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de Madrid



# 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

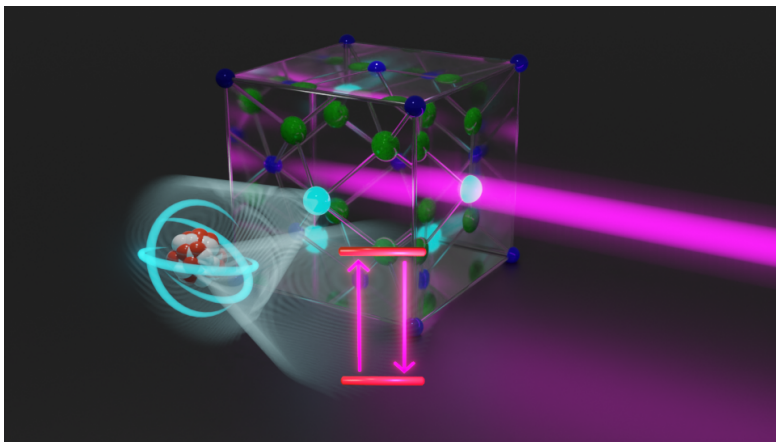
first laser excitation of  
 $^{229\text{m}}\text{Th}$  in crystals:

■  $\text{CaF}_2$ : Tiedau et al., PRL 132 (2024)

$$f = 2020.409(7) \text{ THz}$$

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credit: TU Wien/PTB

⇒ breakthrough on the path towards  $^{229\text{m}}\text{Th} \rightarrow ^{229}\text{Th}$  nuclear clock



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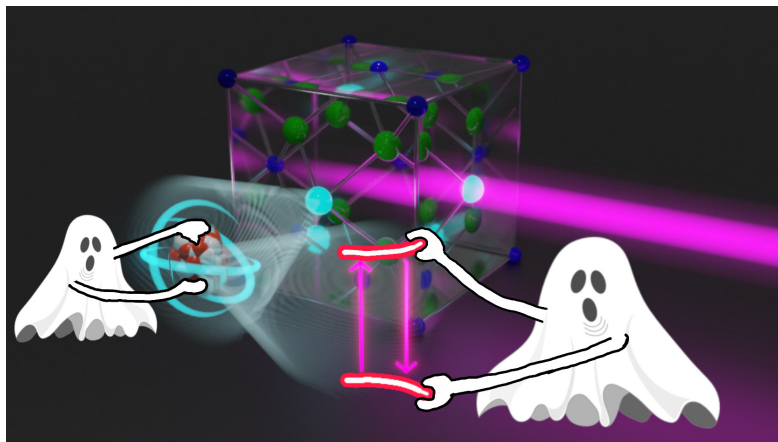
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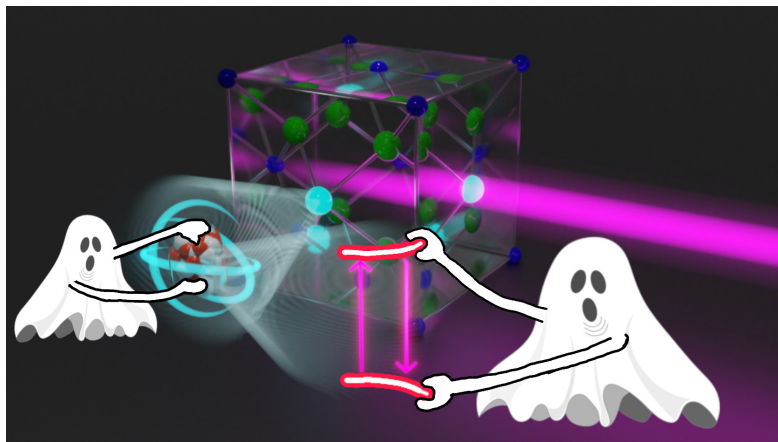
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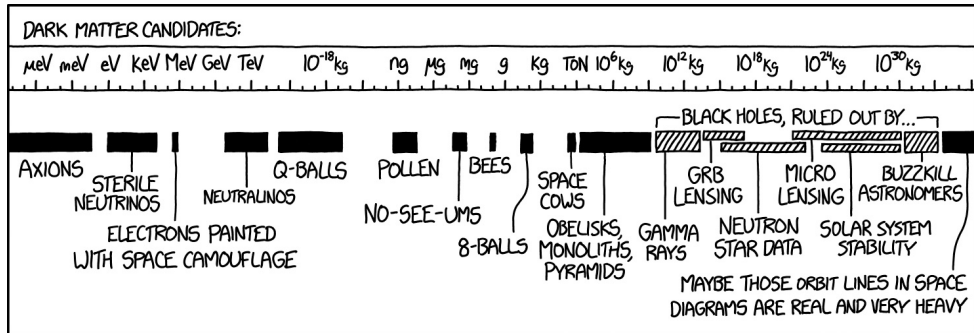


