Nuclear Clock as Quintessometer

based on **arXiv:2503.02932**
w/ S.J. Lee, R. Ozeri, G. Perez,
W. Ratzinger and B. Yu

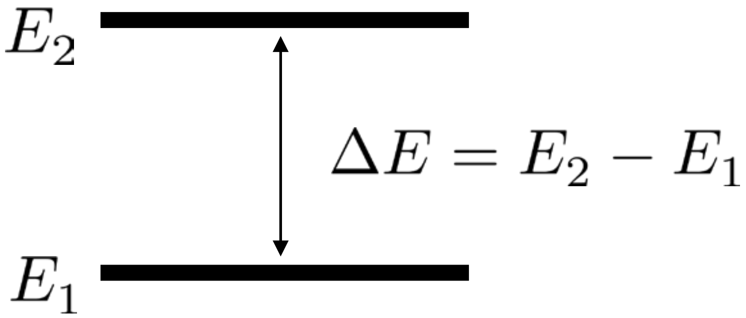
Cédric DELAUNAY
Laboratoire d'Annecy de Physique Théorique

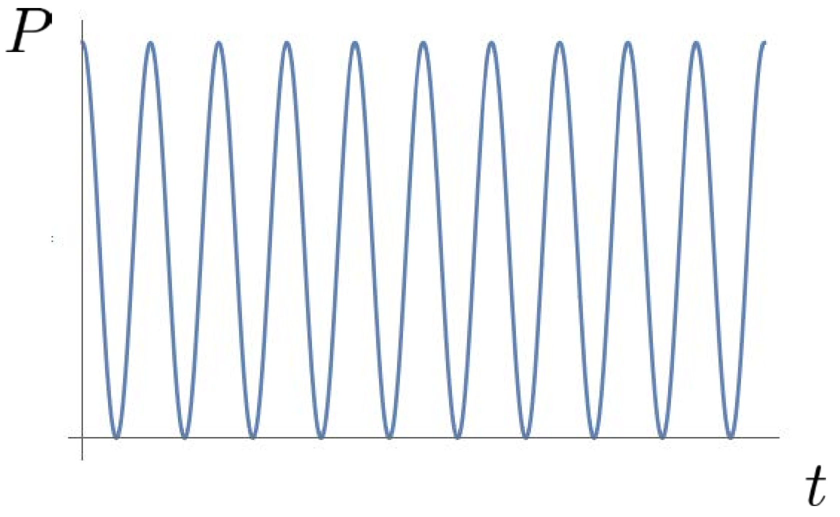
Cosmic WISPERs Workshop | Sofia | September 9, 2025

Nuclear clock

Clock = stable oscillator (and a counter)

atomic/nuclear clocks based on 2-level systems





prepare a superposition $|\psi_0\rangle = \frac{1}{\sqrt{2}}\Big[|1\rangle + |2\rangle\Big]$

at later time $|\psi(t)\rangle = \frac{e^{iE_1}}{\sqrt{2}}\Big[|1\rangle + \exp\left(i\Delta E\, t\right)|2\rangle\Big]$

project back $P(t) \equiv |\langle\psi_0|\psi(t)\rangle|^2 = \cos^2(\Delta E\, t/2)$

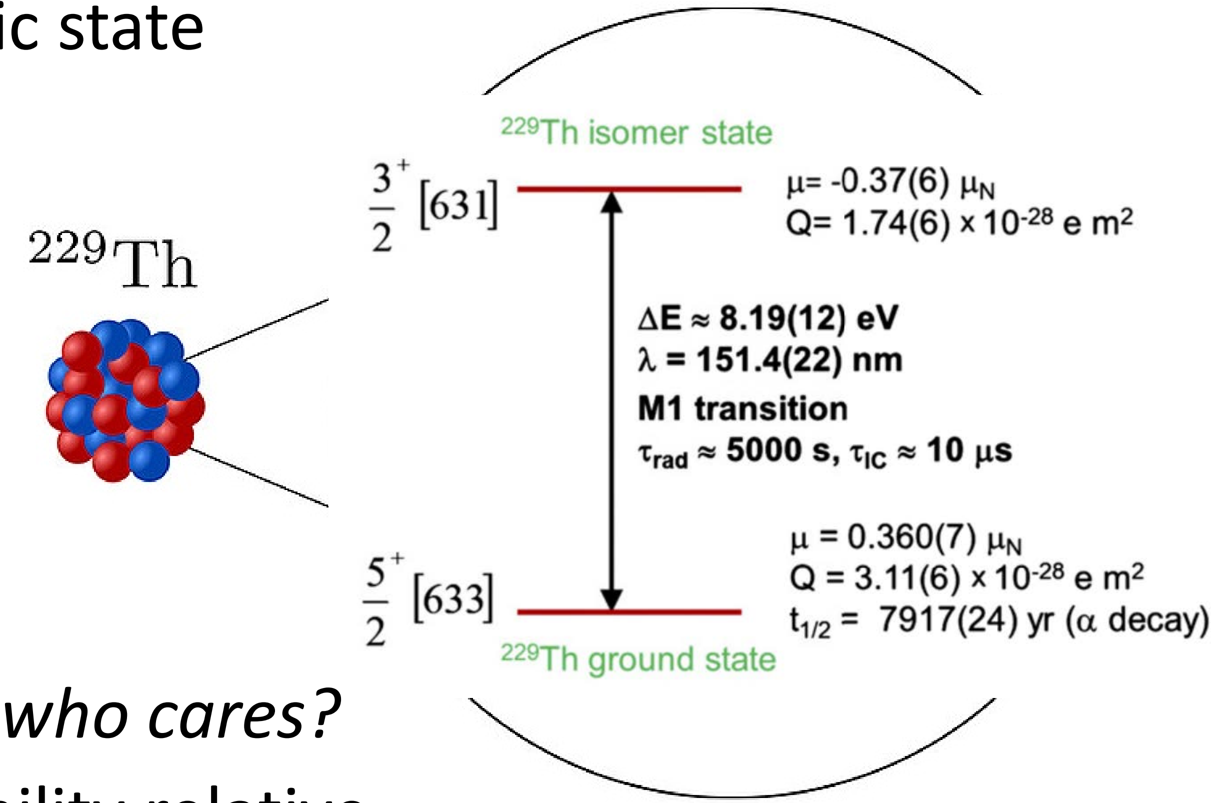
Thorium 229

229Th nucleus has a low isomeric state

$$\Delta E \approx 8\,\mathrm{eV}$$

close enough to optical range

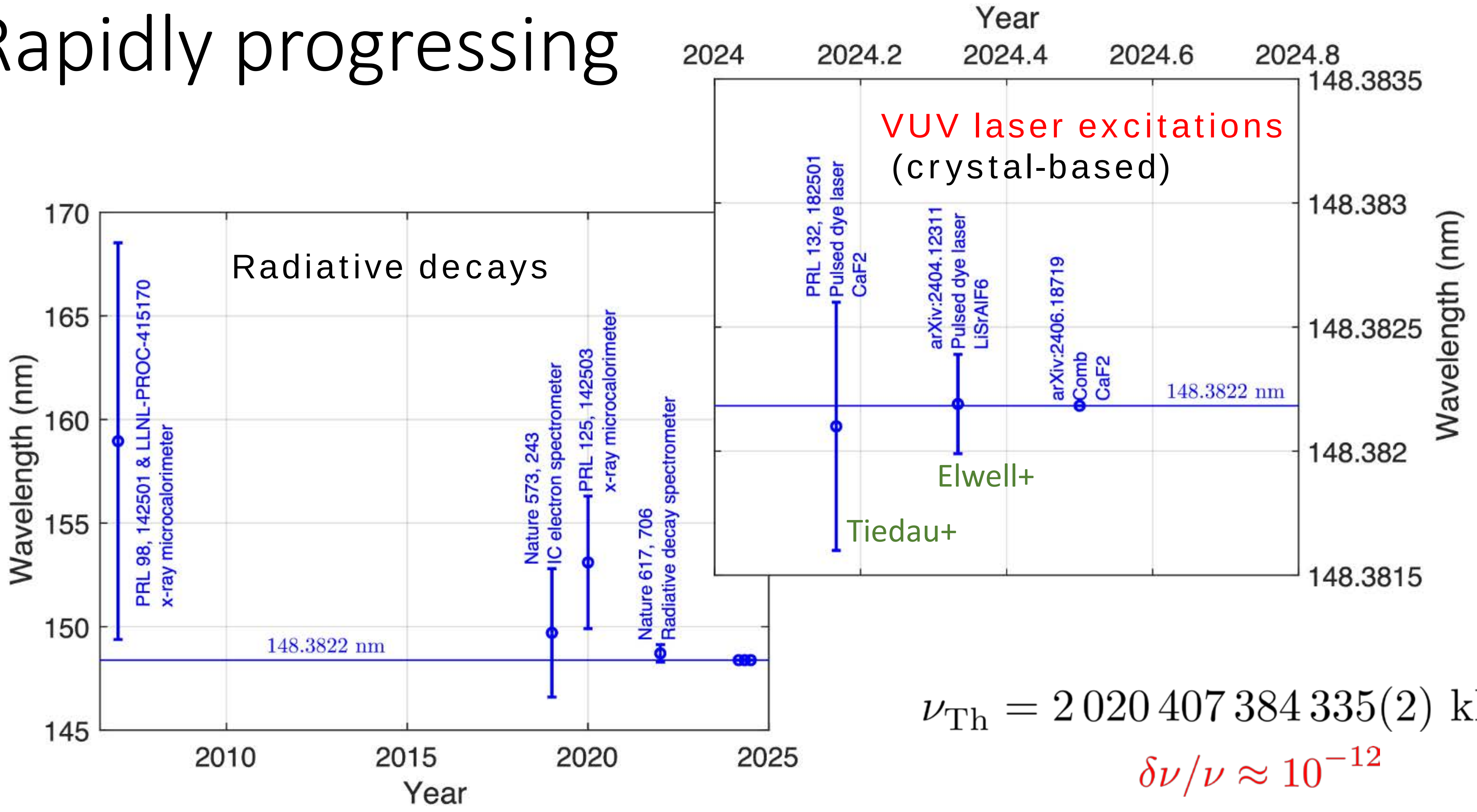
excitable with VUV lasers



We have good atomic clocks, so who cares?

