

Searching for (imperfect) axions around spherical objects with precision

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High Precision Experiments for Light Dark Matter



Outline & rational

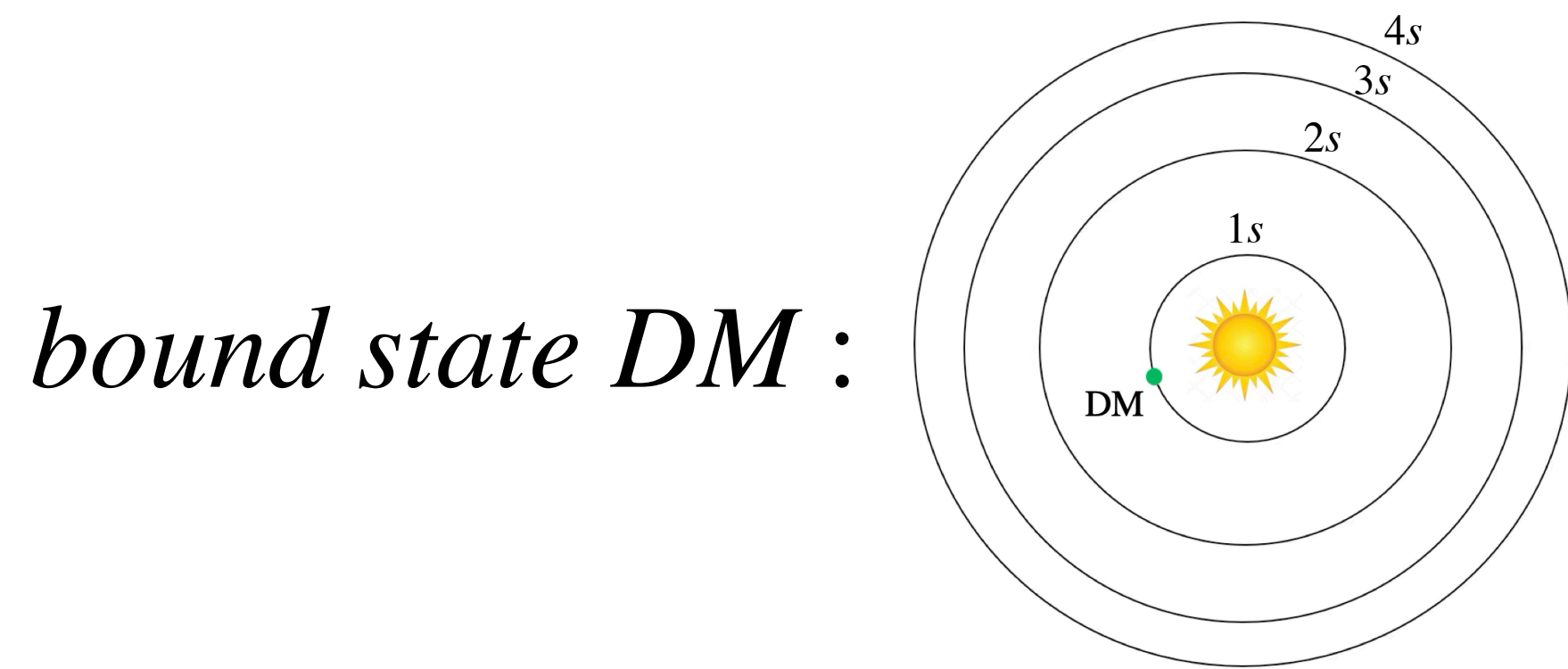
- We know that the DM mass is dominating the galactic dynamics, but, at shorter scales, say AU we know very little
- At these scales DM is subdominant, gravity is dominated by stars & BHs:
We study how (i) this lead to axion capturing around stars; then (ii) study implications for searches - recoherence; (iii) apply for Schwarzschild BHs
- New results related to imperfect axions in cosmology & nuclear clocks

Solving the DM EOM around point sources

- Consider ultralight DM (UDM): it behaves as wave, satisfying (around point

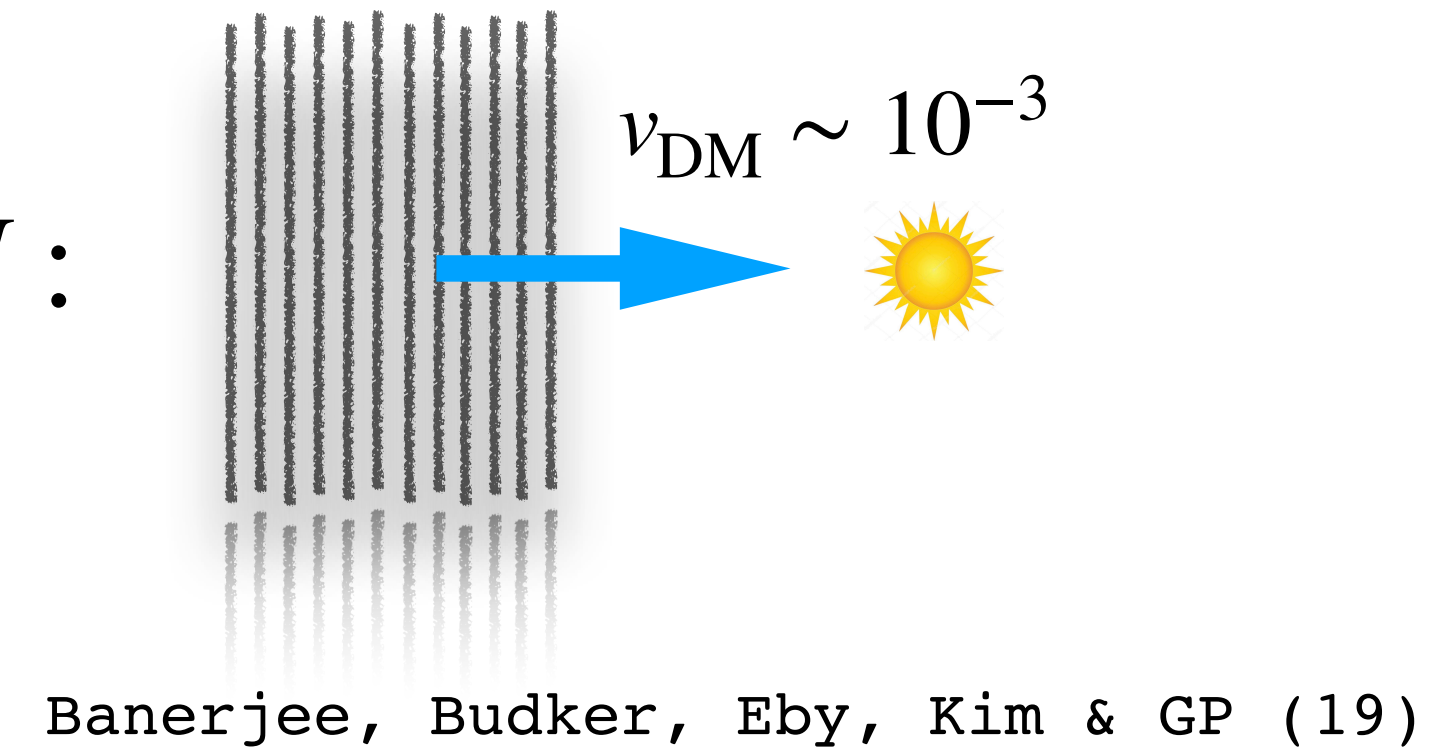
sources): $i\hbar \partial_t \psi = \left[-\frac{\hbar^2}{2m} \nabla^2 + \frac{\alpha}{r} \right] \psi$, (using NR-UDM, $\phi(x, t) = \frac{e^{-imt}}{\sqrt{2m}} \psi(x, t)$ & $\alpha \equiv \frac{GmM}{r}$)

- The eigen modes of this “gravitational-hydrogen” problem are given by:



$$r_{\text{Bohr}}^{-1} \sim m\alpha \sim Gm^2 M_{\text{sun}}$$

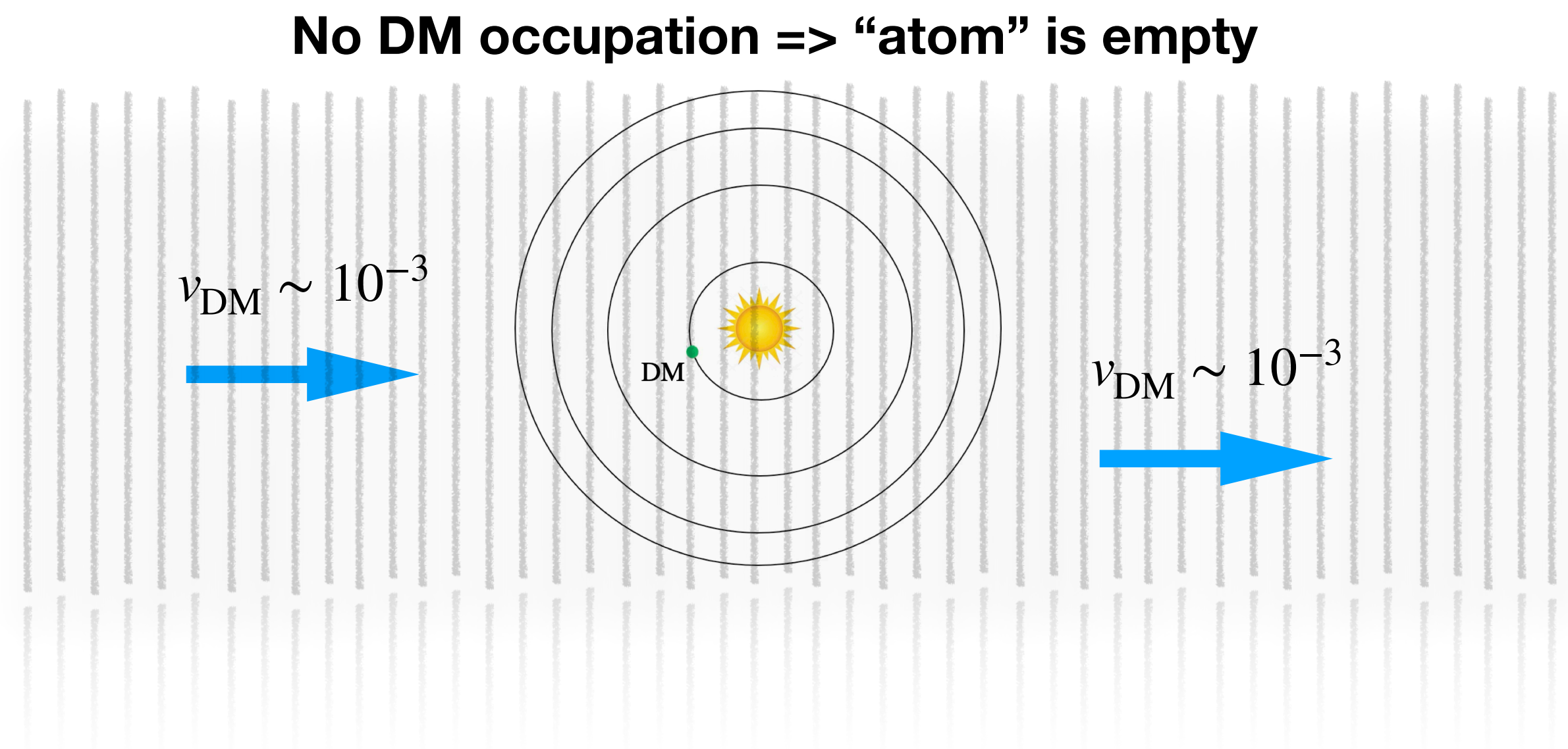
continuous (galactic) wave DM :



Banerjee, Budker, Eby, Kim & GP (19)

Non interaction $\Rightarrow$ no capturing of UDM

- As the galactic DM velocity is much larger than the escape velocity from the sun $v_{\text{DM}} \sim 10^{-3} \gg v_{\text{escape}} \sim 10^{-4}$ we expect the gravitational atom levels to be empty



- Furthermore, in the absence of interactions, no energy loss is possible, which is required for capturing

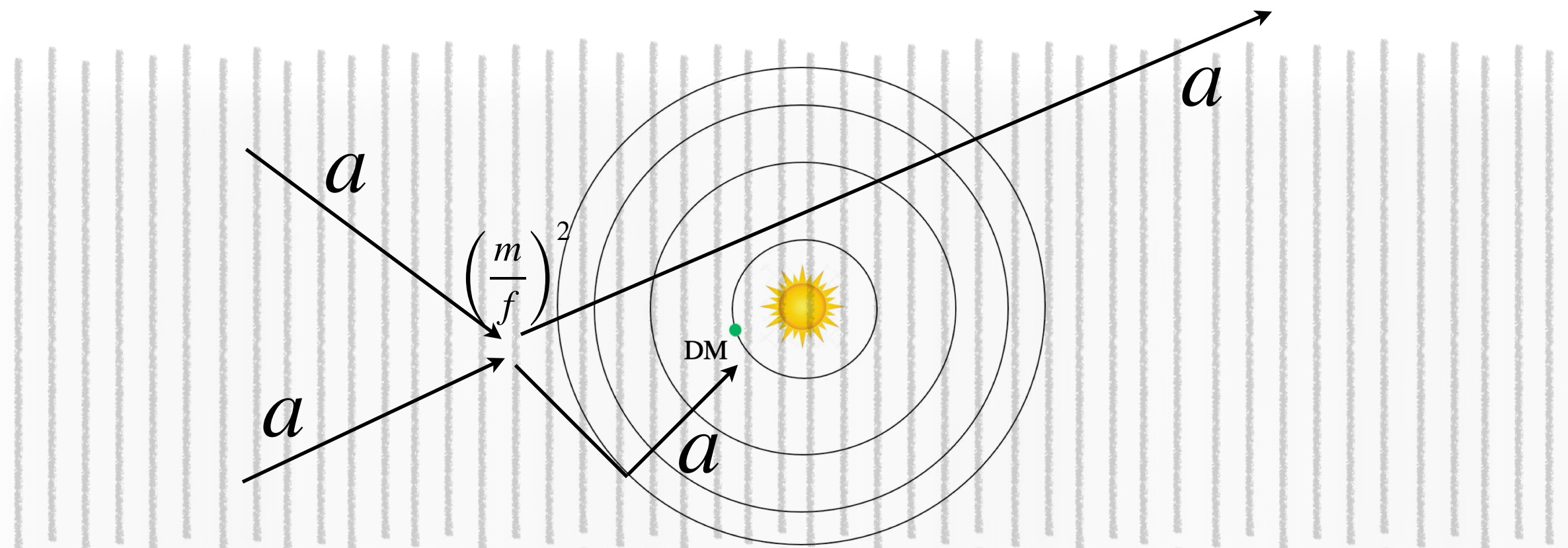
Capturing mechanism via quartic axionic interaction