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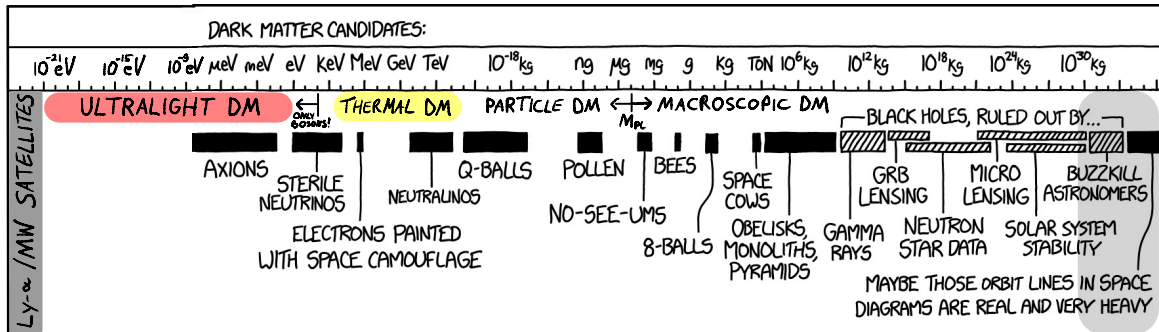
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# Ultralight Dark Matter



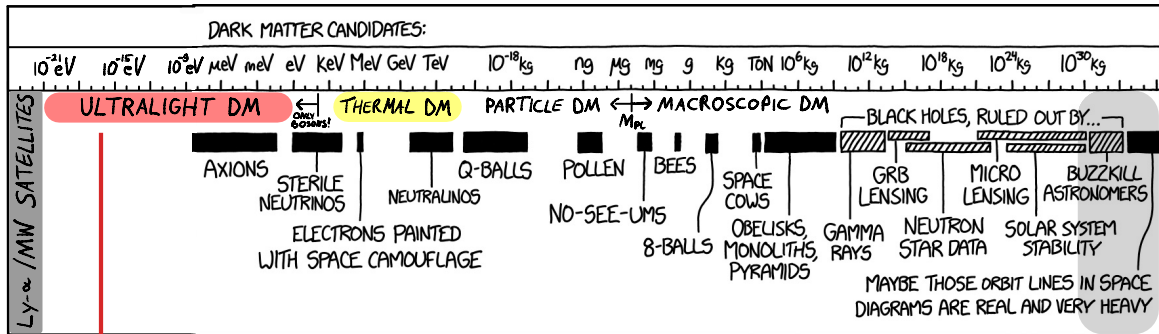
credit: <https://xkcd.com/>

# Ultralight Dark Matter



credit: <https://xkcd.com/> [edited]

# Ultralight Dark Matter



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■ behaves like classical field

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

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

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

# Nuclear-Coupled Dark Matter

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

$$\Rightarrow \Lambda_{\text{QCD}} = \Lambda_{\text{QCD}}^{(0)} (1 + \kappa d_g \phi)$$