metrologists because better stability relative to electronic transitions, due to Faraday screening of external fields

Rapidly progressing

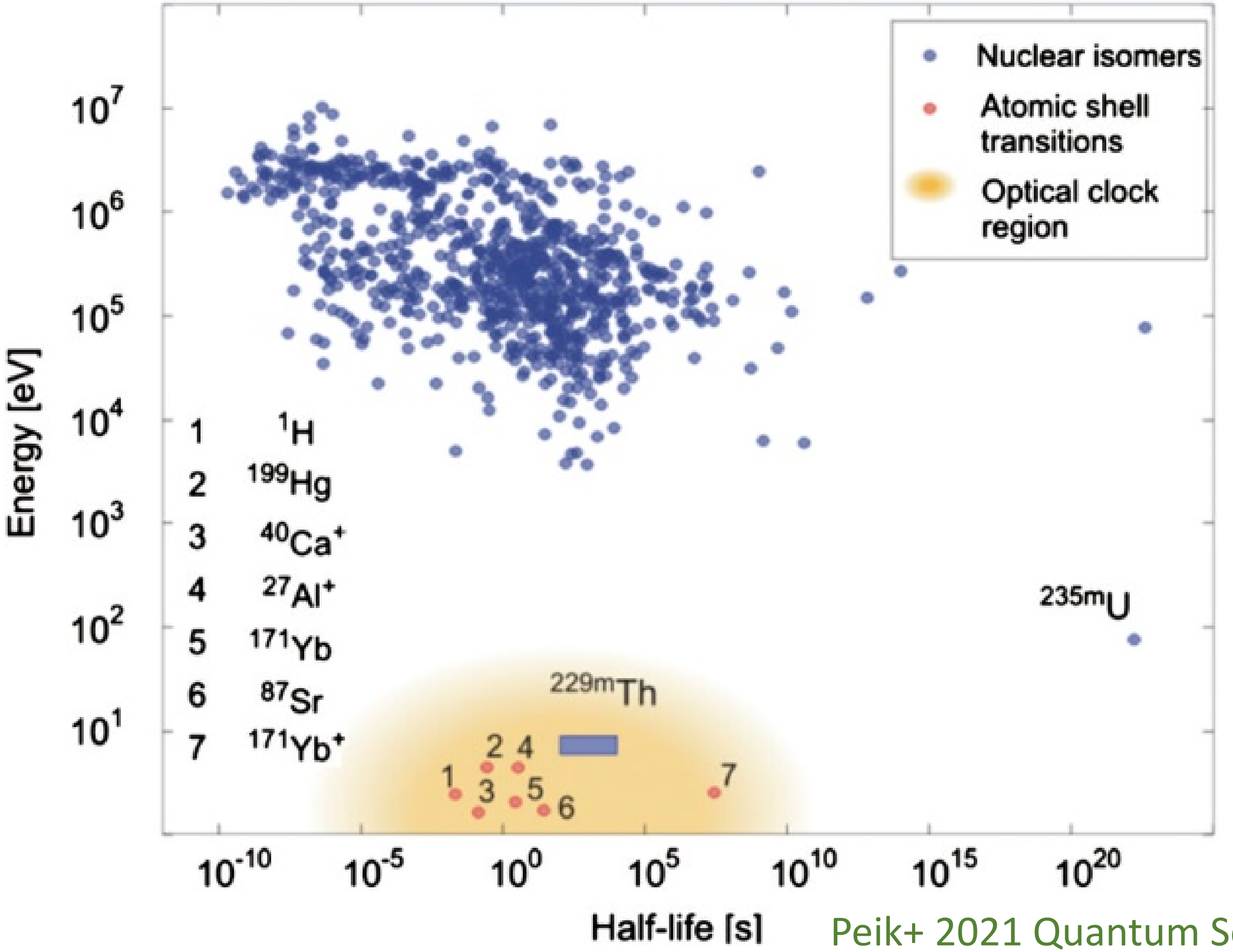


$$\nu_{\mathrm{Th}} = 2\,020\,407\,384\,335(2)\ \mathrm{kHz}$$

$$\delta\nu/\nu \approx 10^{-12}$$

Zhang+ Nature 633, 63-70 (2024)

Thorium 229m is unique (so far)



Peik+ 2021 Quantum Sci. Technol. 6 034002

High BSM sensitivity

Nuclear binding and Coulomb repulsion naively cancel

$$\Delta E = \Delta E_{\rm nuc} + \Delta E_{\rm em}$$

8eV ~ MeV – MeV

Changes in $\Delta E_{\rm nuc,em}$ are amplified in the frenquency

$$\frac{\delta\nu}{\nu} \sim K_g \frac{\delta(\Delta E_{\rm nuc})}{\Delta E_{\rm nuc}} + K_e \frac{\delta(\Delta E_{\rm em})}{\Delta E_{\rm em}}$$

$$K_{g,e} \equiv \Delta E_{\rm nuc,em}/\Delta E \sim \mathcal{O}(10^5)$$

Cancellation

Nuclear modeling of $\Delta E_{\rm em}$

Woods-Saxon distribution $\rho(r,\theta) = \dfrac{\rho_0}{1+\exp\left(\frac{r-R(\theta)}{z}\right)}$

with nonspherical nucleus:

$$R(\theta) = R_0\left[1 + \beta_2 Y_{20}(\theta) + \beta_3 Y_{30}(\theta) + \beta_4 Y_{40}(\theta) + \ldots\right]$$

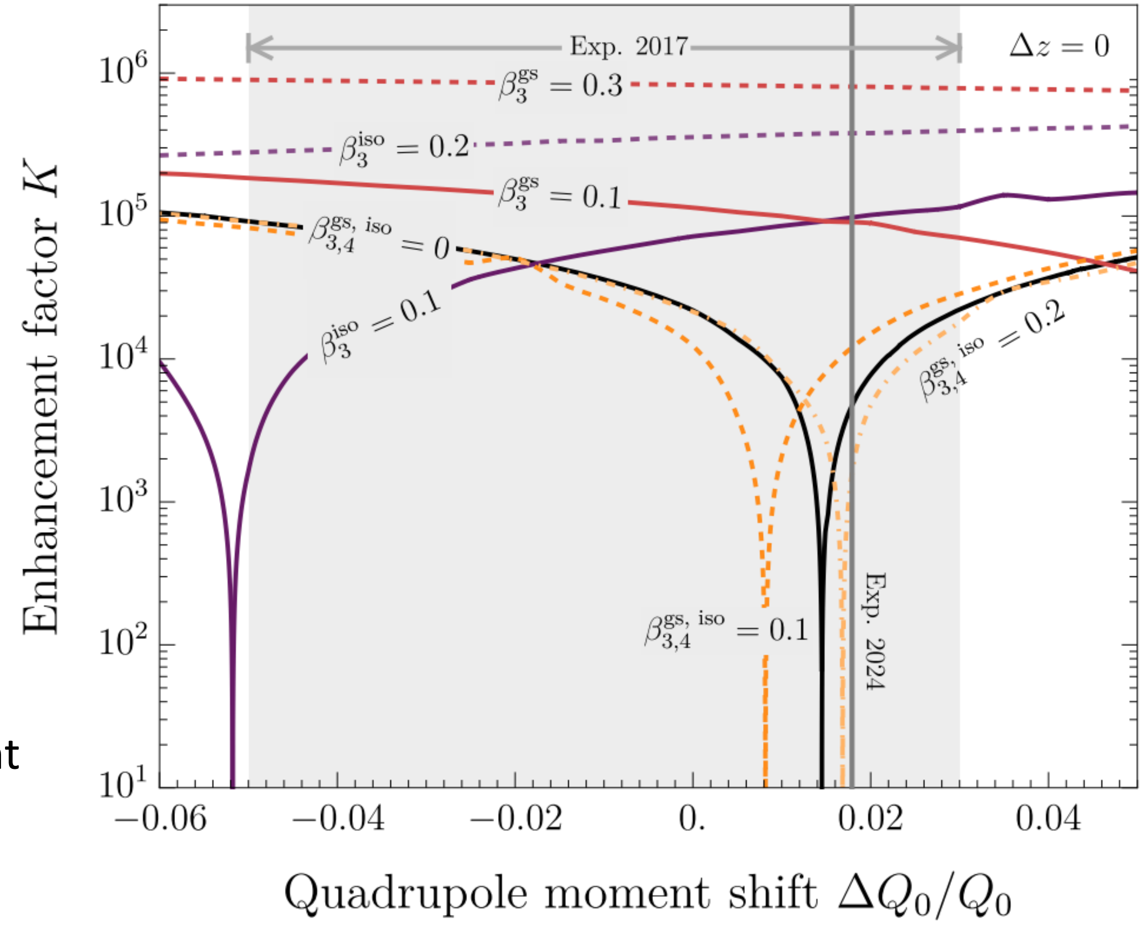
Fix R_0, β_2 with measurements of

$$\langle r^2\rangle \equiv \frac{1}{e\,Z}\int d^3\mathbf{r}\, r^2 \rho(r,\theta)$$ charge radius