- If UDM is axion (motivated to make it light) then it is expected to have

quartic interactions $\mathcal{L} \in \frac{1}{2}(\partial a)^2 - \frac{1}{2}m^2 a^2 + \left(\frac{m}{f}\right)^2 a^4$

Budker, Eby, Gorghetto, Minyuan & GP (23)

- Quartic interactions may lead to energy loss => capturing:



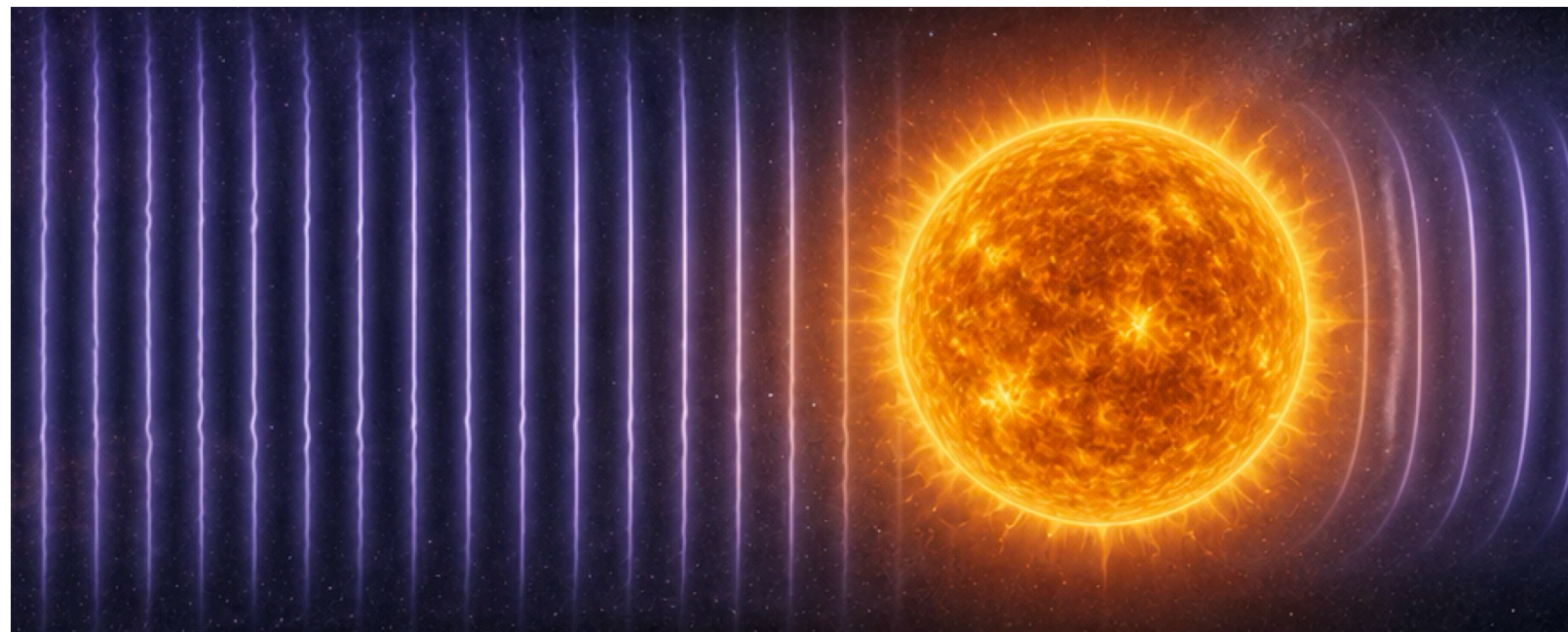
- However generically int' $\left(\frac{m}{10^{-14}\text{eV}} \frac{10^7\text{GeV}}{f} \sim 10^{-30} \right)$ is too weak leading to no effect

Capturing in the focusing regime

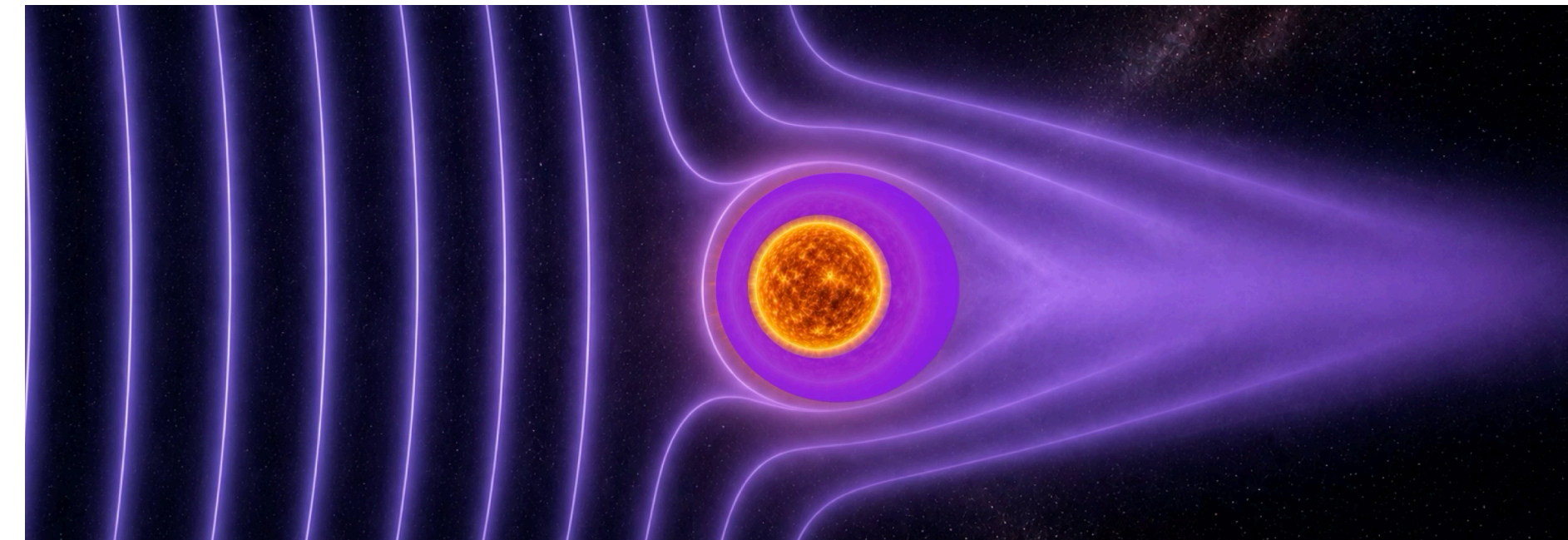
- If the de Broglie wavelength of the incoming wave $\sim$ Bohr radius there's focusing and the matrix element is enhanced :

Budker, Eby, Gorghetto, Minyuan & GP (23)

no focusing $\lambda_{\text{DB}} \ll r_B$



focusing $\lambda_{\text{DB}} \sim r_B$

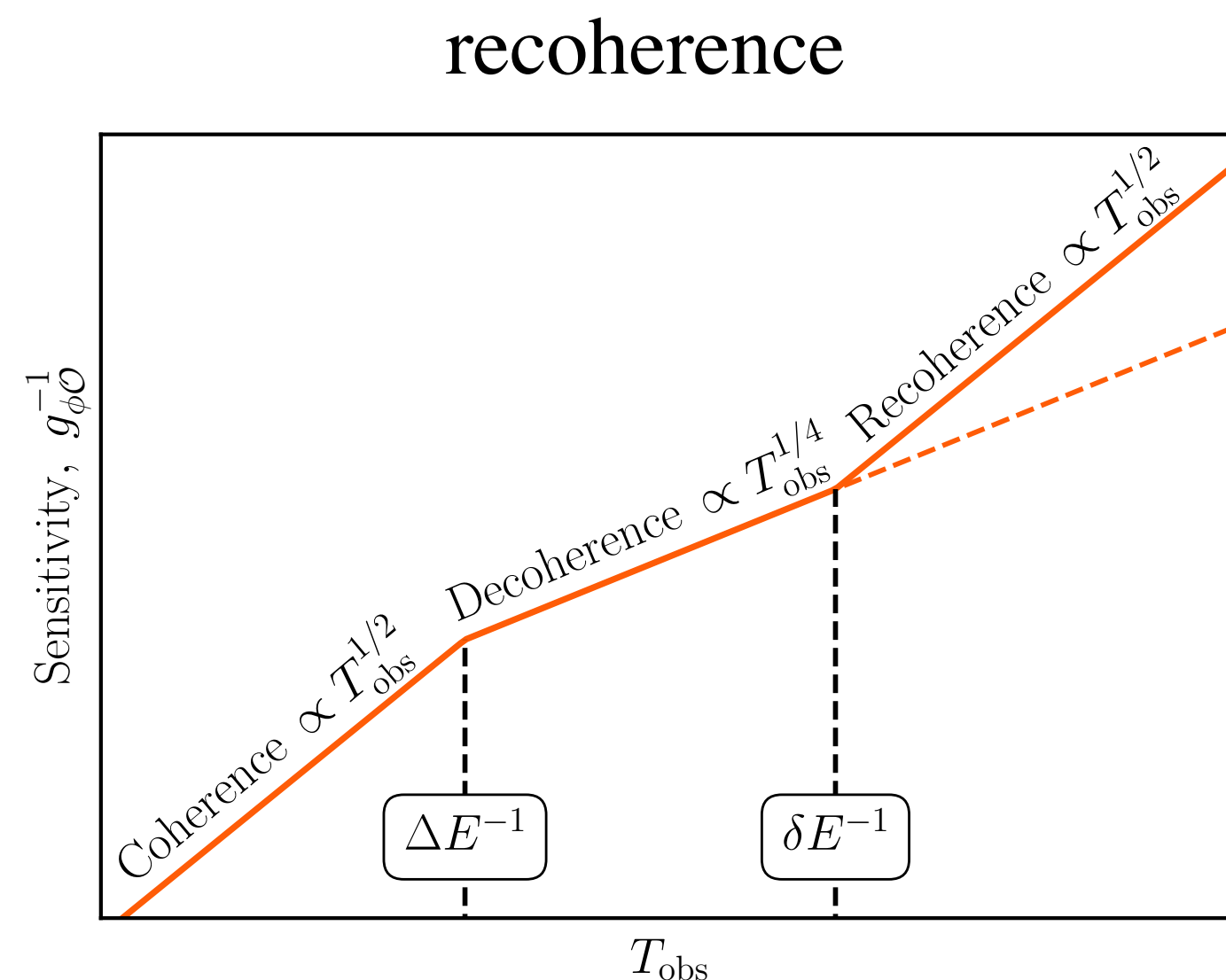


$$\xi \equiv \frac{\lambda_{\text{DB}}}{r_B} \approx \frac{\alpha}{v} \sim \frac{M_*}{M_{\text{sun}}} \frac{m}{10^{-14} \text{ eV}} \frac{v}{10^{-3}} \Rightarrow r_B \sim \text{AU}$$