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$\Rightarrow$  oscillations in  $^{229}\text{Th}$  frequency:

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

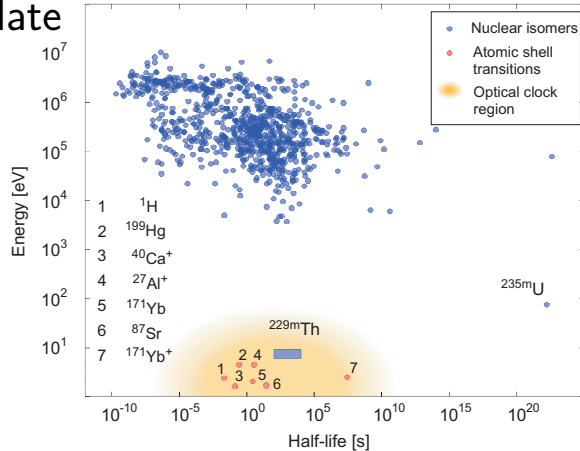


# $^{229}\text{Th}$ as a Nuclear Clock Candidate

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

■ lifetime:  $\tau \approx 30$  min

■ energy:  $\omega = 8.36$  eV (2020 THz)



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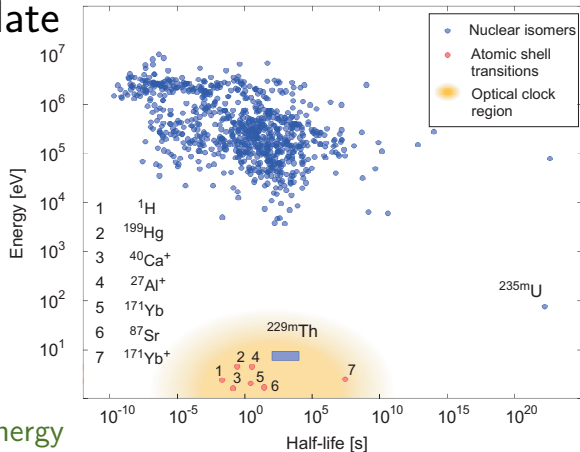
sensitivity to  $\Lambda_{\text{QCD}}$ :

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

$\sim 8 \text{ eV} \Rightarrow \text{cancellation}$

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

Coulomb energy  $\rightarrow \propto \alpha_{\text{EM}}$   
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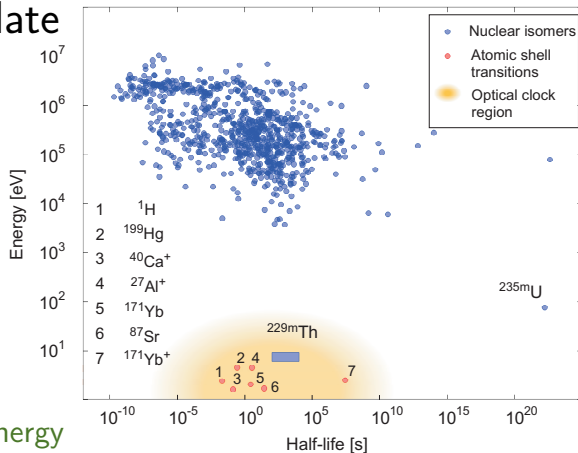
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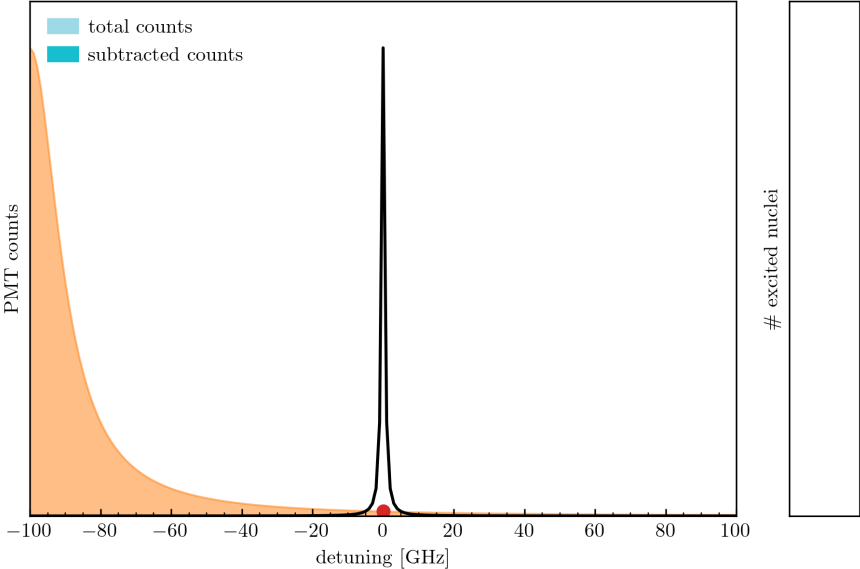
$\rightarrow \sim \mathcal{O}(\text{MeV})$