$$Q_0 \equiv \int d^3\mathbf{r}\, r^2 \rho(r,\theta)\left[3\cos^2(\theta) - 1\right]$$ quadrupole moment

then vary $\beta_{3,4}$

Caputo+ 2407.17526



Hidden forces

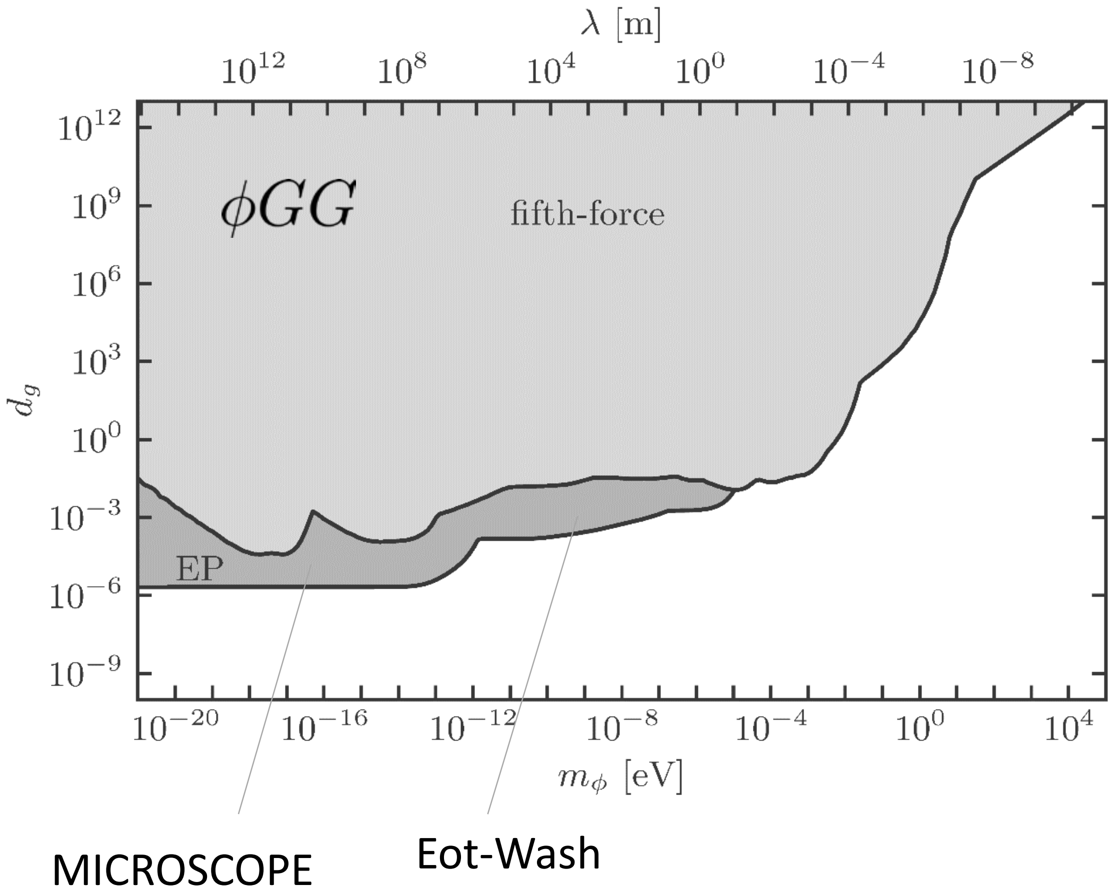
Ultralight scalar interactions

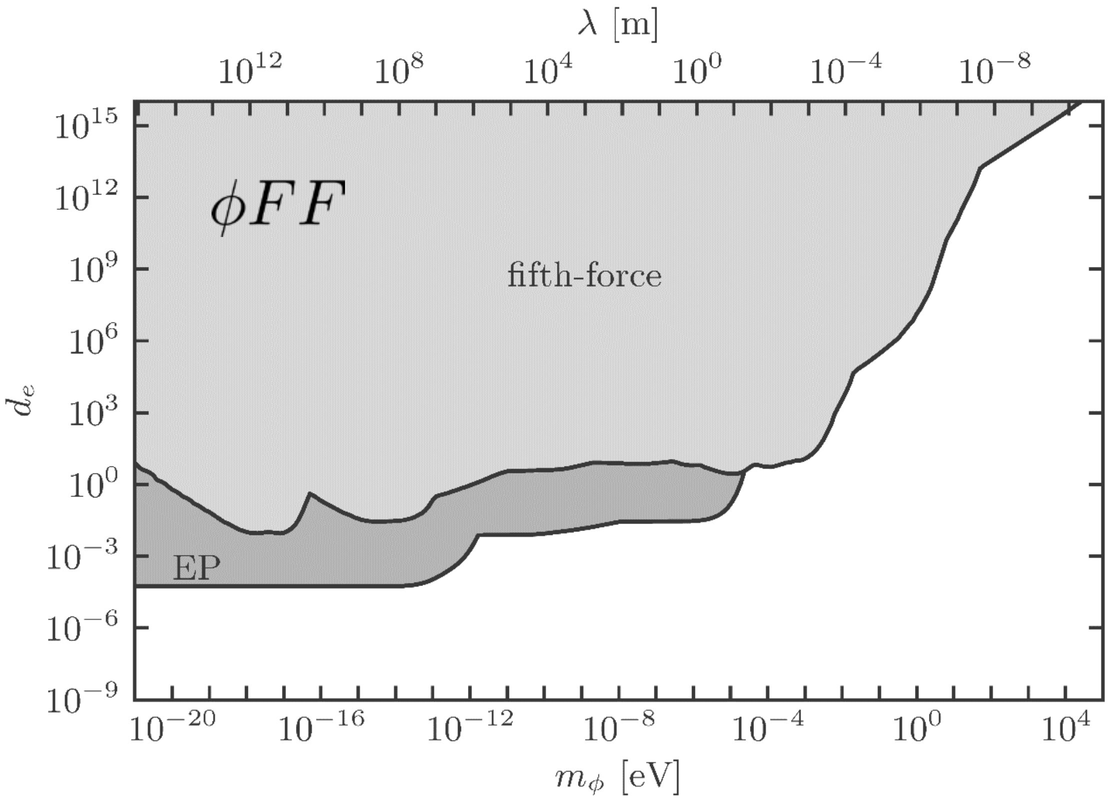
$$\mathscr{L}_{\text{int}} = \left[\frac{d_e}{16\pi\alpha} F_{\mu\nu}F^{\mu\nu} - \frac{d_g \beta(\alpha_s)}{4\alpha_s} G^a_{\mu\nu} G^{a\mu\nu} - d_{m_e} m_e \, \bar{e}e - \sum_{q=u,d,s} \left(d_{m_q} + \gamma_{m_q} d_g\right) m_q \bar{q}q\right] \boxed{\frac{\phi}{M_{\text{Pl}}} \equiv \varphi}$$

normalized such that $\dfrac{\mathrm{d}\log\alpha}{\mathrm{d}\varphi} = d_e \,, \quad \dfrac{\mathrm{d}\log\Lambda_{\text{QCD}}}{\mathrm{d}\varphi} = d_g \,, \quad \dfrac{\mathrm{d}\log m_{e,q}}{\mathrm{d}\varphi} = d_{m_{e,q}}$