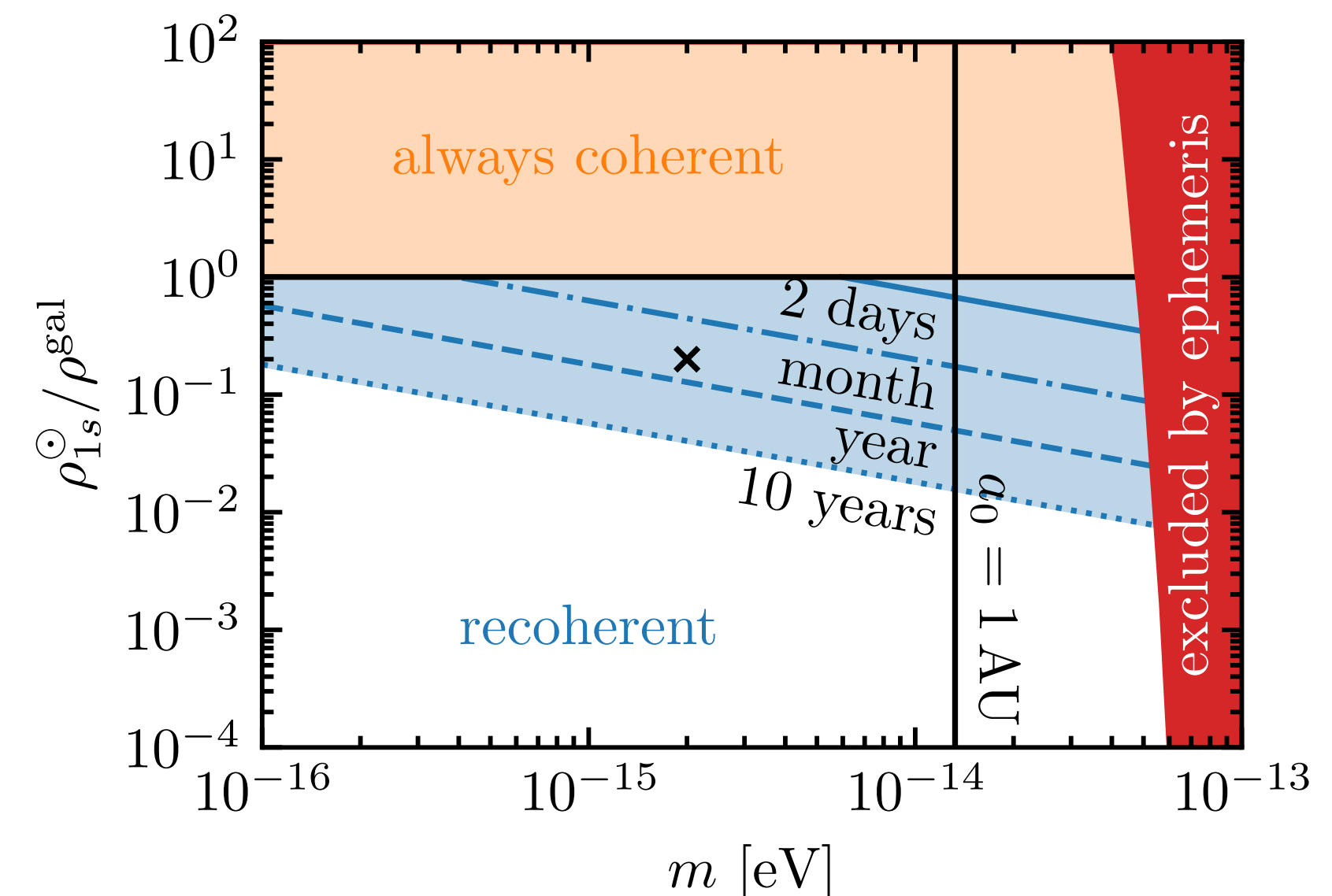
- Solar axion capturing time: $\tau_{\text{rel}} \equiv \frac{64m^7 v_{\text{dm}}^2}{\lambda^2 \rho_{\text{dm}}^2} \simeq 9 \text{ Gyr} \left[\frac{f_a}{10^8 \text{ GeV}} \right]^4 \left[\frac{m}{10^{-14} \text{ eV}} \right]^3 \left[\frac{0.4 \text{ GeV/cm}^3}{\rho_{\text{dm}}} \right]^2 \left[\frac{v_{\text{dm}}}{240 \text{ km/s}} \right]^2$

Briefly, several important implications

- The DM density around us can be enhanced by up to 10^5
- Naive coherent time enhanced by at least $\left(\frac{v_{\text{gal}}}{v_{\text{esc}}}\right)^2 \sim 10^2$, needs rethinking Banerjee, Budker, Eby, Kim & GP (19)
- Standard $\tau_{\text{coh}} \approx 1/m\sigma^2$ ignores DM discrete bounded component Paranjape, GP, Ratzinger & Sankaranarayanan (26)
- Once $T_{\text{obs}} \gtrsim 1/\delta E$, τ_{coh} grows linearly again — recoherence



1s halo - shaded region dominated by captured DM

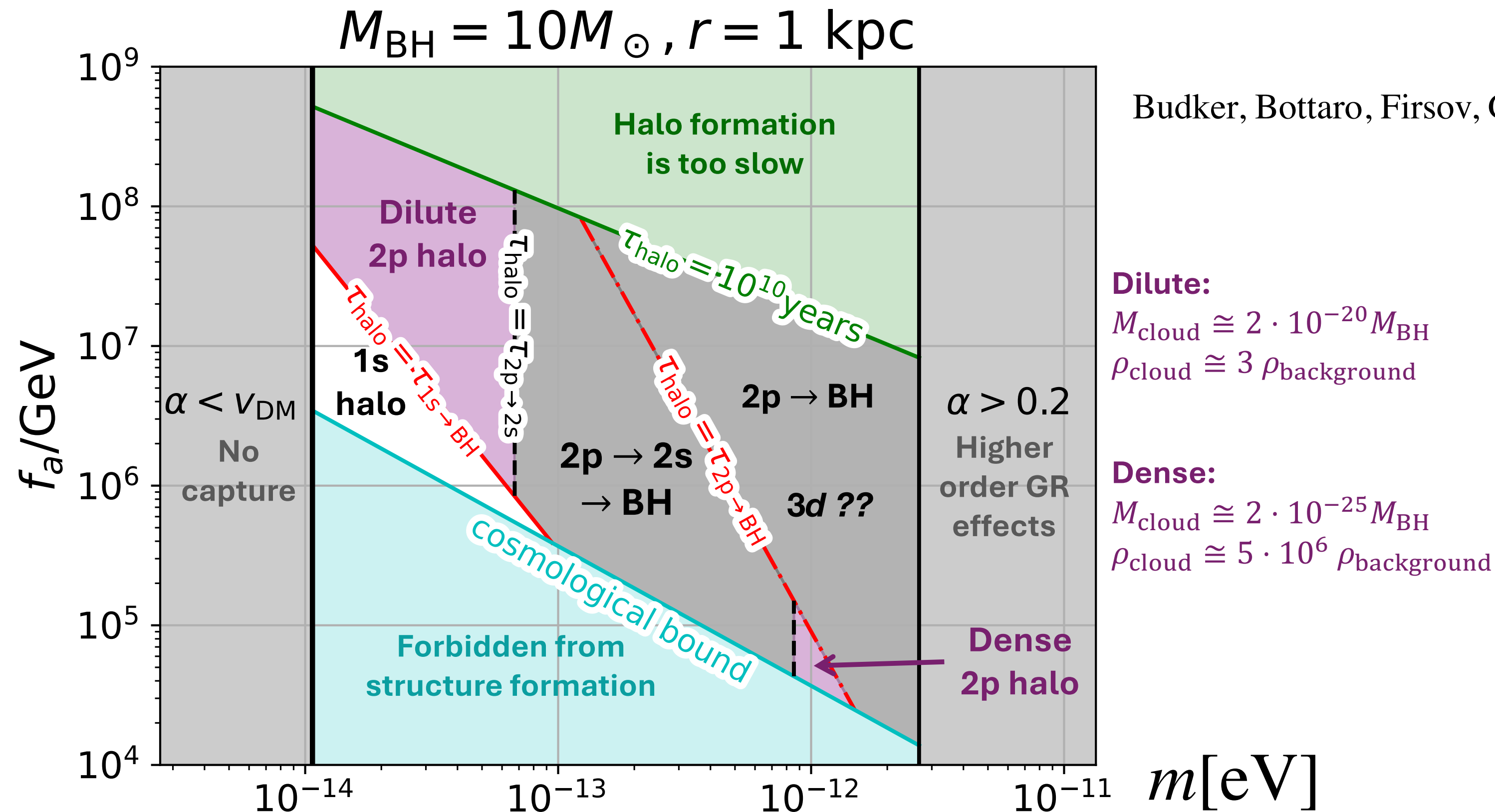


Schwarzschild (SC) black hole (BH) DM capturing

- Capturing applies to SC BH, however, with several modifications, as states are not stable (quasi-bound states), $\Gamma \propto m\alpha^{5+4l}$; for solar mass BH:

$$\tau_{n0} \sim 10^{10} \text{ yr } n^3 \left(\frac{\alpha}{10^{-4}} \right)^{-5} \left(\frac{m}{10^{-14} \text{ eV}} \right)^{-1}, \quad \tau_{n1} \sim 10^{27} \text{ yr } n^3 \left(\frac{\alpha}{10^{-4}} \right)^{-9} \left(\frac{m}{10^{-14} \text{ eV}} \right)^{-1}$$

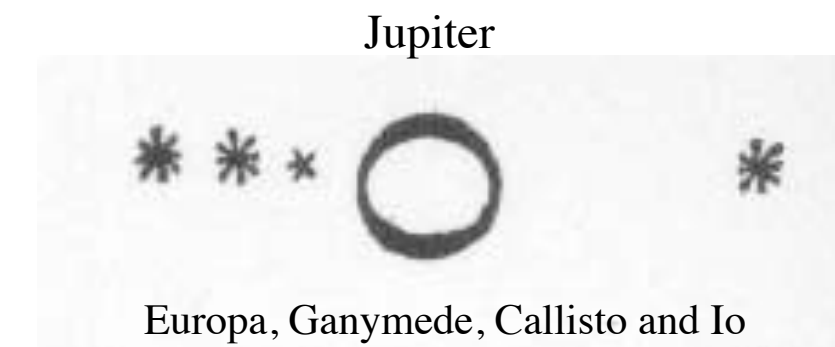
Baumann, Chia, Stout & Haar (19)



Budker, Bottaro, Firsov, GP, Steuer, Telem, in prep'

The era of thorium (nuclear clock) supremacy

Why is nuclear clock so special



Th-229 progression of precision in isomeric-line's $\delta f/f$:

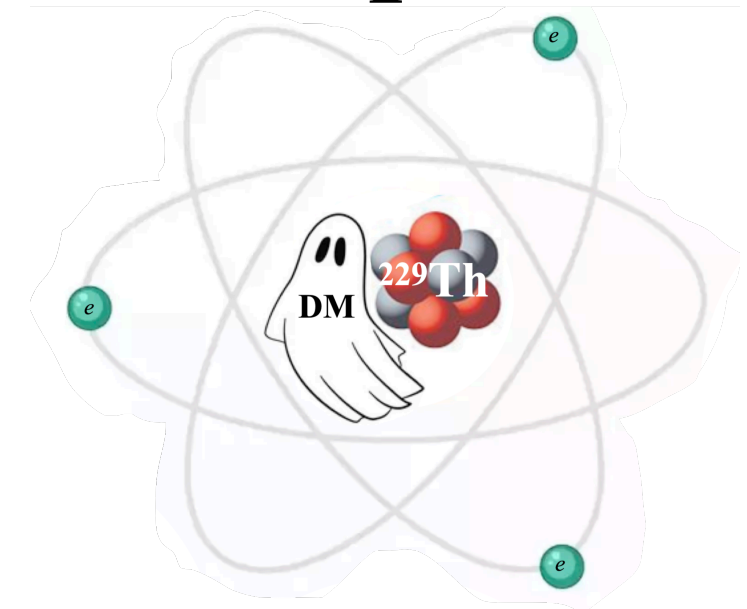
1:10 (2020) $\Rightarrow$ 1:10³ (2022) $\Rightarrow$ 1:10⁶ (Mar/Apr/24) $\Rightarrow$ 1:10¹¹ (Jun/24) $\Rightarrow$ 1:10¹³ (26) $\Rightarrow$ 1:10¹⁴ (26)

Furthermore, as we see next, there's a 10⁸⁻¹⁰ enhanced sensitivity factor to dark matter (DM) & beyond physics $\Rightarrow$ a new era

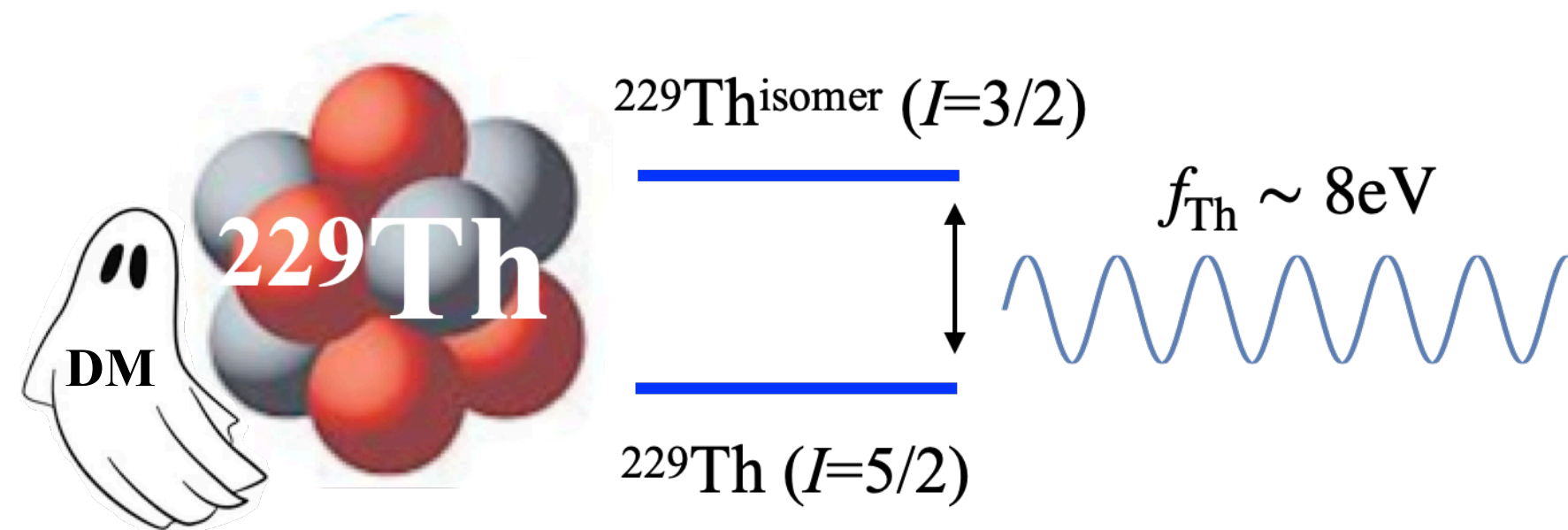
More in Konstantin's talk

what makes nuclear clock so special ?