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

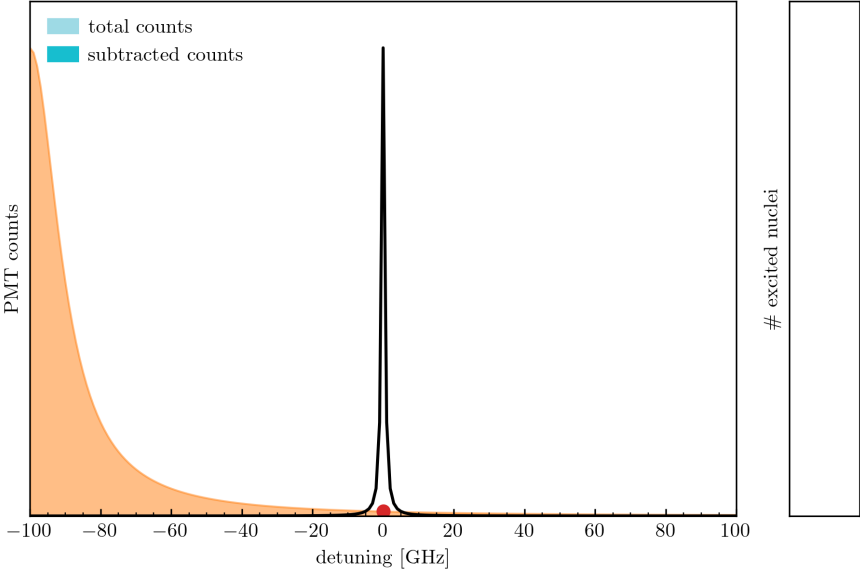


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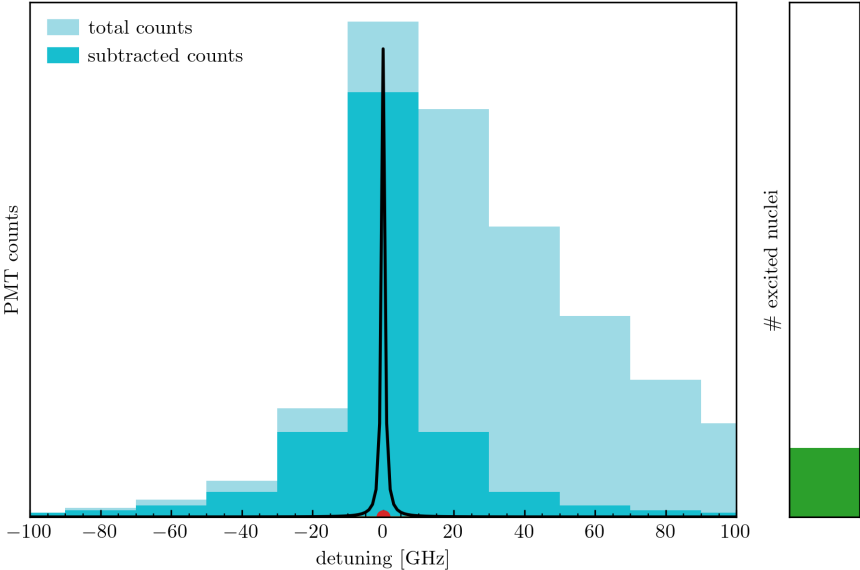
# Excitation Spectrum