Damour-Donoghue '10

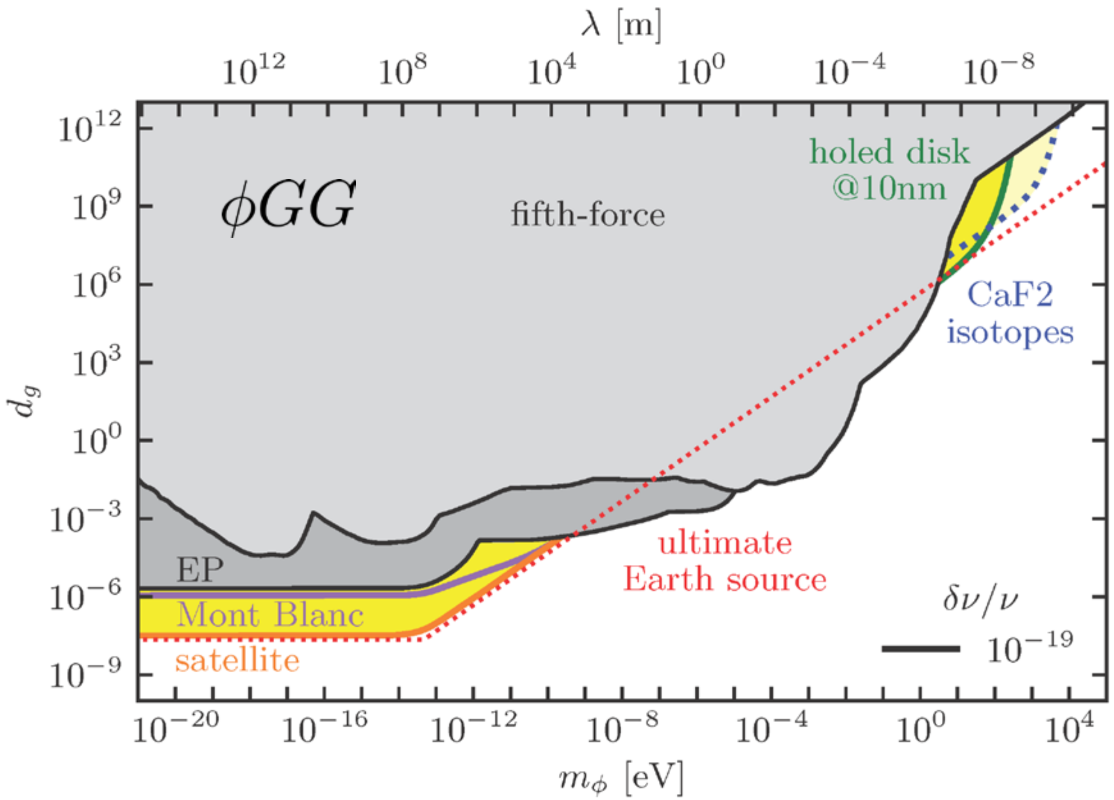
Current constraints

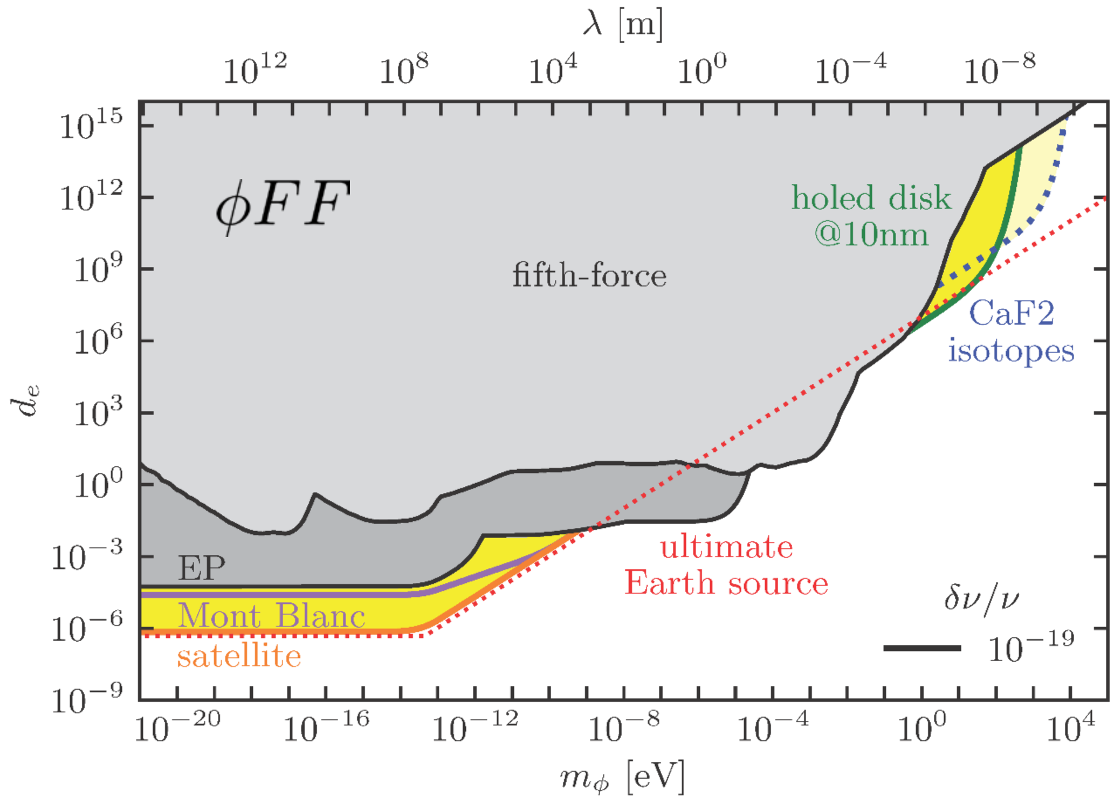




Projected sensitivities

significant improvements expected both at large and small distances assuming $\delta\nu/\nu = 10^{-19}$





Scalar-field solutions near a source

Massive bodies source nonzero scalar fields:

$$Q(\boldsymbol{r}) = (d \log m_A(\boldsymbol{r})/d\alpha, \cdots)$$

dilatonic charges

$$d = (d_e, d_g, \cdots)$$

linear couplings

$$\left(\boldsymbol{\nabla}^2 - m_\phi^2\right) \phi(\boldsymbol{r}) = \frac{Q(\boldsymbol{r}) \cdot d}{M_{\mathrm{Pl}}} \rho(\boldsymbol{r})$$

source density

Around the source: $\phi(\boldsymbol{r}) = \frac{1}{M_{\mathrm{Pl}}} \int \mathrm{d}^3\boldsymbol{r}' \, \phi_G(\boldsymbol{r}, \boldsymbol{r}') \, Q(\boldsymbol{r}') \cdot d \; \rho(\boldsymbol{r}')$

Green's function

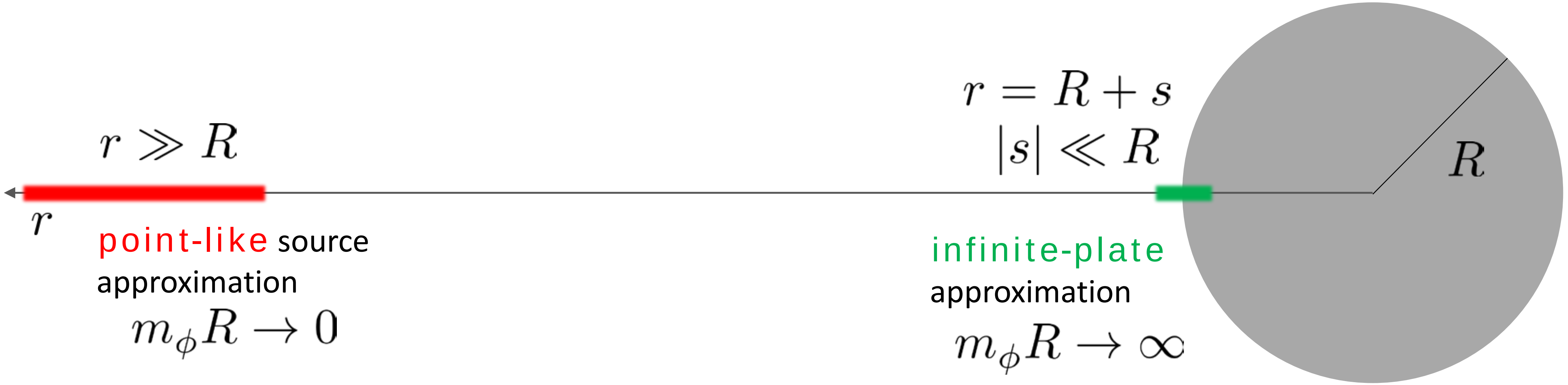
$$\phi_G(\boldsymbol{r}, \boldsymbol{r}') = -\frac{e^{-m_\phi |\boldsymbol{r}-\boldsymbol{r}'|}}{4\pi |\boldsymbol{r}-\boldsymbol{r}'|}$$

Spherical Homogeneous Sources

2 regimes = long and short distance

from the source

$$M = \frac{4\pi}{3}\rho R^3$$



point-like source approximation

$m_\phi R \to 0$

infinite-plate approximation

$m_\phi R \to \infty$

$$\phi_{\text{point}}(r) \approx -Q \cdot d \frac{M}{M_{\text{Pl}}} \frac{e^{-m_\phi r}}{4\pi r}$$

$$\phi_{\text{plate}}(R+s) \approx -Q \cdot d \, \frac{\rho}{2 M_{\text{Pl}} m_\phi^2} \begin{cases} e^{-m_\phi s} & , \; s > 0 \\ 2 - e^{-m_\phi |s|} & , \; s < 0 \end{cases}$$

