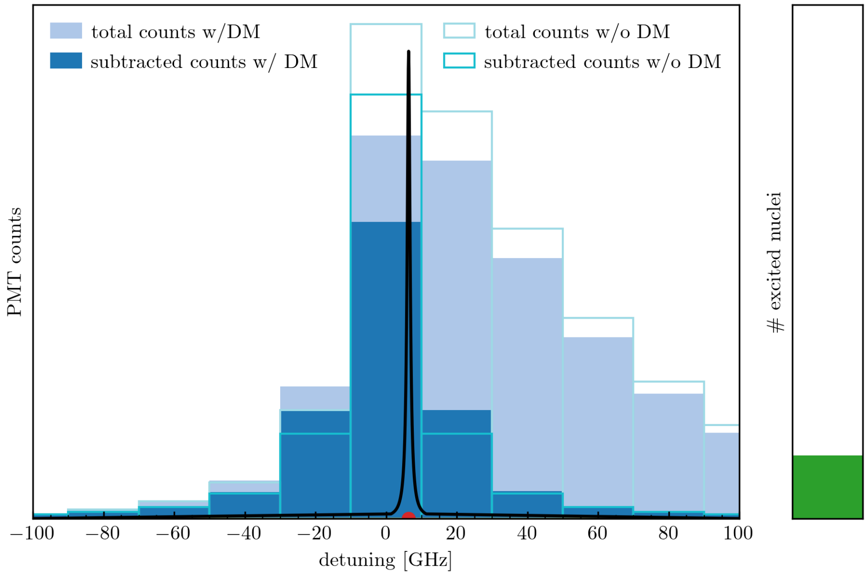


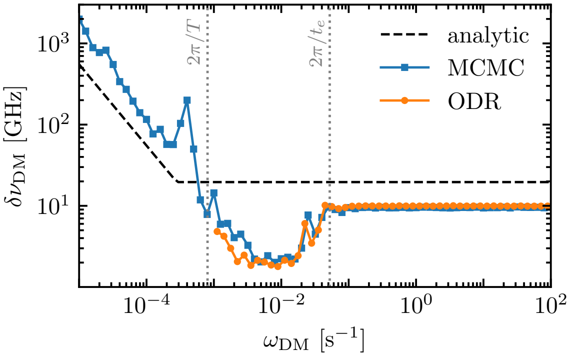
Lineshape Fit to Tiedau et al.

fit to excitation data at fixed $\omega_{\rm DM}$
to constrain $\delta f_{\rm DM}$

- $\omega_{\rm DM} T \ll 1$: linear drift between scans

$$\delta f_{\rm DM} \lesssim \frac{\sigma_{\rm Th}}{\omega_{\rm DM} T}$$

$\sigma_{\rm Th}$ – uncertainty



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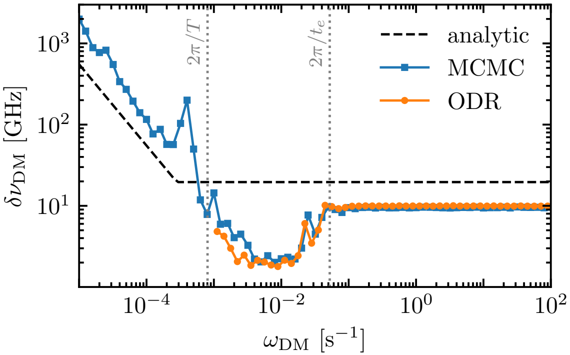

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- $\omega_{\rm DM}(t_e + t_d) \gg 1$: broadening by $2\,\delta f_{\rm DM}$