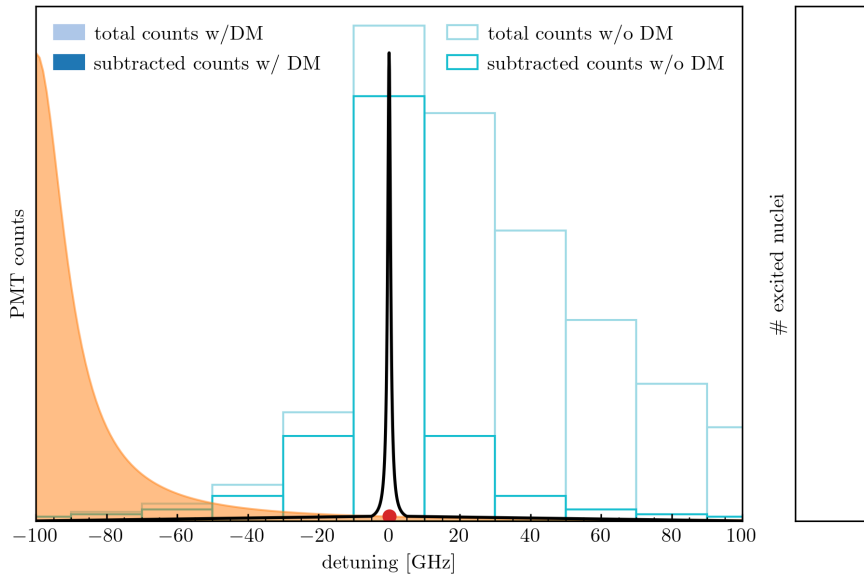
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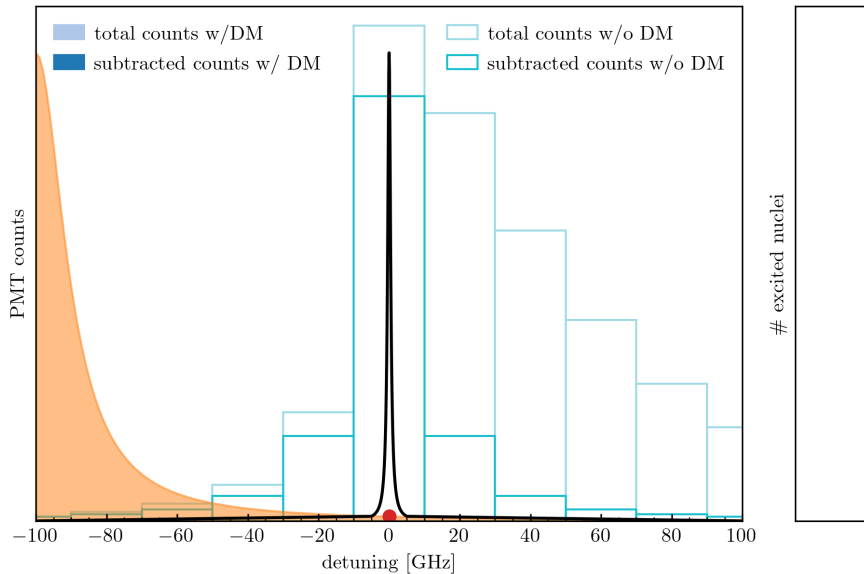
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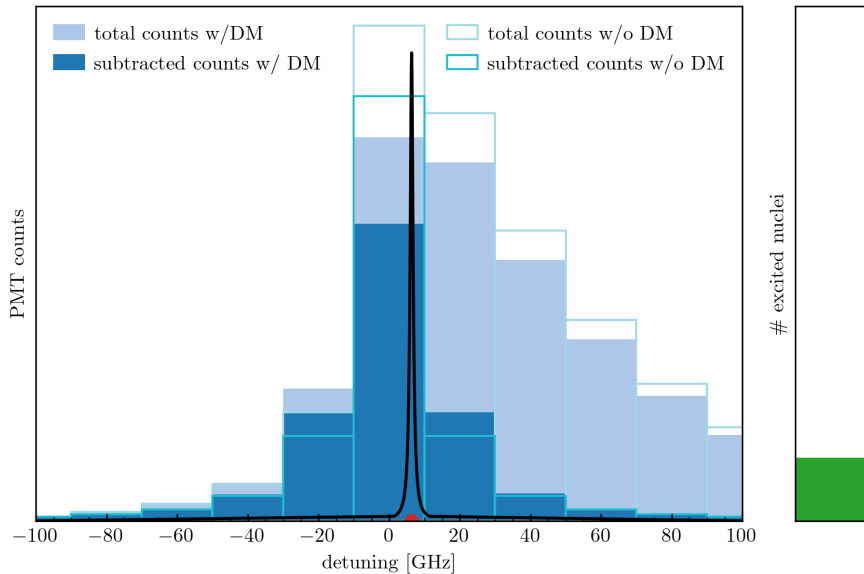