Quintessometers

Th229 clock will provide best probes for hidden forces of various ranges

Basic scheme

Move a nuclear clock close to a source in a controlled way

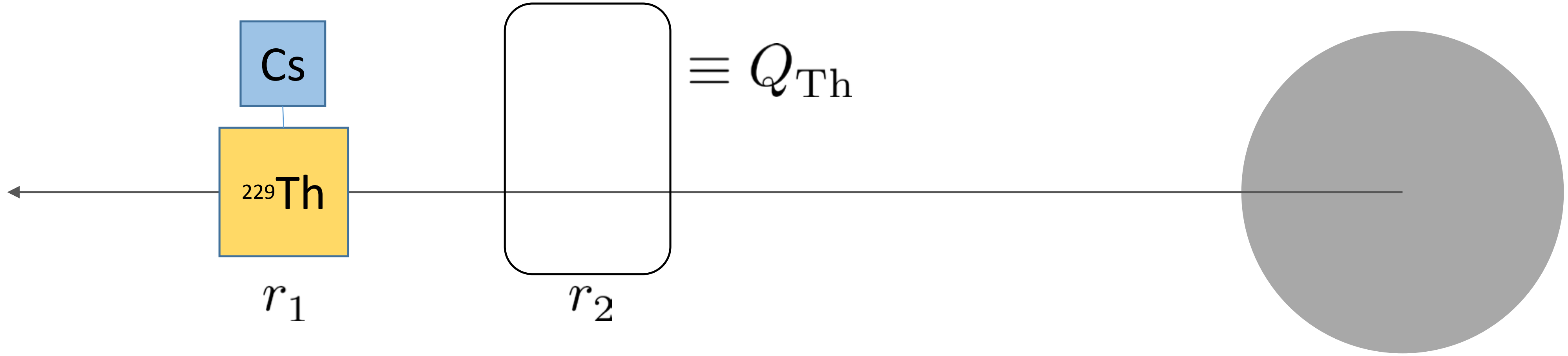
The clock frequency will change due to interaction with the ambient field that varies with distance $\delta\phi = \phi(r_2) - \phi(r_1) \neq 0$

$$\frac{\delta\nu_{\mathrm{Th}}}{\nu_{\mathrm{Th}}} = K_{\mathrm{Th}} \cdot d \, \frac{\delta\phi}{M_{\mathrm{Pl}}}$$ + effect from gravity-field gradient (time dilation)

$K_{\mathrm{Th}} = (K^{e}_{\mathrm{Th}}, K^{g}_{\mathrm{Th}}, \cdots)$ nuclear clock sensitivity coefficients

Quintessometer

nuclear/electronic clock comparison



universal gravitational effects cancel out

the clocks still respond differently to $\delta\phi$

$$\frac{\delta(\nu_{\rm Th}/\nu_{\rm el})}{\nu_{\rm Th}/\nu_{\rm el}} = (K_{\rm Th} - K_{\rm el}) \cdot d\ \frac{\delta\phi}{M_{\rm Pl}}$$

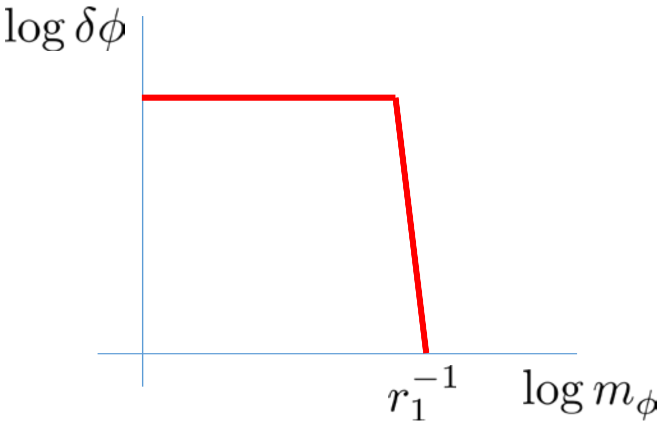
no loss in sensitivity: $K_{\rm Th} \gg K_{\rm el}$

$\delta\phi$ scalings

- Point-source $m_\phi R \to 0$

  taking $r_2 \to \infty$

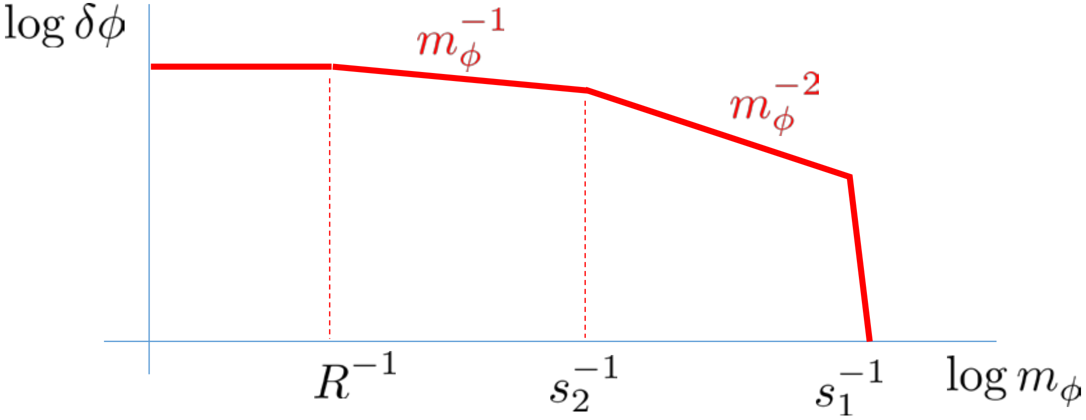
$$\delta\phi_{\text{point}} \propto \frac{e^{-m_\phi r_1}}{r_1}$$



- Infinite-plate $|s_{1,2}| = |r_{1,2} - R| \ll R$

  for $m_\phi R \to \infty$

$$\delta\phi_{\text{plate}} \propto m_\phi^{-2} \left(e^{-m_\phi s_1} - e^{-m_\phi s_2}\right)$$



Large distance probes

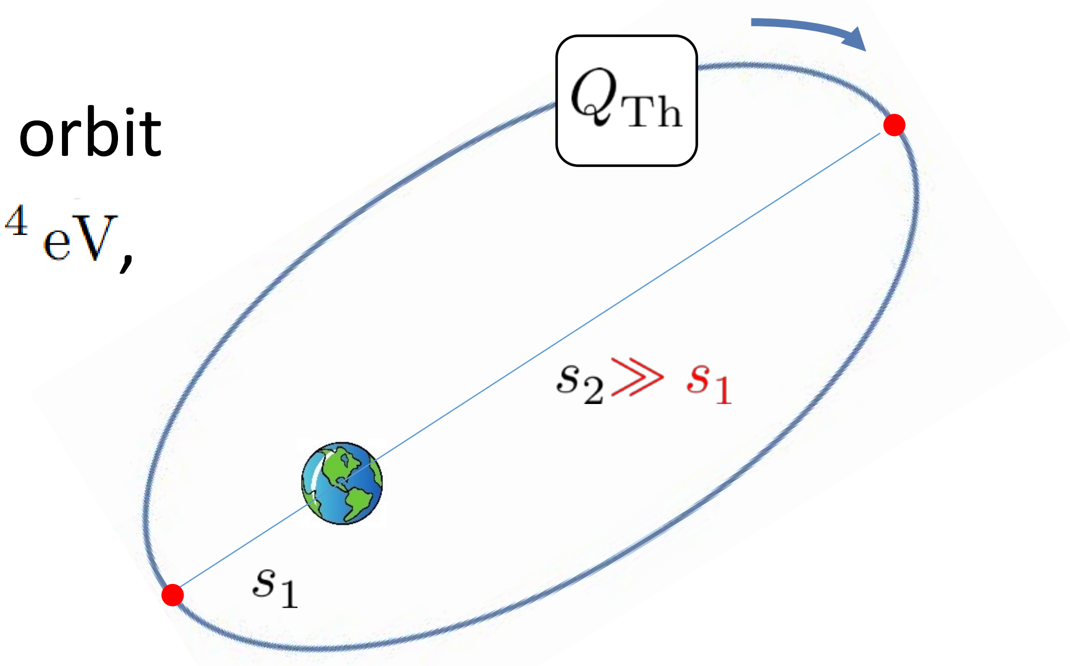
using Earth as a source

Clock in space

Monitor a quintessometer along an elliptic orbit

For long-range forces $m_\phi \lesssim R_\oplus^{-1} \approx 3 \times 10^{-14}\,\mathrm{eV}$,

and high altitude $s_1 \gtrsim R_\oplus$:



$$\delta\phi_{\rm point} \propto \frac{e^{-m_\phi r_1}}{r_1} \simeq \frac{e^{-m_\phi s_1}}{s_1}$$

exponentially suppressed for $m_\phi s_1 > 1$

yielding a sensitivity to ϕGG of

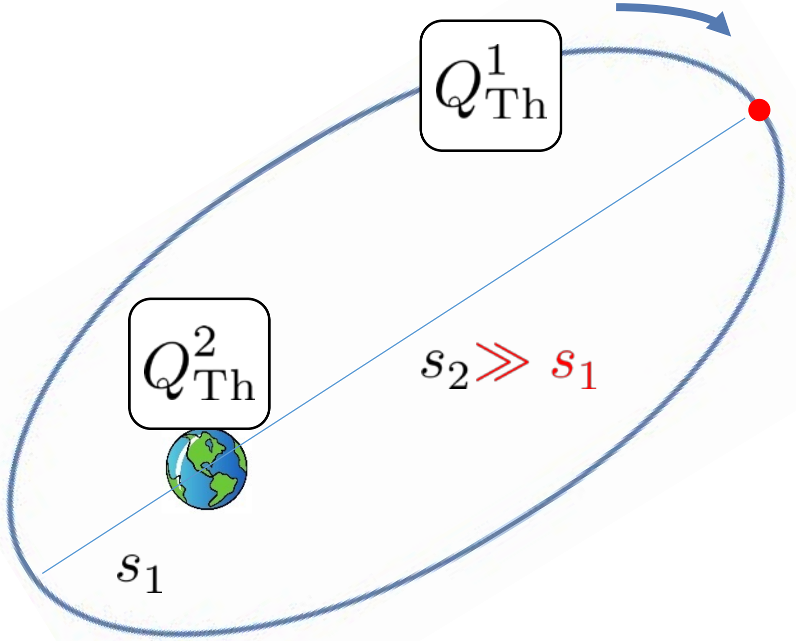
$$|d_g| \approx 3\times10^{-8} \left[\frac{5.5\ \mathrm{g/cm^3}}{\rho_\oplus}\right]^{1/2} \left[\frac{K_g}{10^5}\right]^{-1/2} \left[\frac{\delta\nu/\nu}{10^{-19}}\right]^{1/2} \times \sqrt{s_1/R_\oplus}$$

only rely on clock stability (not accuracy), as the clock is compared to itself

Clocks in space vs on the ground

Compare quintessometers on the ground and at far distance in space

$Q^1_{\rm Th}$ at s_2 isn't affected, but $Q^2_{\rm Th}$ is!