Motivated ultralight DM (UDM) dominantly couples to nuclear sector => exp. challenge:
sensitivity of atomic probes is suppressed by $R_{\text{nuc}}^{\text{atom}} \sim 10^{3-5}$



- Th-229 => dual-benefit:



(i) directly probe nuclear part (avoiding $R_{\text{nuc}}^{\text{atom}}$);

(ii) boost factor - $f_{\text{Th}} = \Delta E_{\text{nuc}} - \Delta E_{\text{EM}} \sim 8 \text{ eV} \ll \Delta E_{\text{nuc,EM}} \Rightarrow K_{\text{canc}} \sim \frac{\Delta E_{\text{nuc,EM}}}{f_{\text{Th}}} \sim 10^5 \gg 1$

Enhancement of $R_{\text{nuc}}^{\text{atom}} \times K_{\text{canc}} \sim 10^{8-10}$ relative to current probes of DM!

Present and near future implications

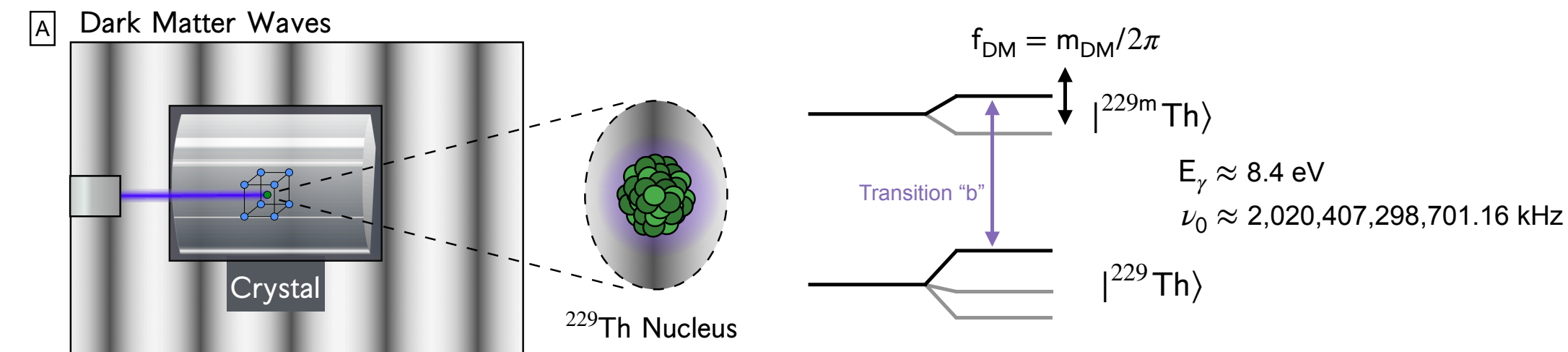
See Konstantin's talk

- 2026: $\frac{\delta f}{f} \sim 10^{-14}$, this should be translated to effective sensitivity:
$$\frac{\delta f}{f} / (R_{\text{atom}}^{\text{nuc}} \times K_{\text{canc}}) \sim 10^{-22..-24}$$
 of atomic clocks, going beyond the frontier!
- It leads to the following questions:
 - (i) Can we search for DM via Th-229 now (before nuclear clocks construction)?
 - (ii) Quantify K_{canc} ?

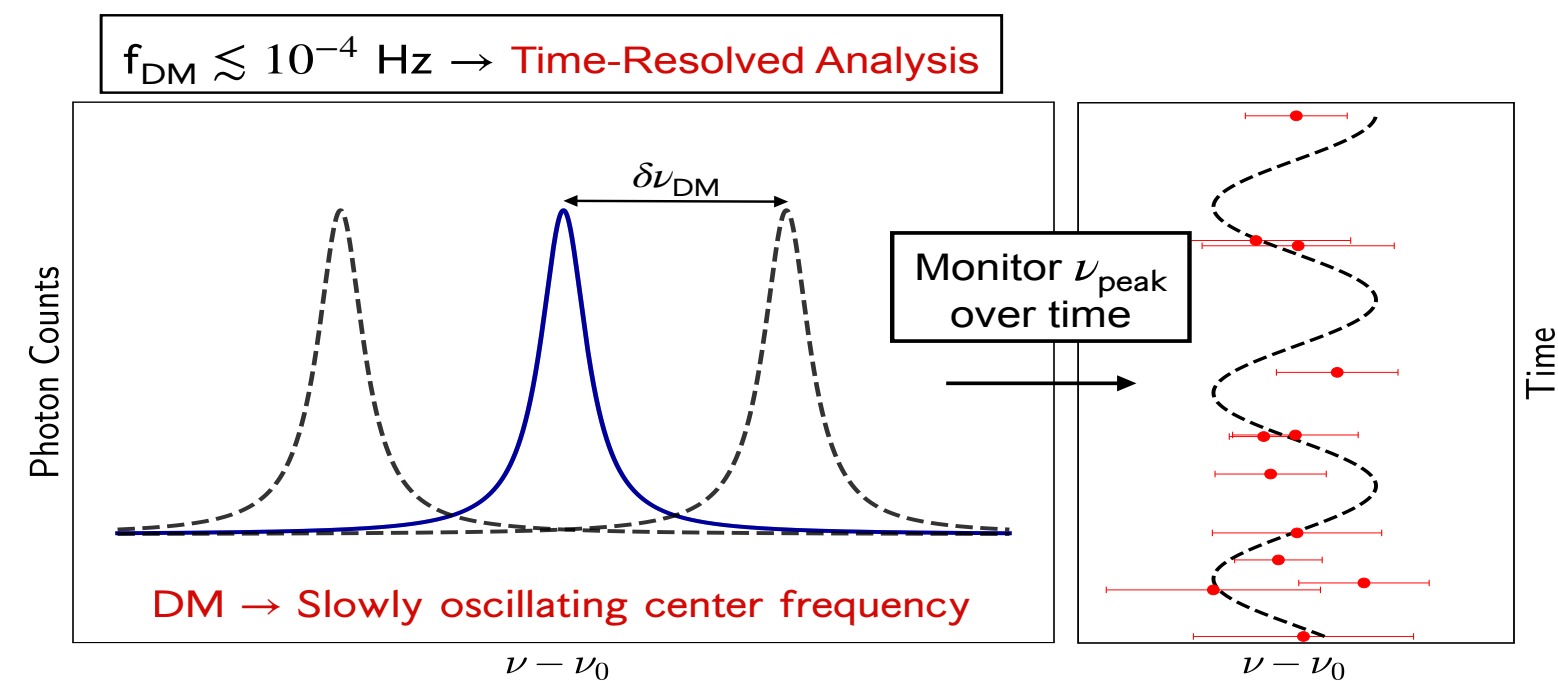
Line analysis - way before Th-clocks, can find DM today!

- The DM affects the spectrum in 2 ways:

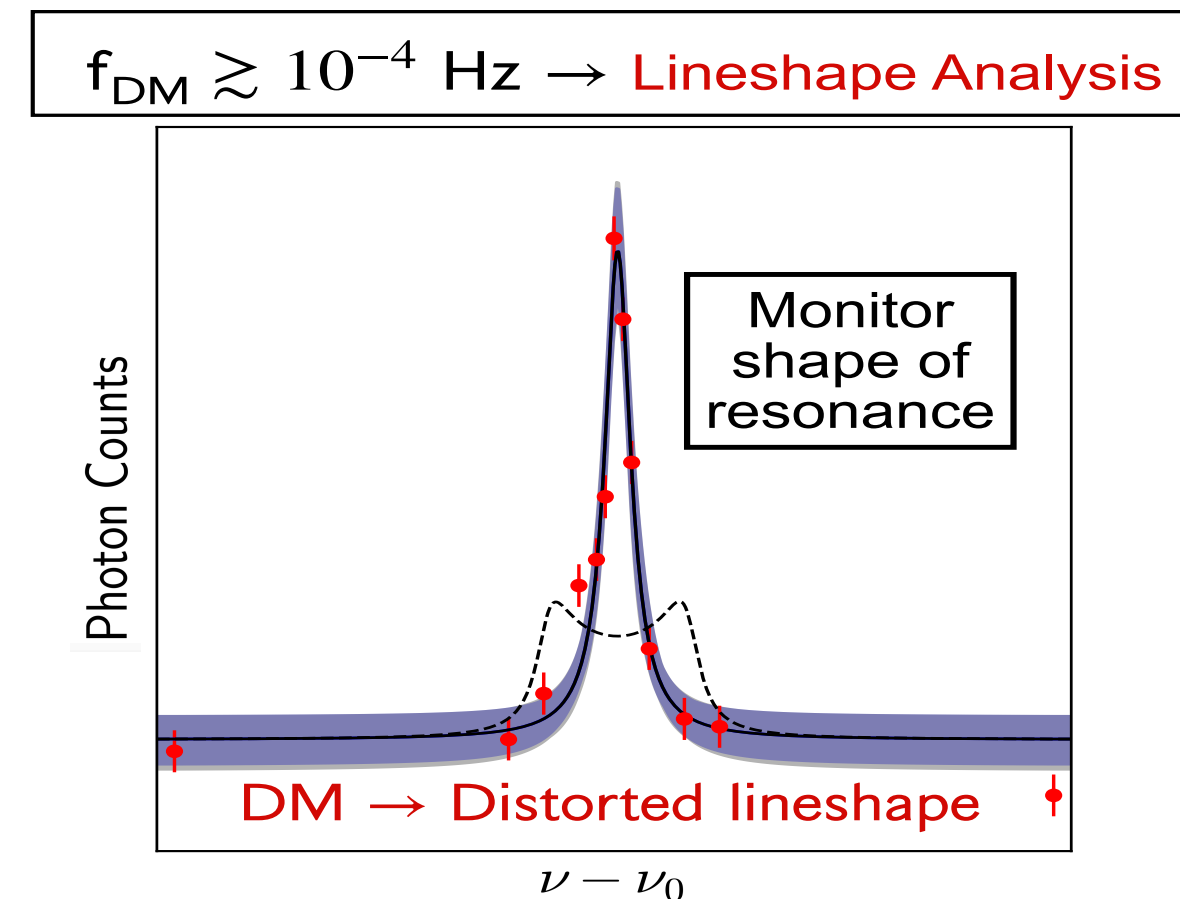
Fuchs, Kirk, Madge, Paranjape, Peik, **GP**, Ratzinger & Tiedau (24);



- (i) Slow oscillation - time resolved, location of the line's peak oscillates



- (ii) Fast oscillation, line's shape modified



Probing Ultralight Dark Matter at the Mega-Planck Scale with the Thorium Nuclear Clock

Jason Arakawa,^{1,2,*} Jack F. Doyle,³ Elina Fuchs,^{4,5,†} Jacob S. Higgins,³
Fiona Kirk,^{6,7,5,‡} Kai Li,³ Tian Ooi,³ Gilad Perez,^{6,§} Wolfram Ratzinger,^{6,¶}
Marianna S. Safronova,¹ Thorsten Schumm,^{8,**} Jun Ye,^{3,††} and Chuankun Zhang³