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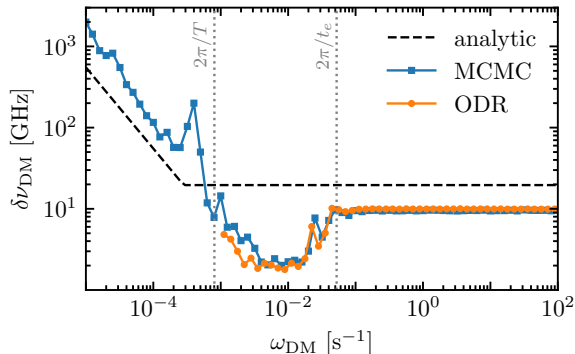


# Lineshape Fit to Tiedau et al.

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

■  $\omega_{\text{DM}}T \ll 1$  : linear drift between scans

$$\delta f_{\text{DM}} \lesssim \frac{\sigma_{\text{Th}}}{\omega_{\text{DM}}T} \quad \sigma_{\text{Th}} - \text{uncertainty}$$



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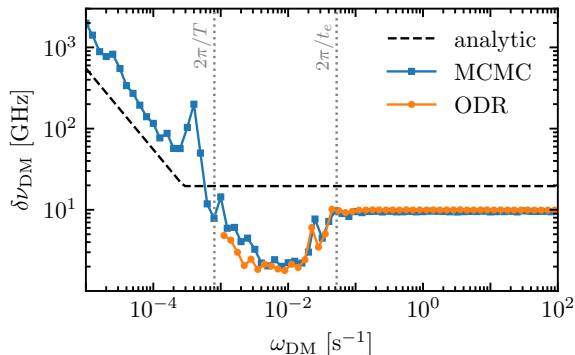
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- $\omega_{\text{DM}}(t_e + t_d) \gg 1$  : broadening by  $2\delta f_{\text{DM}}$