For $m_\phi \lesssim R_\oplus^{-1} \approx 3 \times 10^{-14}\,{\rm eV}$:

$$\delta\phi_{\rm point} \propto \frac{e^{-m_\phi R_\oplus}}{R_\oplus}$$

and

$$|d_g| \approx 3{\times}10^{-8} \left[\frac{5.5\ {\rm g/cm^3}}{\rho_\oplus}\right]^{1/2} \left[\frac{K_g}{10^5}\right]^{-1/2} \left[\frac{\delta\nu/\nu}{10^{-19}}\right]^{1/2}$$

← ultimate sensitivity with Earth as a source

Clocks in space vs on the ground

Compare quintessometers on the ground and at far distance in space

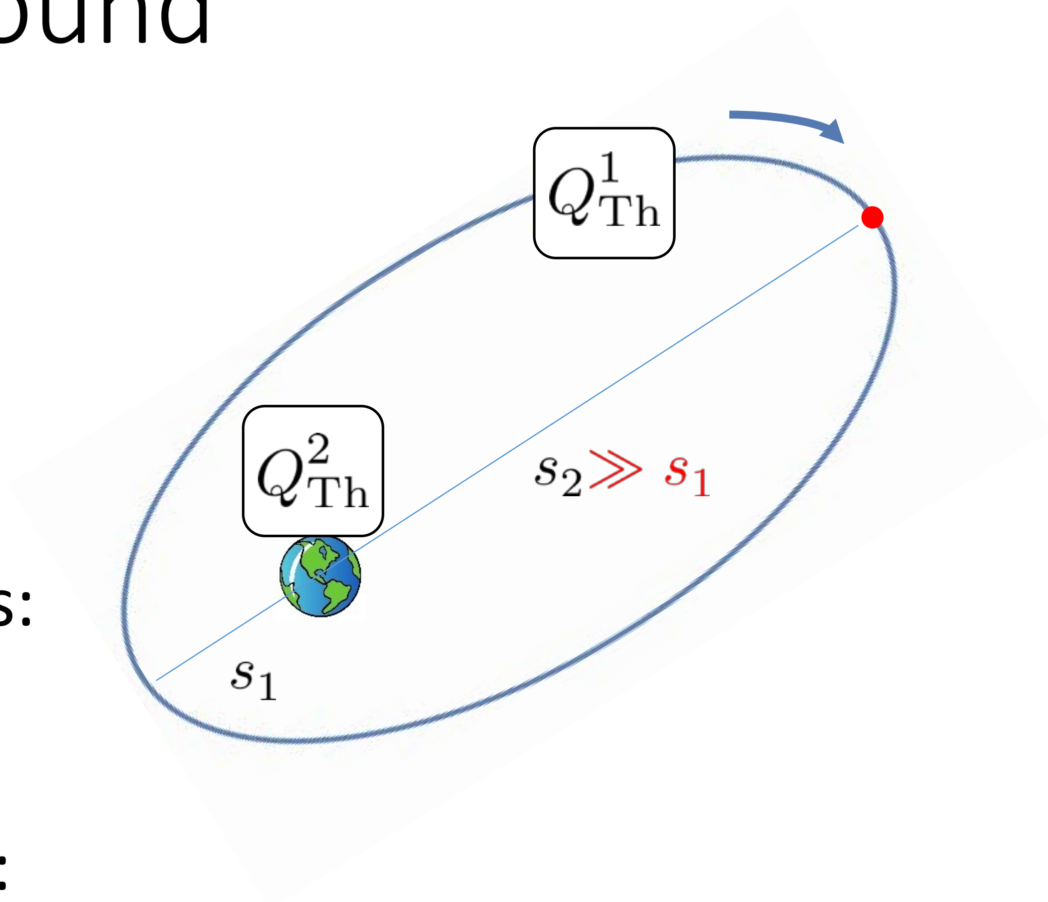
$Q^1_{\rm Th}$ at s_2 isn't affected, but $Q^2_{\rm Th}$ is!

For $m_\phi R_\oplus > 1$ the infinite-plate limit applies:

$$\delta\phi_{\rm plate} \propto m_\phi^{-2}$$

yielding only *linearly* suppressed sensitivity:

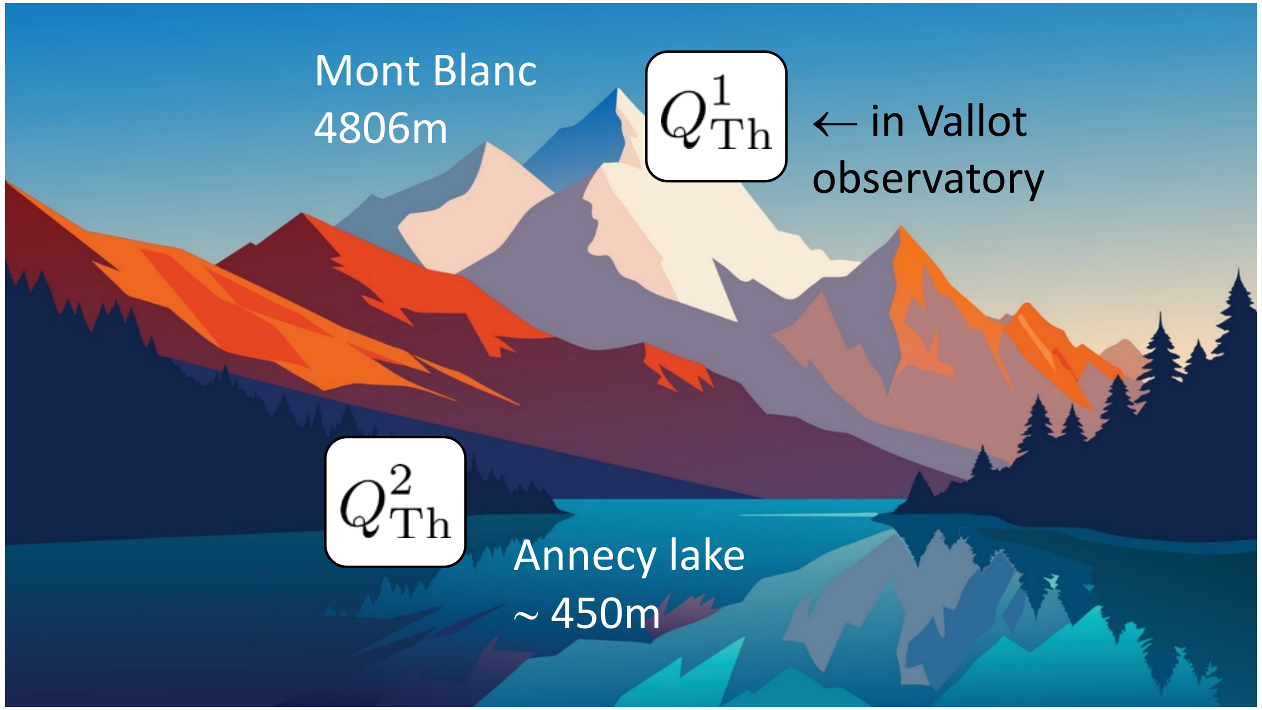
$$|d_g| \approx 3\times 10^{-8} \left[\frac{5.5\ {\rm g/cm^3}}{\rho_\oplus}\right]^{1/2} \left[\frac{K_g}{10^5}\right]^{-1/2} \left[\frac{\delta\nu/\nu}{10^{-19}}\right]^{1/2} \times m_\phi R_\oplus$$