$$\delta f_{\rm DM} \lesssim \Delta f$$

Δf – FWHM

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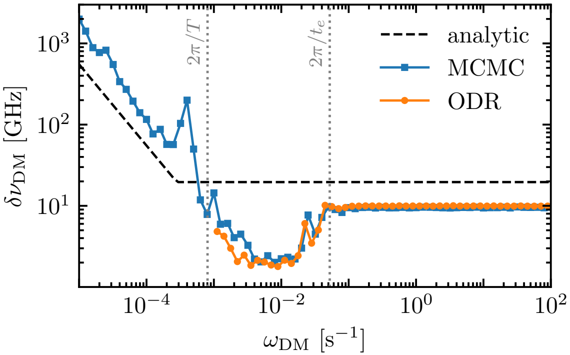
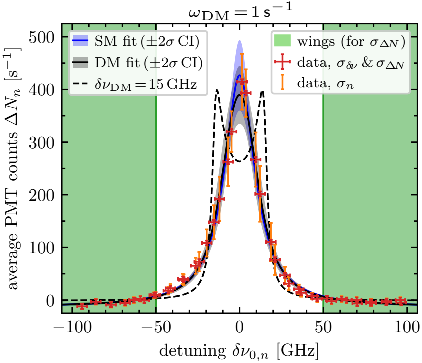
$$\delta f_{\rm DM} \lesssim \Delta f \qquad \Delta f \text{ – FWHM}$$

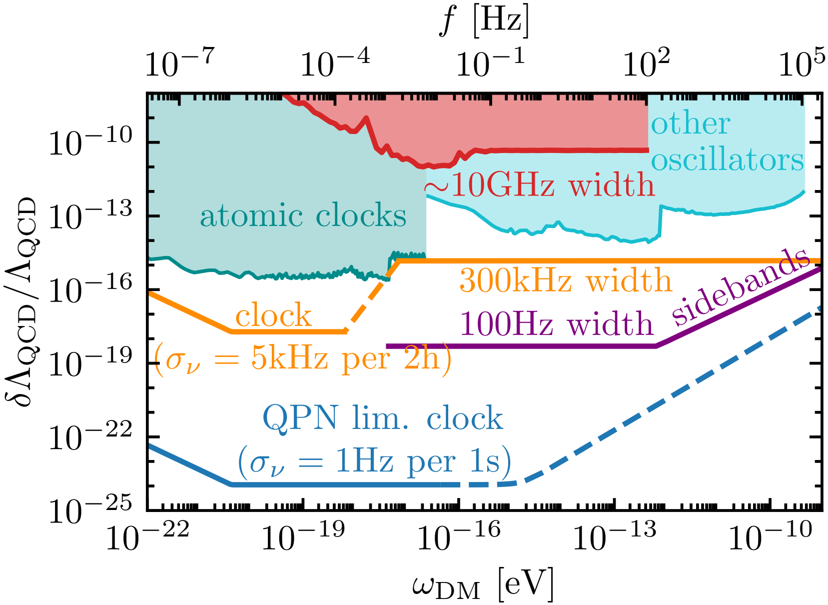
- $\delta f_{\rm DM} \gg \omega_{\rm DM}$: two peaks at $f_{\rm Th} \pm \delta f_{\rm DM}$

$$\langle I(f) \rangle \propto \frac{\theta\left(1 - \left|\frac{f - f_{\rm Th}}{\delta f_{\rm DM}}\right|\right)}{\sqrt{\delta f_{\rm DM}^2 - (f - f_{\rm Th})^2}}$$