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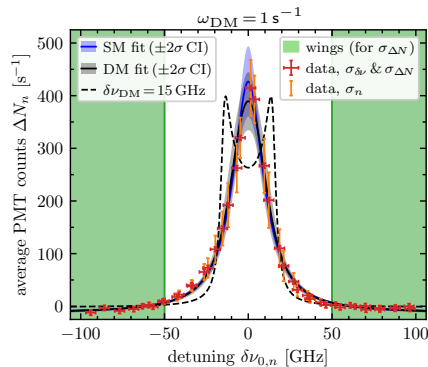
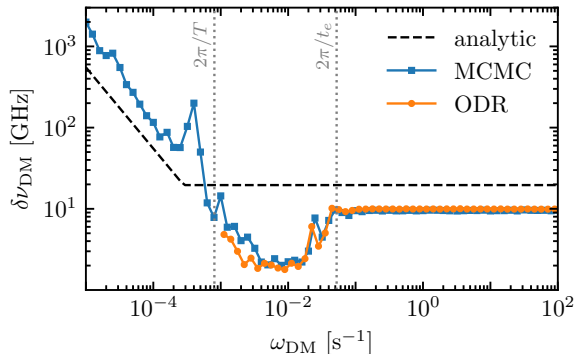
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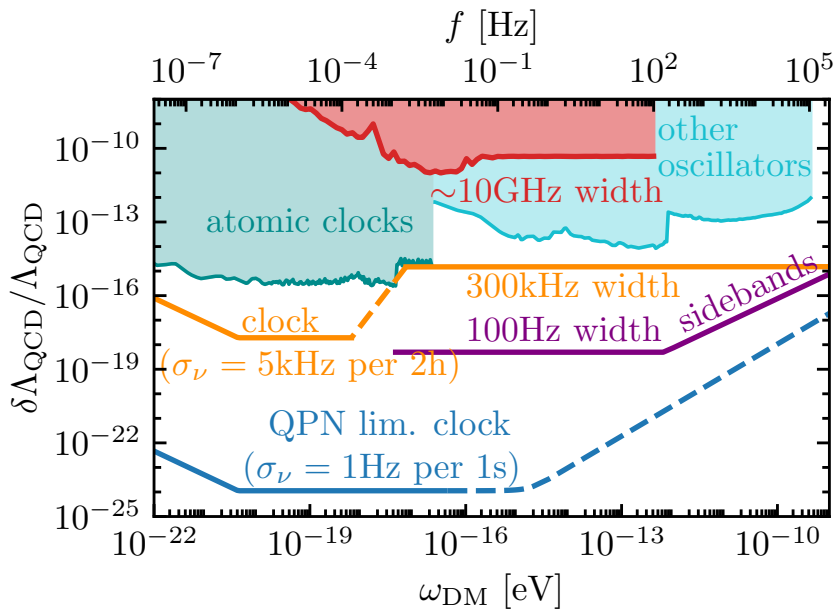
$$\delta f_{\text{DM}} \lesssim \Delta f \quad \Delta f - \text{FWHM}$$

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

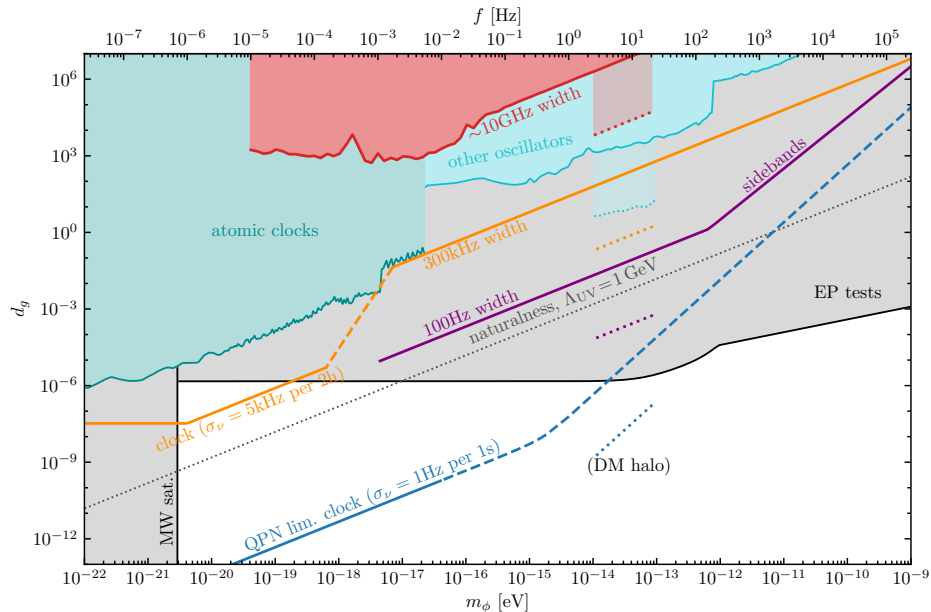
$$\langle I(f) \rangle \propto \frac{\theta \left( 1 - \left| \frac{f - f_{\text{Th}}}{\delta f_{\text{DM}}} \right| \right)}{\sqrt{\delta f_{\text{DM}}^2 - (f - f_{\text{Th}})^2}}$$