Clocks on the ground

Compare quintessometers at different altitude points

eg. sea-level vs. high mountain



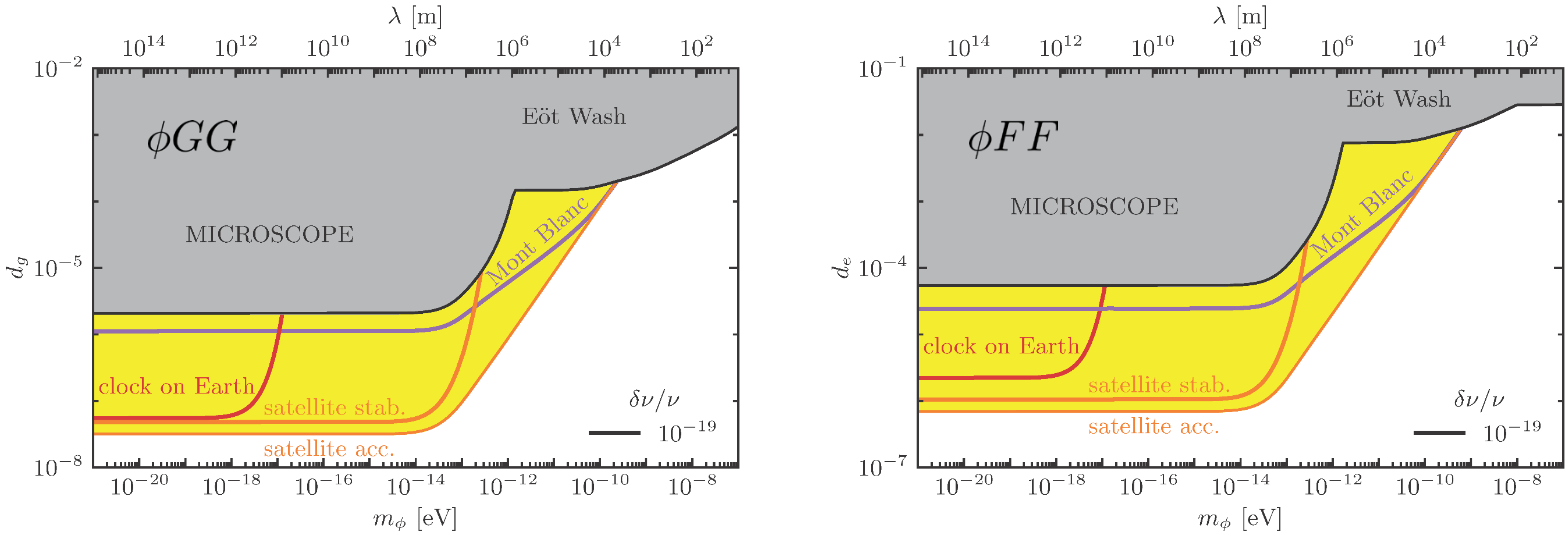
For $m_\phi \lesssim R_\oplus^{-1} \approx 3 \times 10^{-14}\,\mathrm{eV}$:

$$|d_g| \approx 2 \times 10^{-6} \left[\frac{1\,\mathrm{km}}{h}\right]^{1/2} \left[\frac{5.5\,\mathrm{g/cm^3}}{\rho_\oplus}\right]^{1/2} \left[\frac{\delta\nu/\nu}{10^{-19}}\right]^{1/2}$$

$\times\sqrt{m_\phi R_\oplus}$ for $R_\oplus^{-1} < m_\phi < h^{-1}$

$\times\sqrt{R_\oplus/h}\,(m_\phi h)$ for $m_\phi > h^{-1}$

Large distance sensitivities



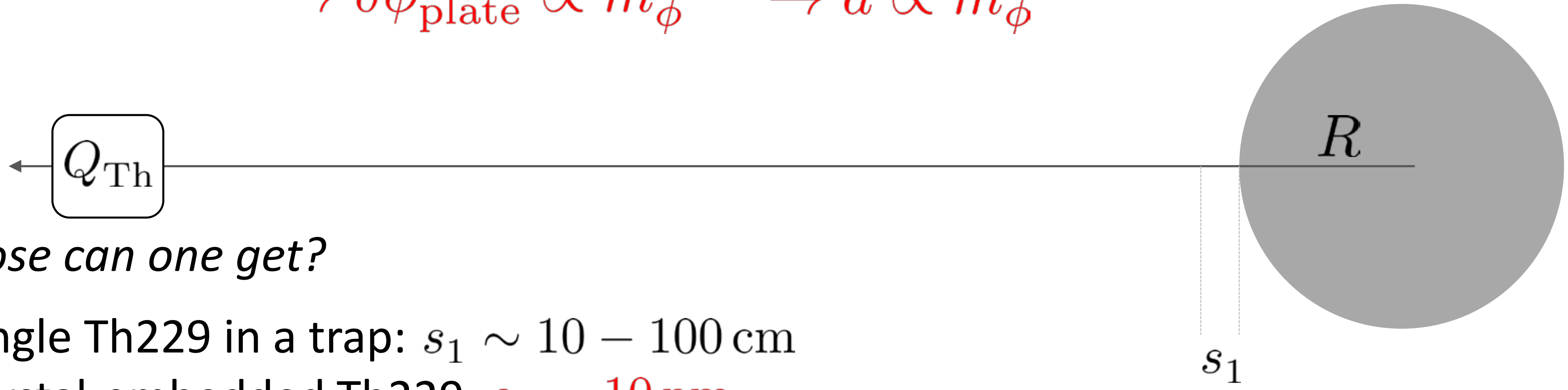
- Quintessometers could probe 2 orders of magnitude below EP tests
- Reaching uncharted territories already with ground-based experiments

Small distance probes

Getting close to Th229

Bring large source ($m_\phi R \gg 1$) very close ($s_1 \ll R$) to Th229 from infinity ($s_2 \to \infty$)

$$\to \delta\phi_{\mathrm{plate}} \propto m_\phi^{-2} \quad \to d \propto m_\phi$$



How close can one get?

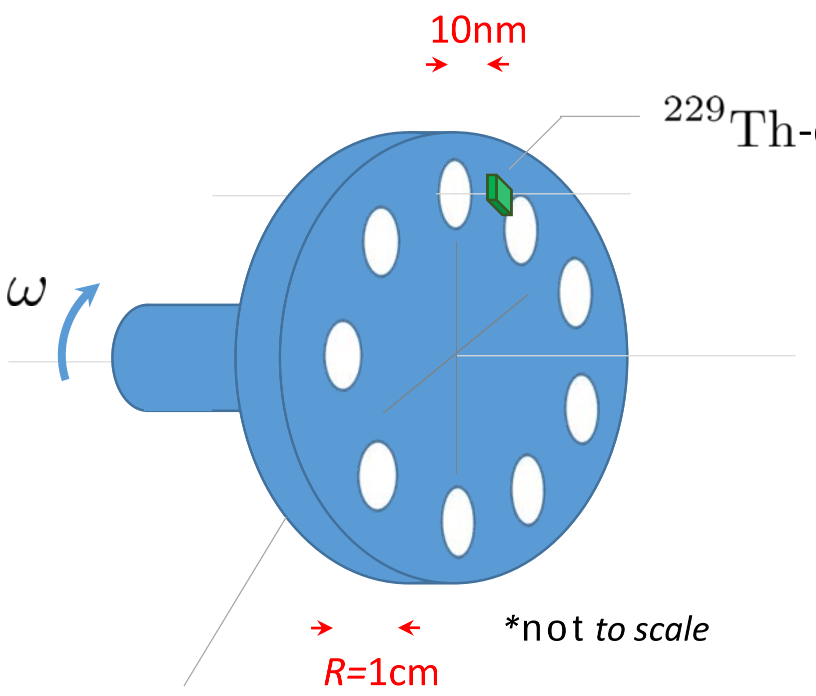
- single Th229 in a trap: $s_1 \sim 10 - 100\,\mathrm{cm}$
- crystal-embedded Th229: $s_1 \sim 10\,\mathrm{nm}$

$$|d_g| \approx 10^7 \left[\frac{m_\phi}{20\,\mathrm{eV}}\right] \left[\frac{\rho_{\mathrm{Pt}}}{\rho}\right]^{1/2} \left[\frac{\delta\nu/\nu}{10^{-19}}\right]^{1/2}$$

for $R^{-1} \ll m_\phi < (10\,\mathrm{nm})^{-1} \approx 20\,\mathrm{eV}$

Rotating Holed disk

Move the source, not the clock!

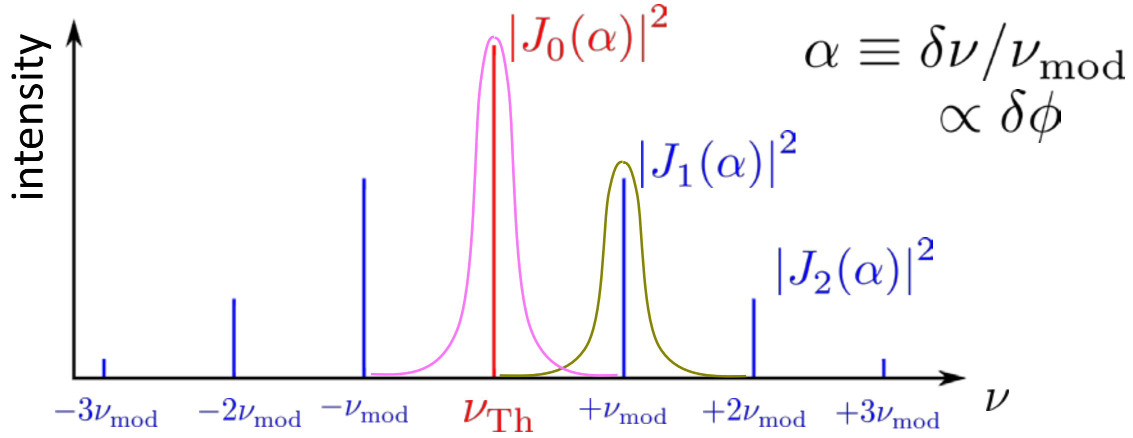


platinum thick disk
gold-coated to suppress Casimir effects

$\delta\phi \neq 0$ induces signal modulation at frequency $\nu_{\rm mod} = N\omega/2\pi$

$\gg \Gamma_{\rm Th} \sim 200\,{\rm Hz}$

Th229 spectrum develops sidebands



Excite ^{229}Th crystal with detuned VUV laser $\nu_{\rm laser} = \nu_{\rm Th} + \nu_{\rm mod}$ and compare to on-resonance excitation $\nu_{\rm laser} = \nu_{\rm Th}$

Host Isotope Shifts?