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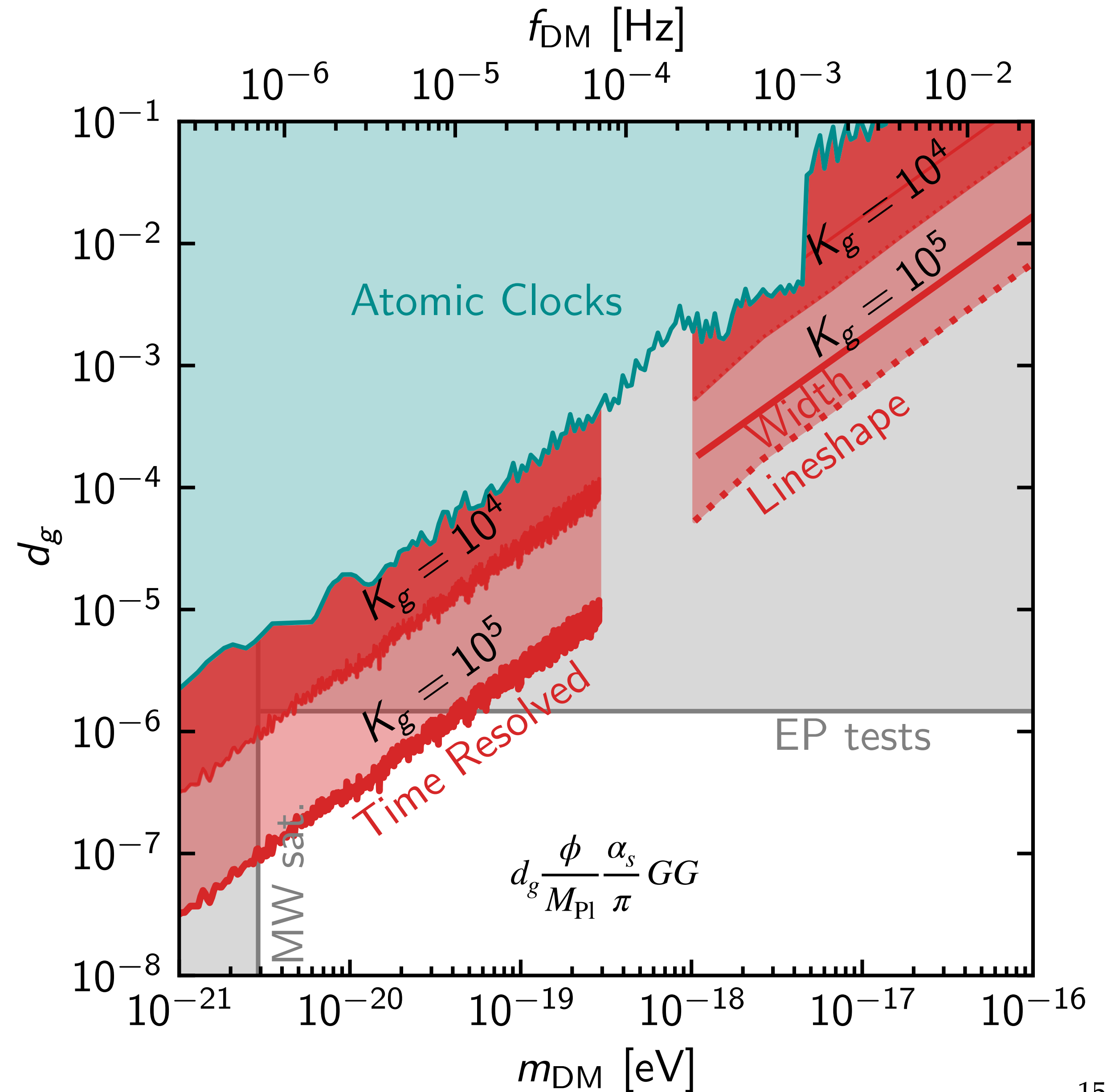
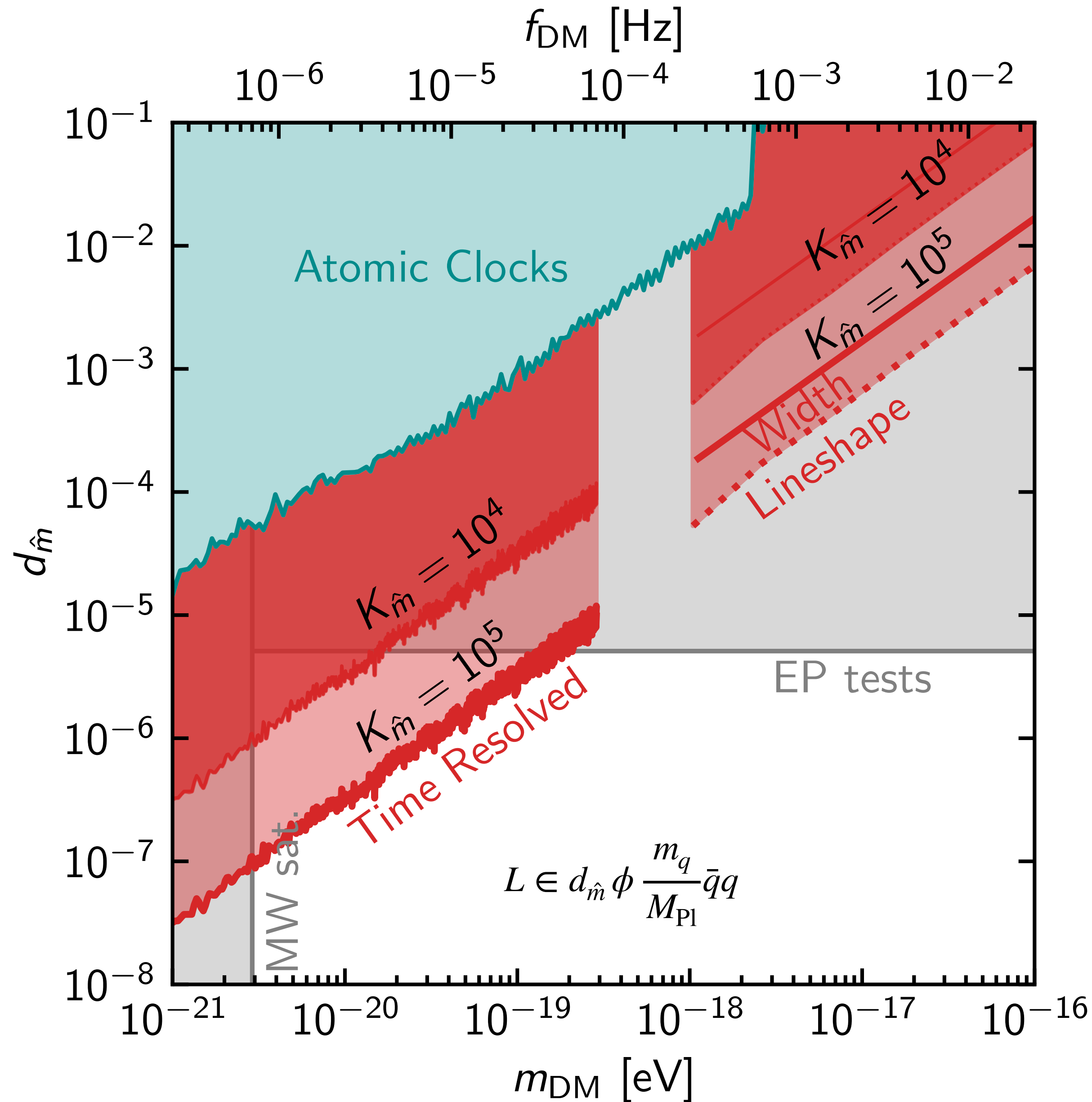
⁸*Vienna Center for Quantum Science and Technology,
Atominstitut, TU Wien, Stadionallee 2, 1020 Wien, Austria*

(Dated: February 20, 2026)

Ultralight dark matter is expected to induce oscillations of nuclear parameters. These oscillations are characterized by extremely weak couplings or high suppression scales, with the Planck scale – the characteristic scale of quantum gravity – serving as a natural benchmark. Probing this phenomenon requires systems with exceptional sensitivity to shifts in nuclear energies. The uniquely low-energy nuclear isomeric transition in ^{229}Th provides such sensitivity: it directly probes the nuclear interaction and, owing to a near cancellation between electromagnetic and nuclear contributions, its response to changes in nuclear structure is greatly amplified. We devise and perform a new type of ultrasensitive search for dark matter which uses the precision nuclear spectroscopy at JILA to set the strongest bounds in the mass range $10^{-21} \text{ eV} \lesssim m_{\text{DM}} \lesssim 10^{-19} \text{ eV}$. Our results probe effective interaction scales exceeding 10^6 times the Planck scale (the Mega-Planck scale) and establish the ^{229}Th system as the leading probe of dark matter couplings to the nuclear sector.

Present and near future implications

2602.16804

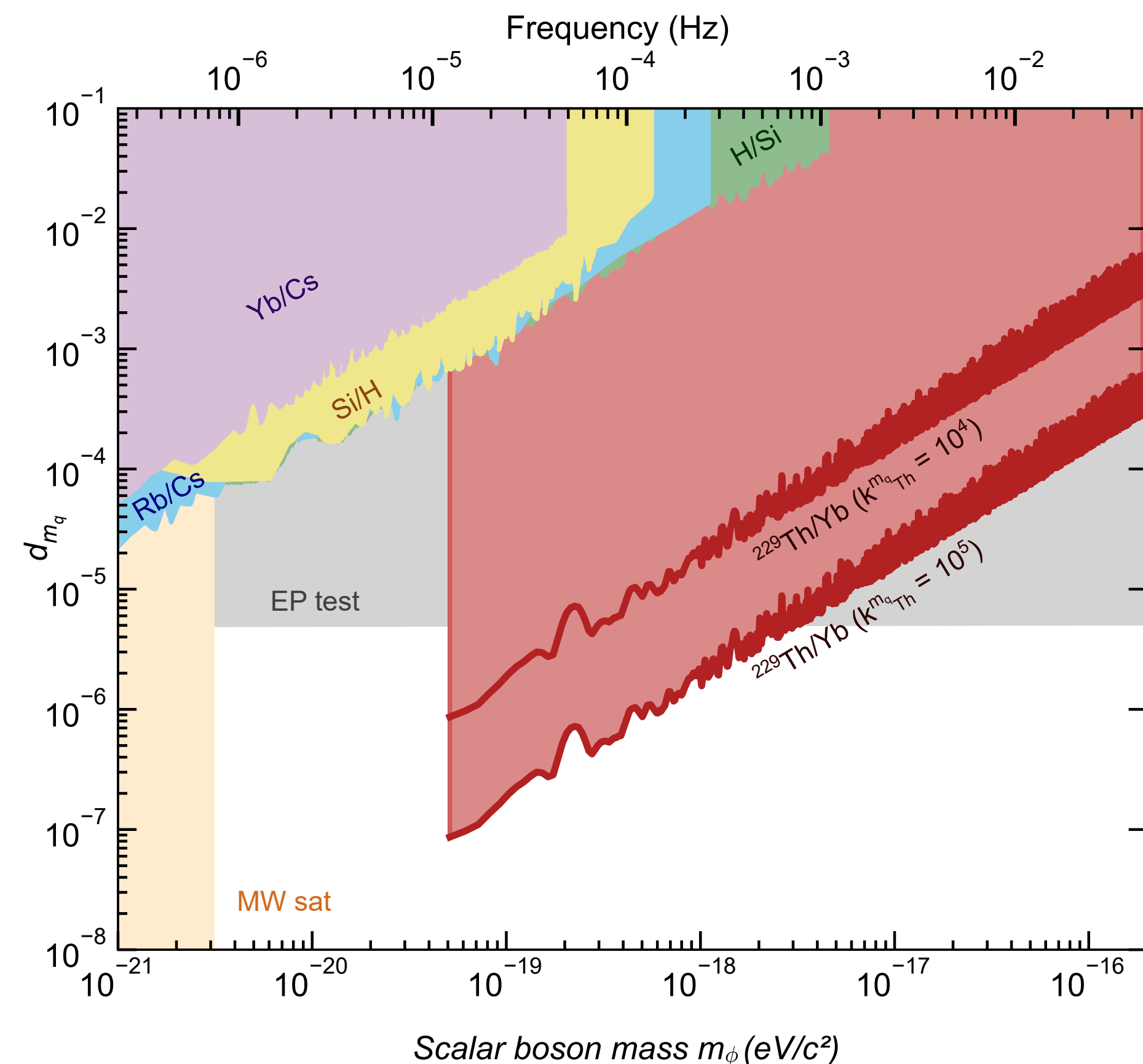
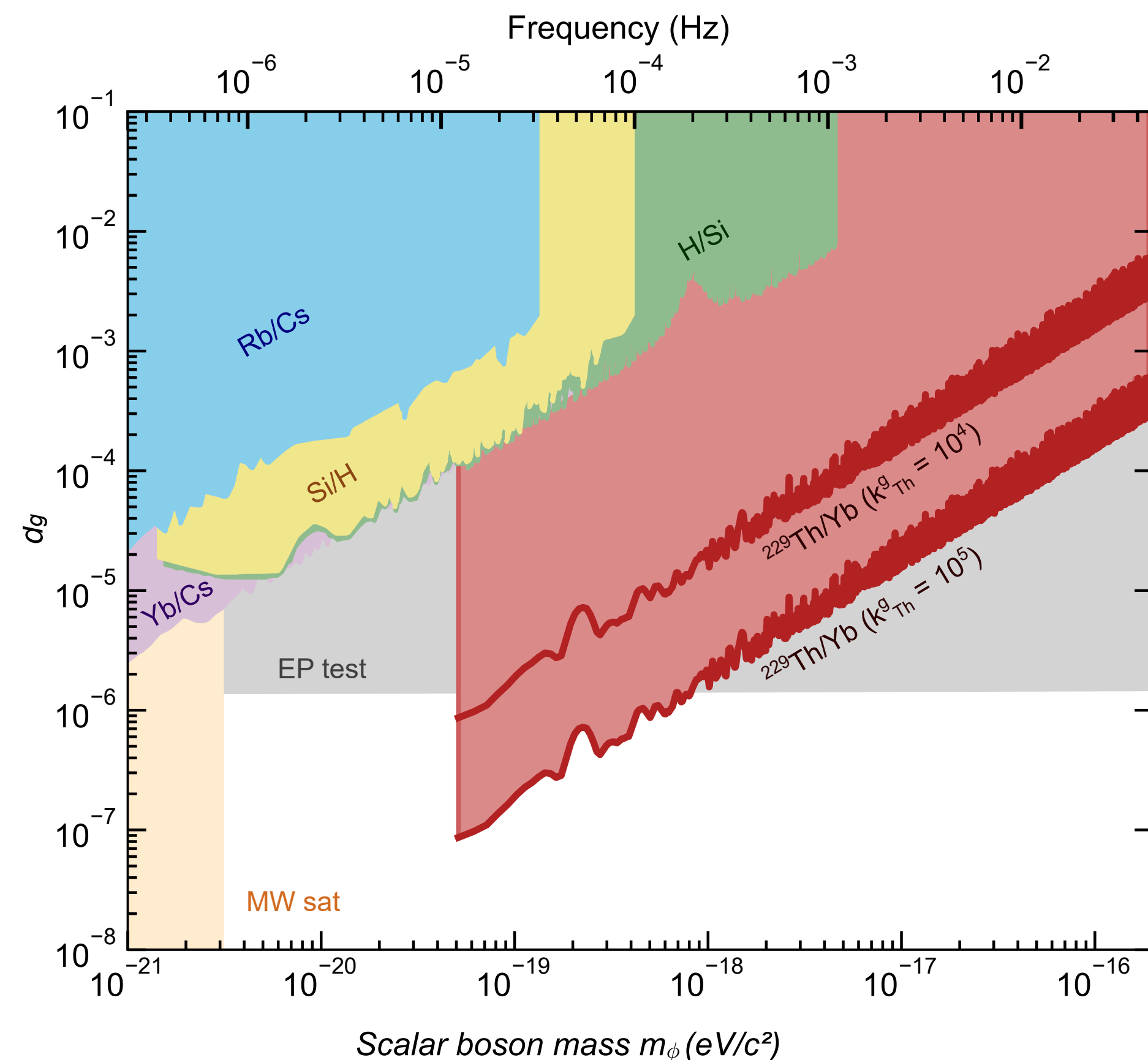