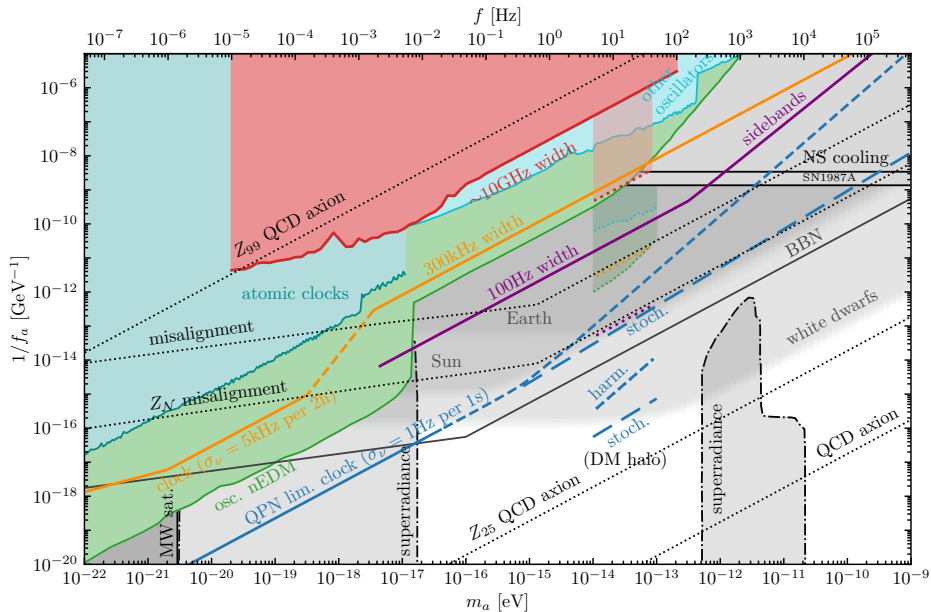
# Bounds on Variations of $\Lambda_{\text{QCD}}$



# 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
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Thank you for your attention!



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Backup

# Excitation Lineshape Model

detection efficiency  $\rightarrow$   $\Delta N_n = \varepsilon \int_0^{t_e} dt' \Gamma(t') \int_{t_e}^{t_e+t_d} dt \frac{1}{\tau} e^{-\frac{t-t'}{\tau}},$

excitation probability between  $t'$  and  $t' + dt'$   $\rightarrow$   $\Gamma(t')$

probability for nucleus excited at  $t'$  to decay between  $t$  and  $t + dt$   $\rightarrow$   $\frac{1}{\tau} e^{-\frac{t-t'}{\tau}}$

laser lineshape  $\rightarrow$   $L(f; f_L(t'))$  Lorentzian

thorium lineshape  $\rightarrow$   $I(f; f_{Th}(t')) \delta(f - f_{Th}(t'))$

$\Gamma(t') \propto \int df L(f; f_L(t')) I(f; f_{Th}(t'))$

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

count offset  $\rightarrow$   $\Delta N_{\text{off}}$

prefactor  $\rightarrow$   $\mathcal{N}$

laser linewidth  $\rightarrow$   $\Delta_L$

DM modulation  $\rightarrow$   $\delta f_{\text{DM}} \cos(\omega_{\text{DM}} t_e x - \varphi_n)$

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

$f_{\text{Th}} - f_{L,n}$   $\rightarrow$   $\delta f_{L,n}$

$\rightarrow$   $\delta f_{\text{off}}$  detuning offset