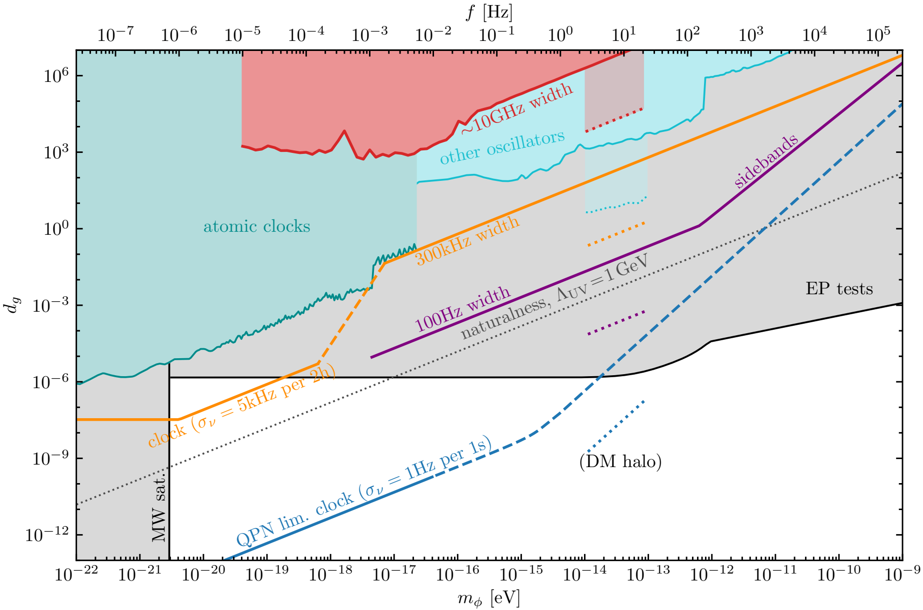




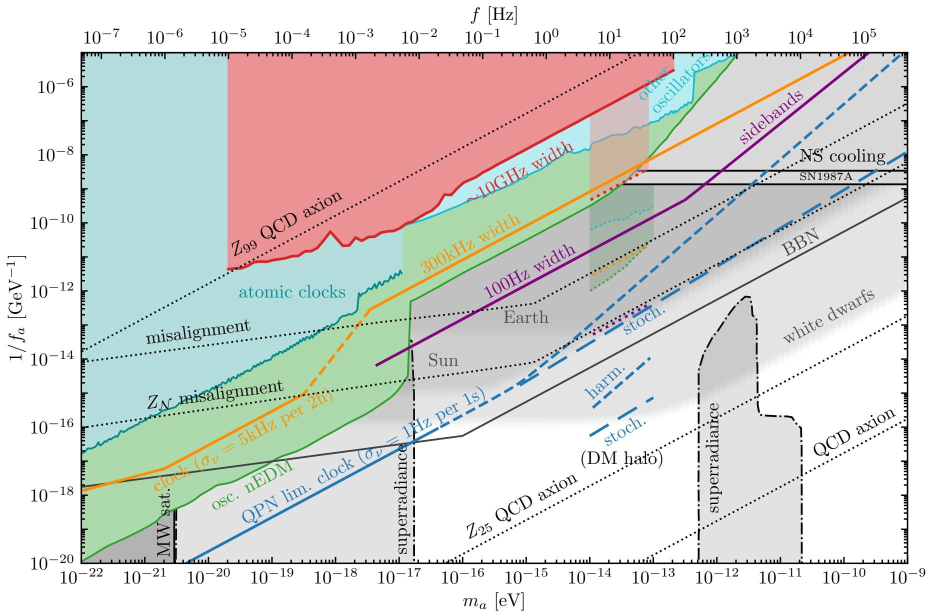
Bounds on Variations of Λ_{QCD}



Scalar Dark Matter Bounds



Axion Dark Matter Bounds



Conclusion

- ULDM can induce oscillations in fundamental constants
- quantum clocks can be used to probe ULDM
- nuclear transitions can be used to probe ULDM even before proper clock operation
- current technology can already probe new parameter space

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Thank you for your attention!

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Backup

Excitation Lineshape Model

detection efficiency

excitation probability between t' and $t' + dt'$

probability for nucleus excited at t' to decay between t and $t + dt$

laser lineshape

thorium lineshape

$$\Delta N_n = \varepsilon \int_0^{t_e} dt' \, \Gamma(t') \int_{t_e}^{t_e+t_d} dt \, \frac{1}{\tau} \, e^{-\frac{t-t'}{\tau}} \, , \qquad \Gamma(t') \propto \int df \, L\Big(f; f_L(t')\Big) \, I\Big(f; f_{\mathrm{Th}}(t')\Big)$$

Lorentzian $\qquad \delta\big(f - f_{\mathrm{Th}}(t')\big)$

$$= \Delta N_{\mathrm{off}} + \mathcal{N} \int_0^1 dx \, \frac{e^{-x t_e/\tau}}{1 + 4\left(\frac{\delta f_n(x)}{\Delta_L}\right)^2}$$

count offset

prefactor

laser linewidth

DM modulation

frequency detuning: $\delta f_n(x) = \delta f_{L,n} + \delta f_{\mathrm{off}} + \delta f_{\mathrm{DM}} \cos\left(\omega_{\mathrm{DM}} t_e x - \varphi_n\right)$

$f_{\mathrm{Th}} - f_{L,n}$

detuning offset