Compare Th229 host-crystals of different isotopes

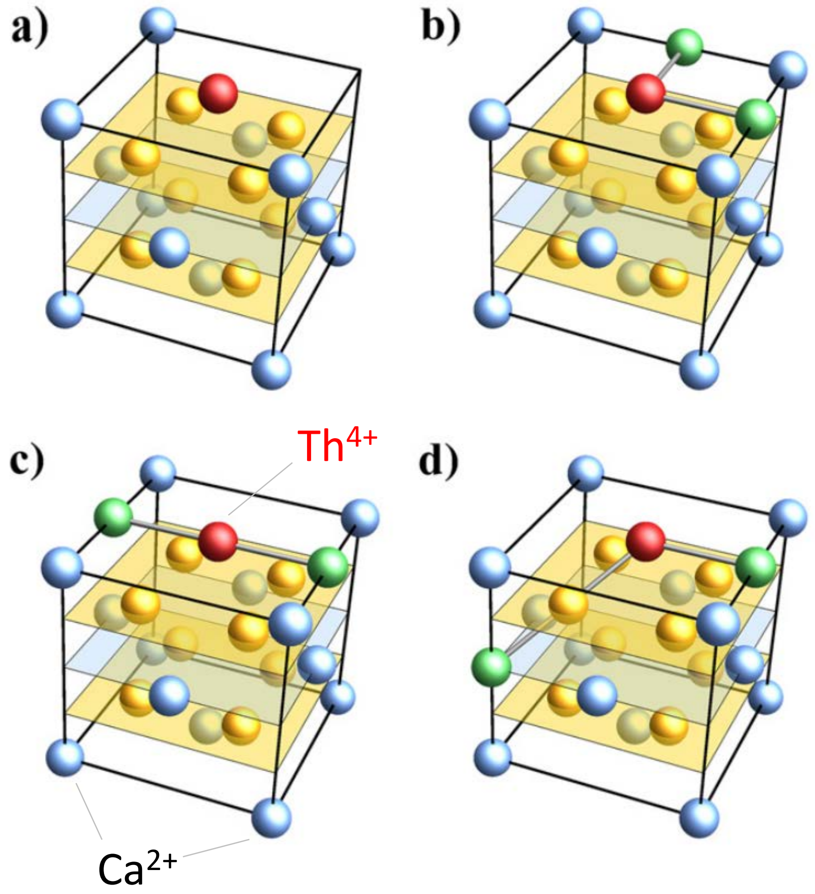
The field is sourced by surrounding atoms in the host at lattice spacing

$$s \gtrsim 0.1 - 1\,\mathrm{nm}$$

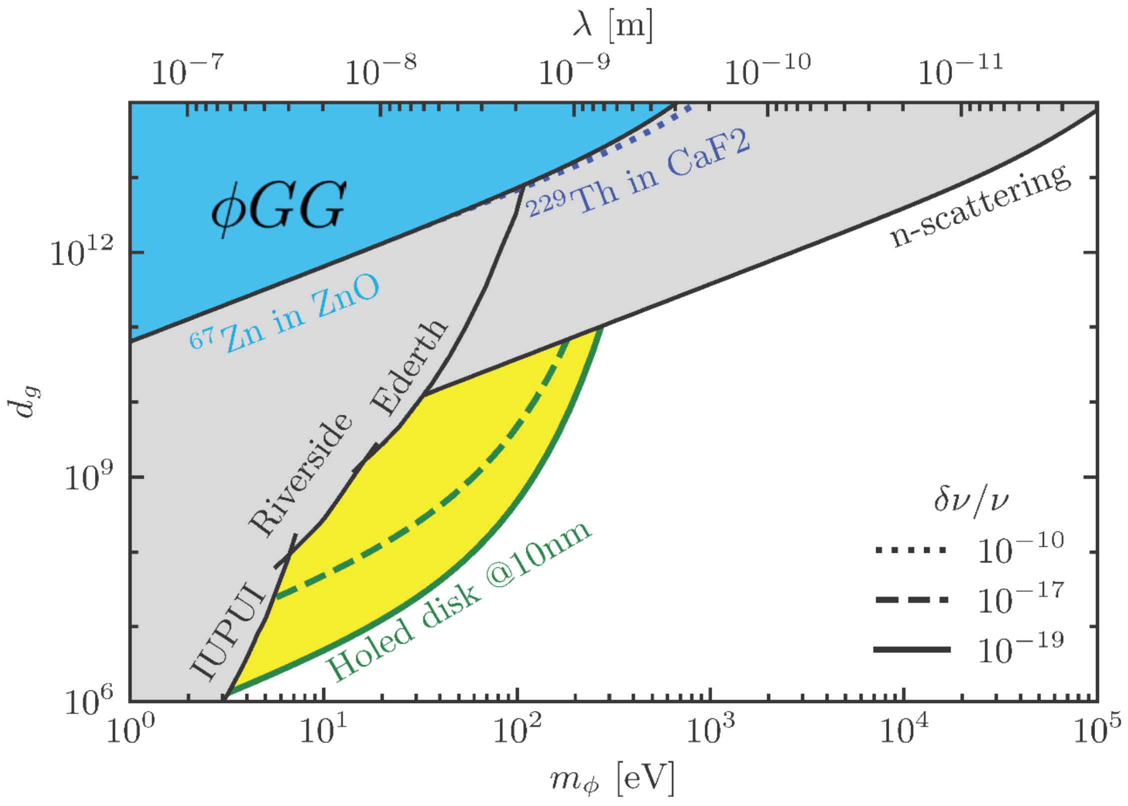
eg. CaF_2 hosts with magic nuclei

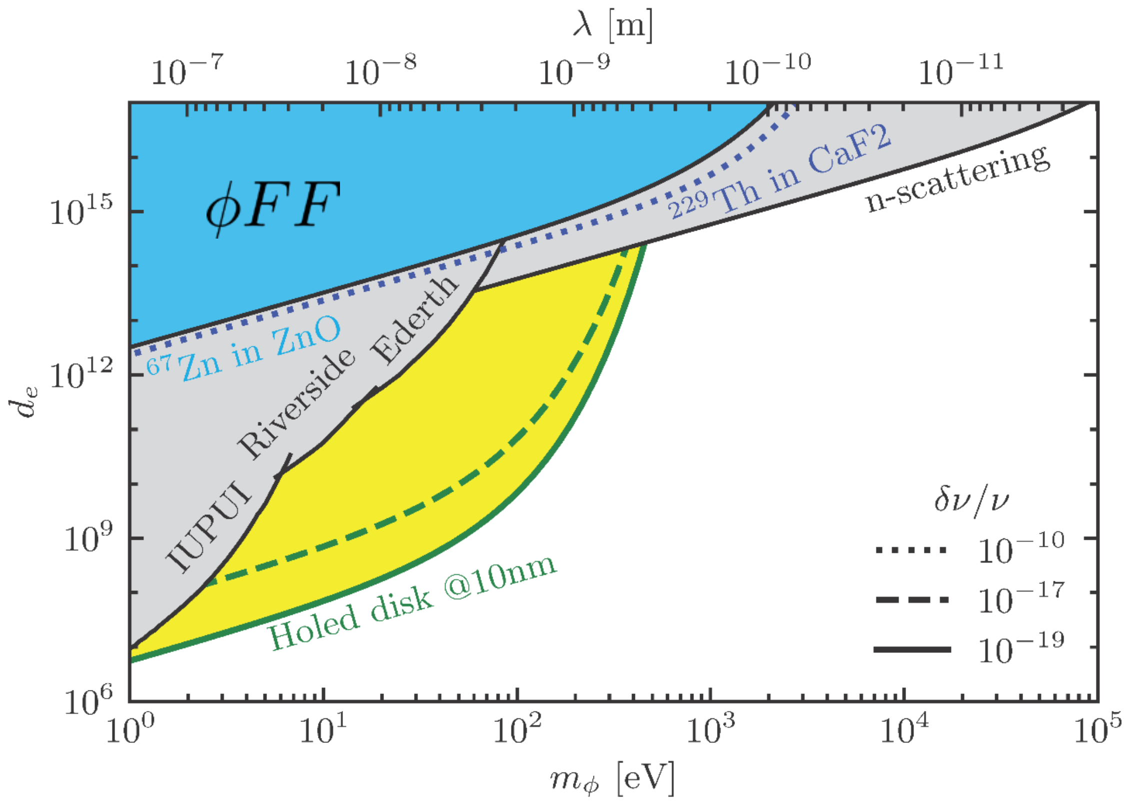
^{40}Ca and ^{48}Ca ($\delta\langle r^2\rangle \approx 0$)

But cell volume changes, EM fields felt by Th229 also, shifting the frequency



Short distance sensitivities





- $Q_{\rm Th}$ + rotating disk could probe 2 orders of mag. below 5th force searches at $m_\phi \sim 10\,\mathrm{eV}$

Conclusions

Conclusions

- Th229 nuclear clock is a fantastic BSM probes
- Huge progress in 2024 ($\delta\nu/\nu \approx 10^{-12}$) from VUV laser excitations

- Once available at $\delta\nu/\nu \sim 10^{-19}$ accuracy (state-of-the art in electronic counterparts), possibilities to build *quintessometers* probing (static) exotic forces with unprecedented precision

  for $m_\phi < 10^{-10}\,\mathrm{eV}$ and $3\,\mathrm{eV} < m_\phi < 300\,\mathrm{eV}$!