Next breakthrough just happened

Morawetz,..., Peik, Schumm (summer); De Col, Riebner,..., Peik, Schumm (summer)

See also: Huang, et al. (summer)

Instead of waiting 20 mins after each excitation for fluorescent light, absorptive spectroscopy has been adopted, w a CW-laser, allowed for much faster sequence => improved time-resolved sensitivity



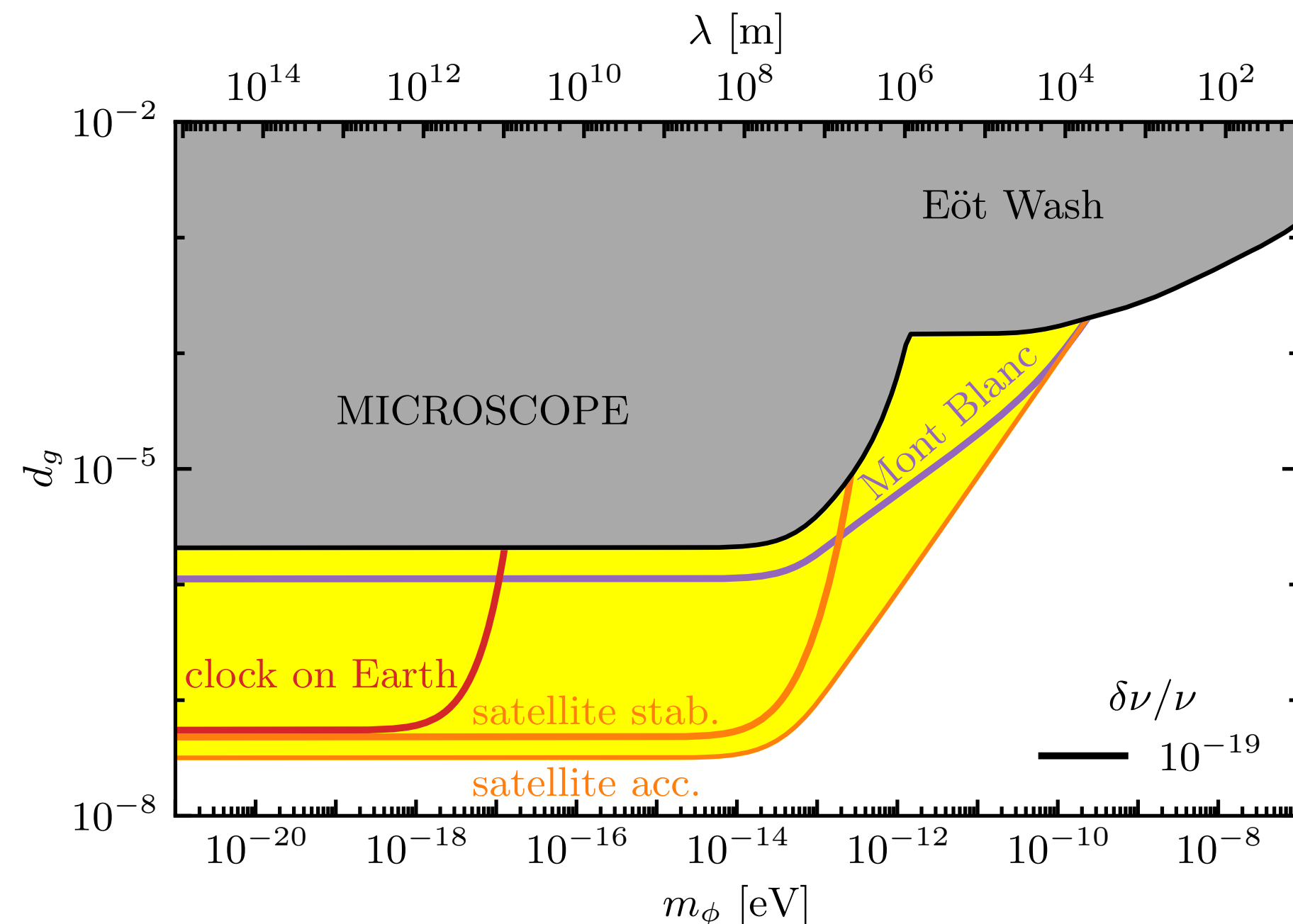
Using nuclear clock to search for (non-DM) light scalars

- Nuclear clock is extremely sensitive to variation in the strong coupling
- Replace time-varying DM with scalar space-dependence value, $\delta\phi$, away from a source;

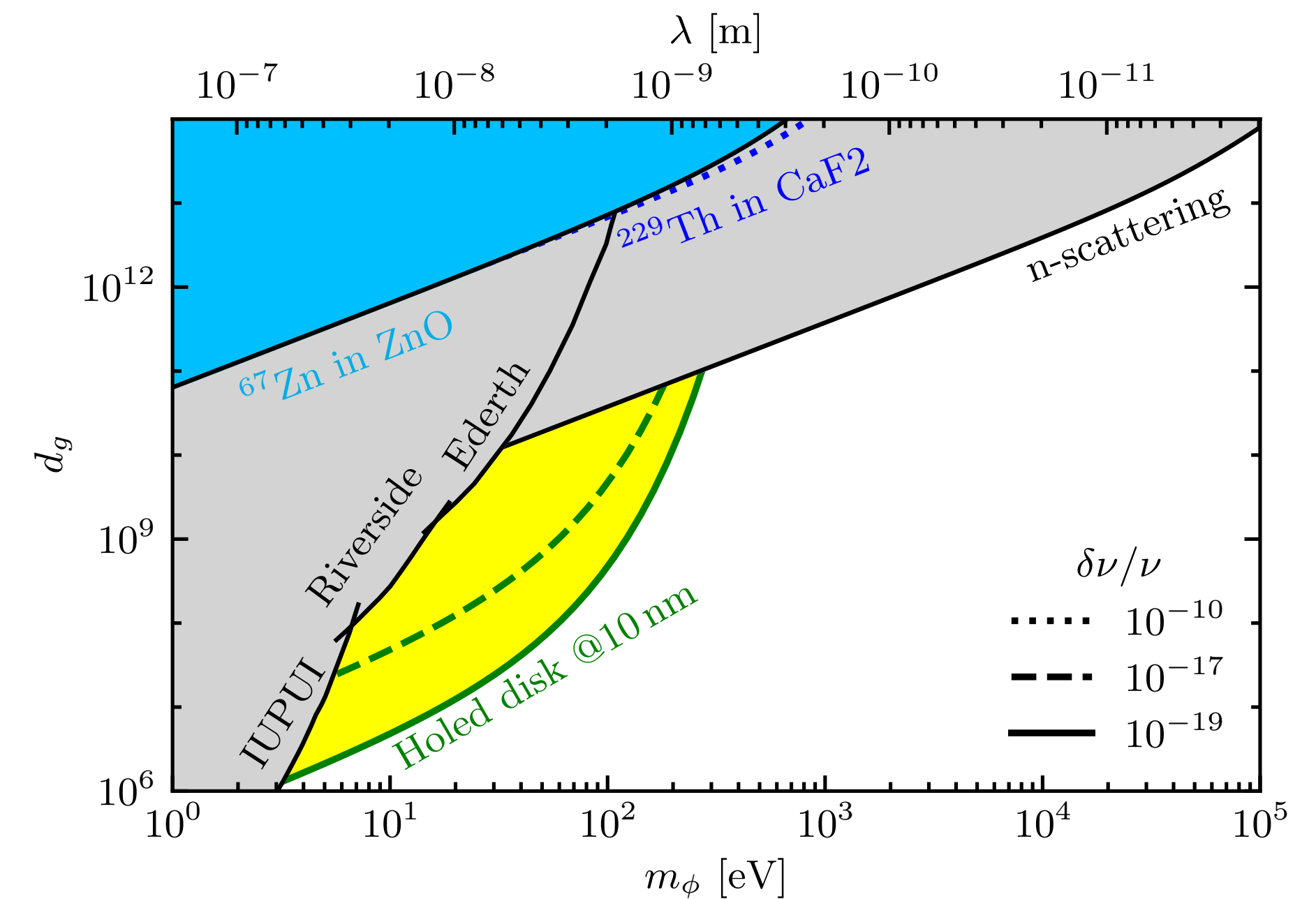
\w: Delaunay, Lee, Ozeri, Ratzinger & Yu (25)

Two limits for such a 5th force search:

small mass, actively varying distance from source



large mass, rotating holed disk, close to clock



The imperfect axion

- (i)* what does imperfect axion means?
- (ii)* domain wall free low quality axion
- (iii)* (first) search of imperfect axion \w nuclear clock

Imperfect axion

For rev.: Di Luzio, Giannotti, Nardi & Visinelli (22)

- Axion models rely on the QCD CP phase, $\bar{\theta} \Rightarrow$ dynamical $\backslash w \langle \bar{\theta} \rangle_a = 0$
- 2 fundamental reasons for why the axion VEV is shifted from zero:
 - (i) quality problem: quantum gravity induces PQ-violating (PQV) terms inducing shift to the axion VEV, $\theta_{\text{eff}} = \langle \bar{\theta} \rangle_a \neq 0 \ll 10^{-10}$ & PQV mass, $\frac{m_{\text{PQ}}}{m_a} \lesssim \sqrt{\bar{\theta}}_{\text{exp}} \lesssim 10^{-5}$
 - (ii) NP-CP-problem $\Rightarrow$ expected TeV CPV would shift the axion from its VEV

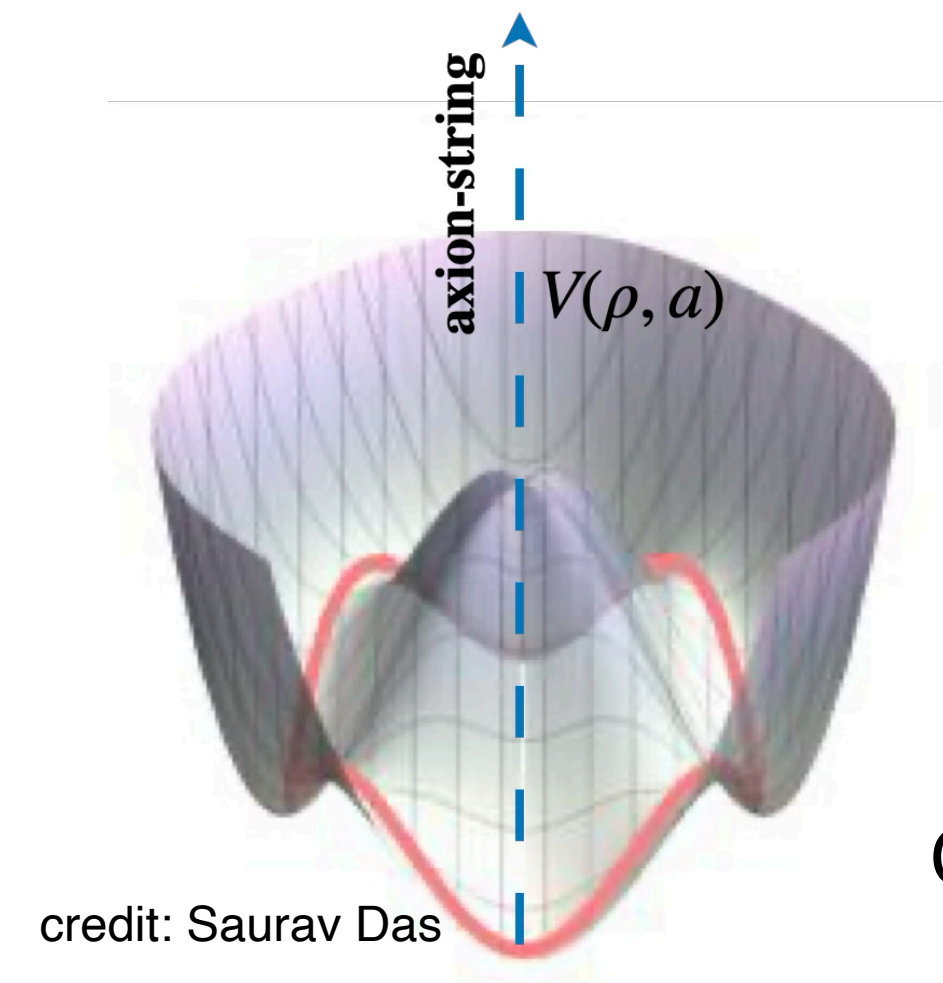
$$\theta_{\text{eff}} = \frac{K'}{K}, \quad \backslash w: K = -i \int d^4x \langle 0 | T \left\{ \frac{\alpha_s}{8\pi} G \tilde{G}(x) \frac{\alpha_s}{8\pi} G \tilde{G}(0) \right\} | 0 \rangle, \quad K' = -i \int d^4x \langle 0 | T \left\{ \frac{\alpha_s}{8\pi} G \tilde{G}(x) C_i \mathcal{O}_i^{\text{CP}}(0) \right\} | 0 \rangle.$$

Pospelov & Ritz (00)

It might not be a bug it's a feature

Domain walls (DWs) free low quality axion

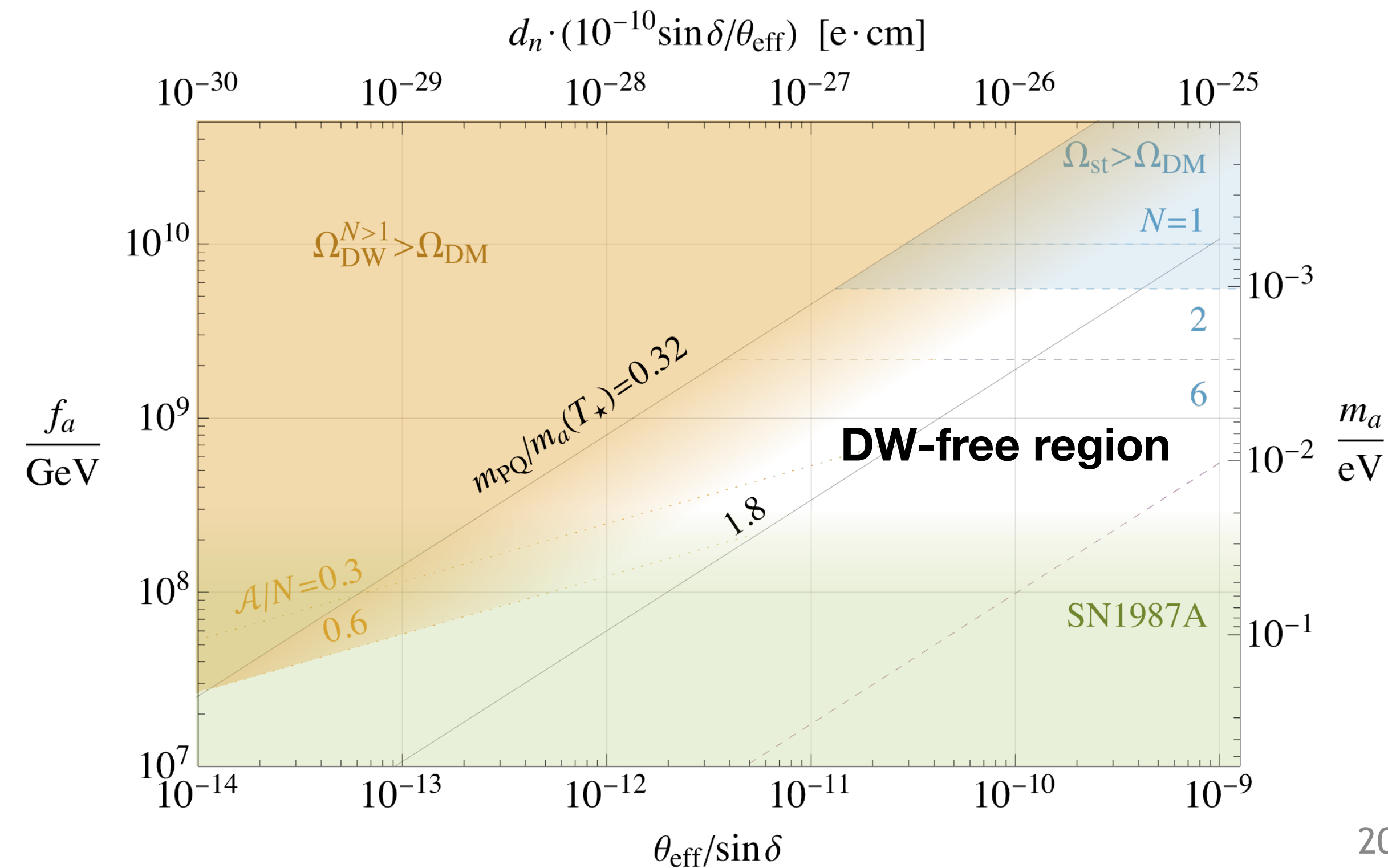
- If the UV PQ sector consists of $N > 1$ fund' quarks $\Rightarrow$ axion potential is $\cos(Na/f)$ leading to N equivalent minima $\Rightarrow$ DWs problem for QCD-strings



Gorghetto, Hardy, GP & Stelzl (26)

- We show that quality-PQV operators could resolve this problem if before the DWs are form the constant PQV mass dominates the axion dynamics.

Next gen' n-EDM exp' $\Rightarrow$ strong test



Imperfect axion & nuclear clock

- Axion couples quadratically to pions leading to oscillation of energy levels in atoms &

nuclear clocks: $\frac{\delta m_\pi^2}{m_\pi^2} \approx 0.1 \theta^2$, w $\theta \equiv a/f$ Kim & GP (22)

- Using the dep. of charge radius and/or nucleon masses on m_π , we expect $\frac{\delta f_{\text{Th}}}{f_{\text{Th}}} \approx 10^3 \theta^2$
Banerjee et al. (25)

- For imperfect axions we expect however: $\frac{\delta f_{\text{Th}}}{f_{\text{Th}}} \approx 10^3 (\theta^2 + 2\theta_{\text{eff}} \theta)$

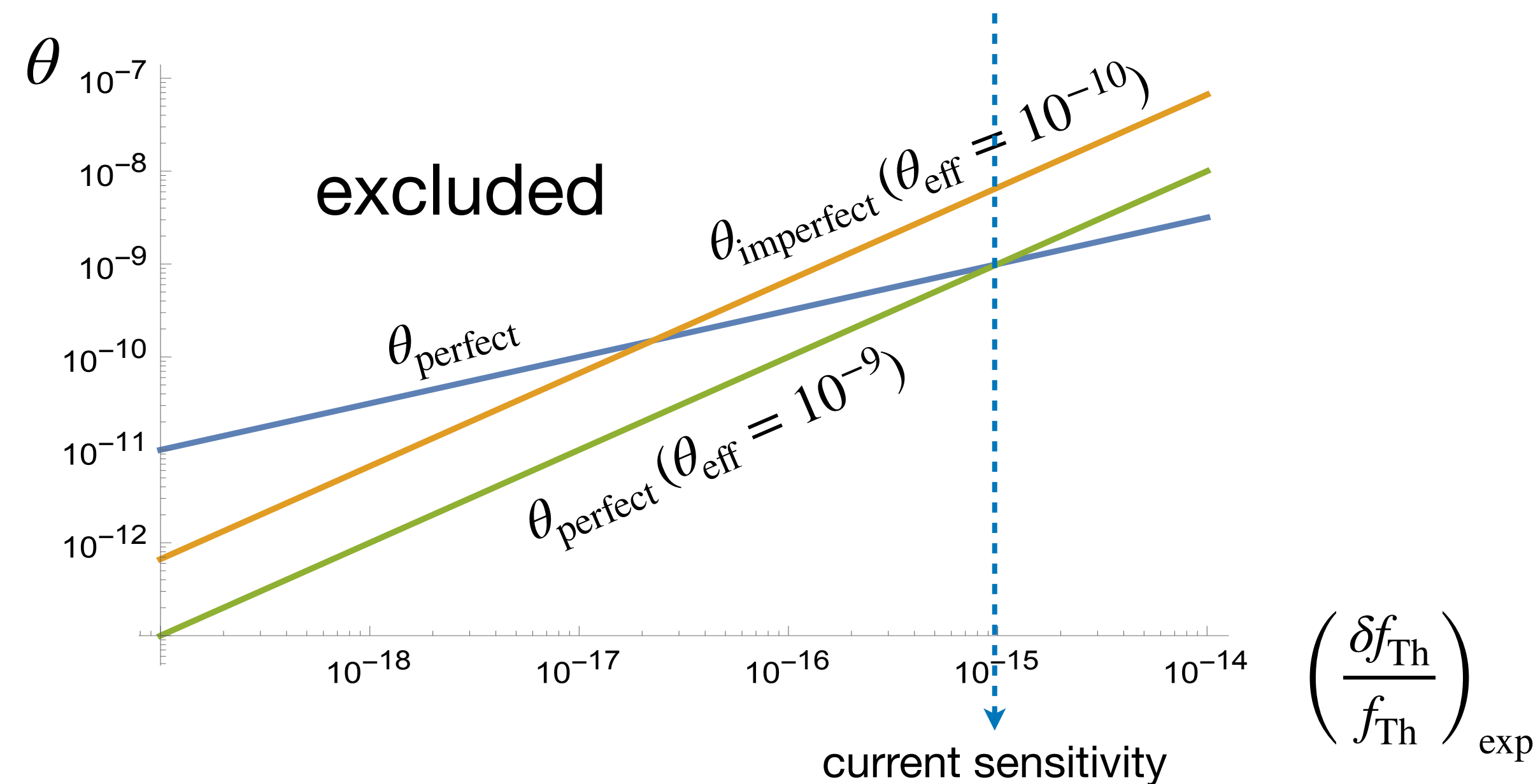
Bottaro, Caputo, GP, Soreq & Stanzione, to appear

Linear & quadratic imperfect axion's nuclear clock searches

Bottaro, Caputo, GP, Soreq & Stanzione, to appear

- Imperfect couplings, $\frac{\delta f_{\text{Th}}}{f_{\text{Th}}} \approx 10^3 (\theta^2 + 2\theta_{\text{eff}} \theta)$, lead to several new implications:

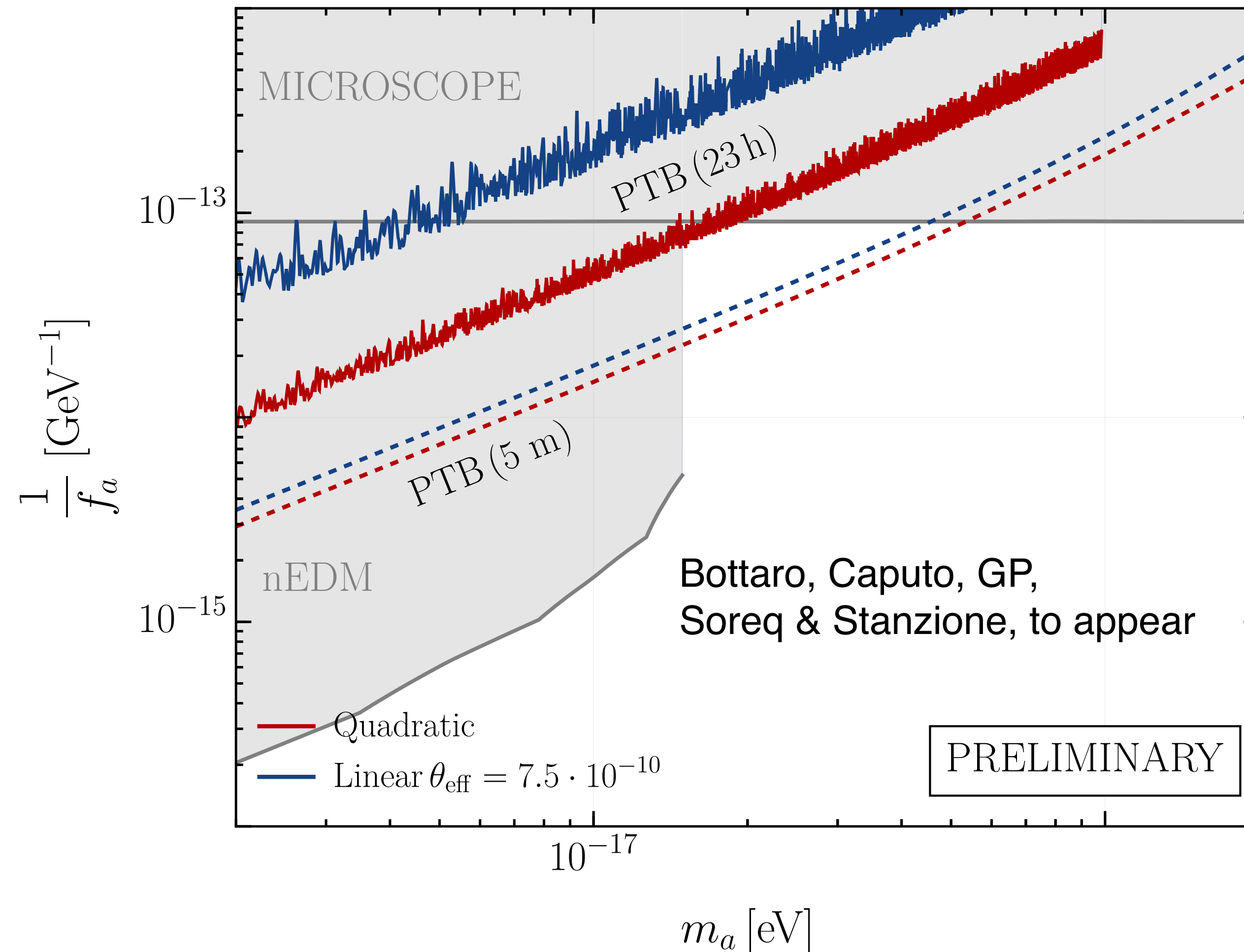
(i) Different scaling: $\theta_{\text{perfect}} \lesssim 10^{-1} \sqrt{\frac{K_{\theta}}{10^3}} \sqrt{\left(\frac{\delta f_{\text{Th}}}{f_{\text{Th}}}\right)_{\text{exp}}} \quad \& \quad \theta_{\text{imperfect}} \lesssim 10^7 \frac{10^{-10}}{\theta_{\text{eff}}} \frac{K_{\theta}}{10^3} \left(\frac{\delta f_{\text{Th}}}{f_{\text{Th}}}\right)_{\text{exp}}$



- (ii) Entered era where linear (imperfect) $\sim$ quadratic (imperfect) calls for combined 2-freq' search

Projection, imperfect vs perfect axion sensitivity @ nuclear clock

- Using PTB's summer result's & estimation of sensitivity progress we project:



Summary & overview

- UDM could be captured around astrophysical objects
- Leading to rich phenomenology including enhanced density, longer coherent time, recoherence, bosenova ...
- First look at (SC) BH: mechanism seems to hold including $2p$ capturing
- We have entered the era of nuclear clock supremacy
- Studying the imperfect axion seems theoretically motivated, discussed implication for cosmology (DW-problem) & new signals at nuclear clocks.

Backups

(first) search of imperfect axion \ w nuclear clock

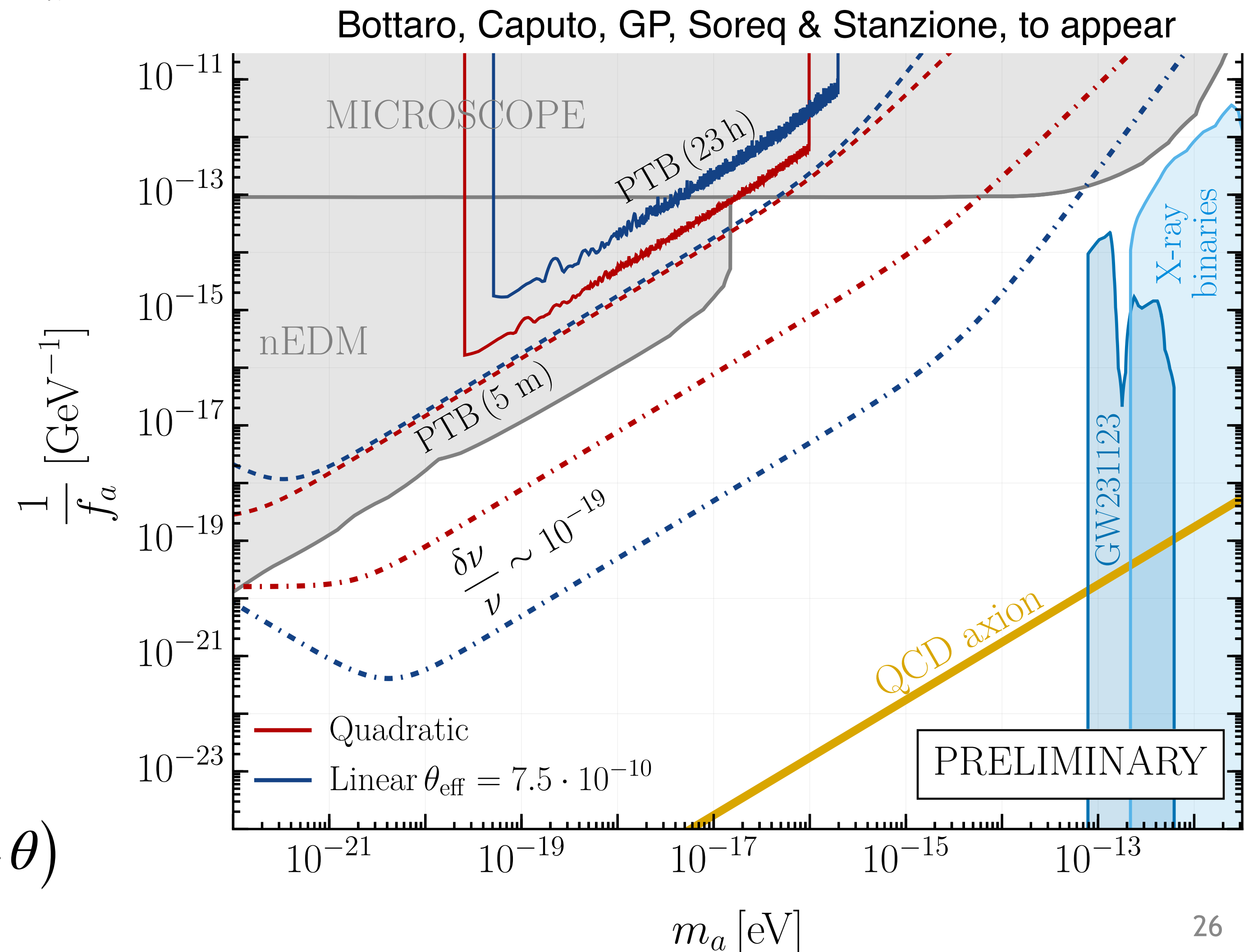
- Axion couples quadratically to pions $\frac{\delta m_\pi^2}{m_\pi^2} \approx 0.1 \theta^2$, w $\theta \equiv a/f$

leading to oscillation of energy levels
in atoms & nuclear clocks Kim & GP (22)

- Using the dep. of the charge radius
on pion mass we can convert it to the
nuclear EM dependence: Banerjee et al. (25)

$$\frac{\delta f_{\text{Th}}}{f_{\text{Th}}} \approx 10^3 \theta^2, \text{ assume } K_{\text{EM}} \sim 10^5$$

- Implies a new type of search for the
imperfect axion: $\frac{\delta f_{\text{Th}}}{f_{\text{Th}}} \approx 10^3 (\theta^2 + 2\theta_{\text{eff}} \theta)$



How robust is the sensitivity factor?

with: Andrea Caputo, Doron Gazit, Hans Werner Hammer, Joachim Kopp , Gil Paz & Konstantin Springmann

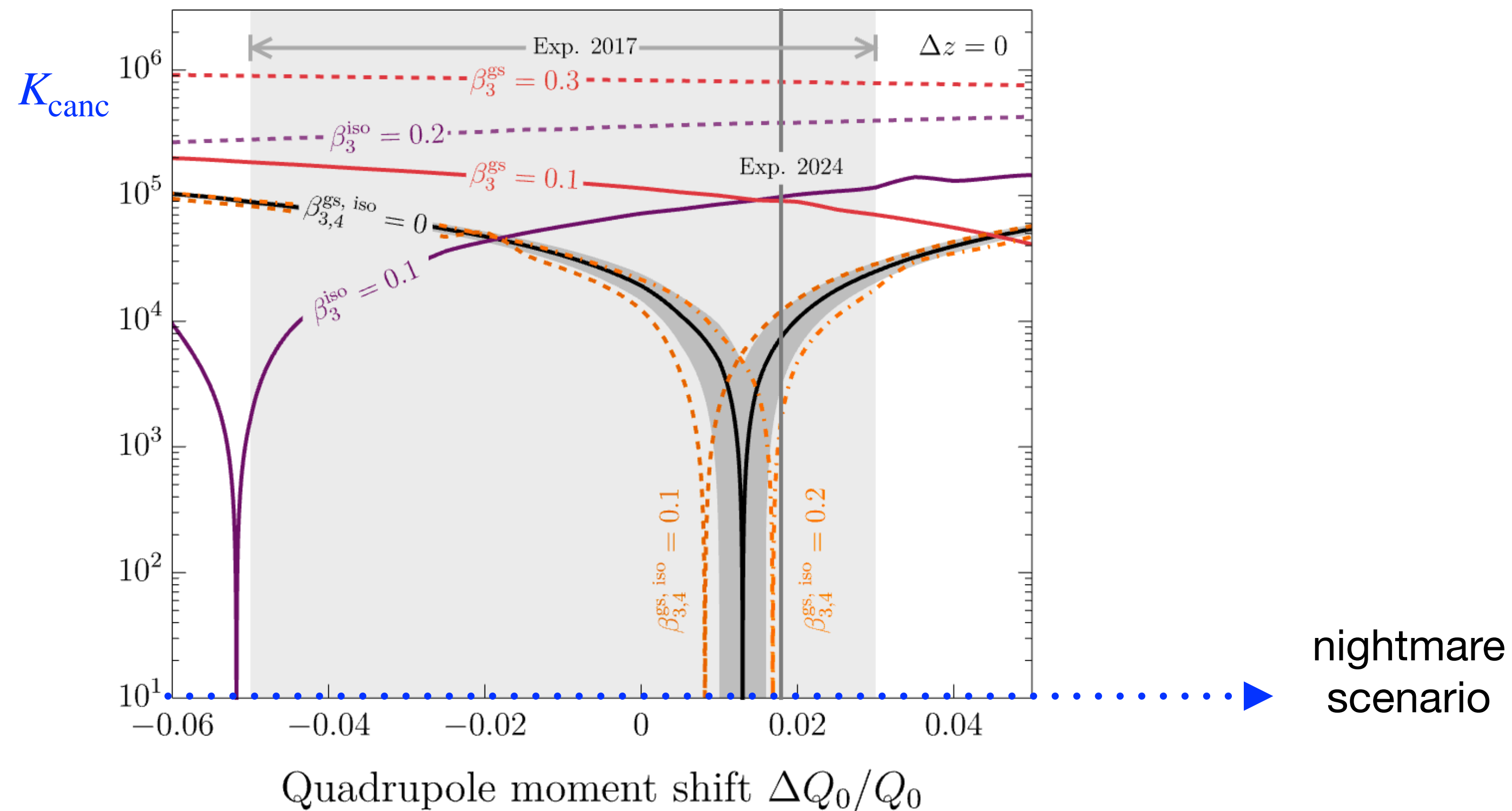
- Can we measure or test this enhancement factor, $K_{\text{canc}} = \Delta E_{\text{nu}} / \Delta E_{\text{nu-clock}} \sim 10^5 \gg 1$?
- Calculation of the nuclear binding energy difference is very challenging ...
- Can instead consider at the electrostatic binding energy of the two states
- We provide two ways to do it:
 - (i) classical approach to the nuclei (charge density is a simple function)
 - (ii) QFT-EFT inspired way, using QM model of the neutron-core system

Berengut, Dzuba, Flambaum & Porsev (09); Fadeev, Berengut & Flambaum (20)

Hammer, König, & van Kolck (19)

Geometrical/classical model

- Given a shape and charge density of both states we can evaluate ΔE_{EM}
- Result depends on number of variables (some are measured some are not)

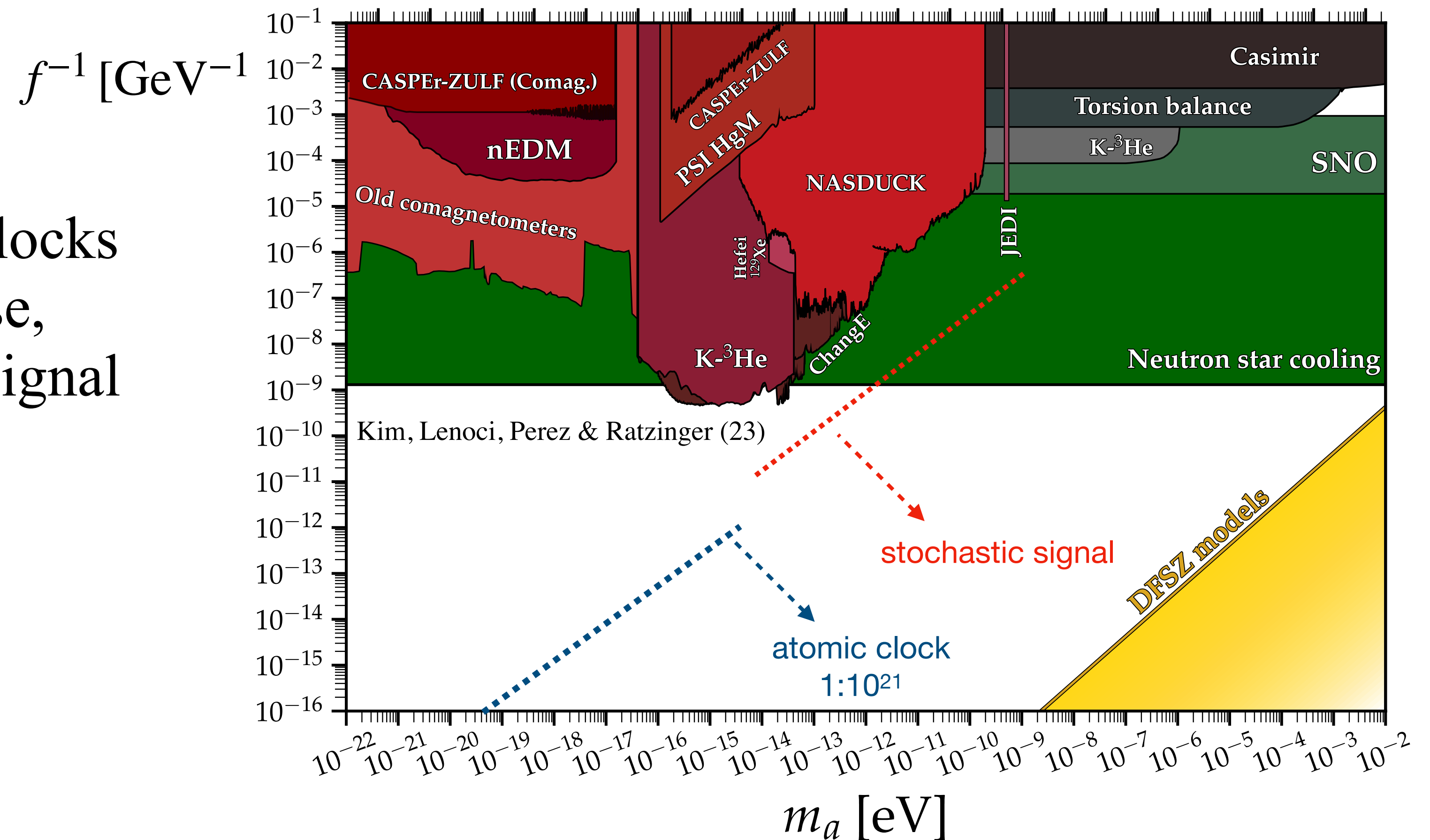


Q_0 = quadrupole moment, Δ = state difference,
 $\beta_{3,4}$ = higher moments, Δa = thickness via WS (Fermi) distribution

Power spectrum of quadratic (axion) UDM, the stochastic signal

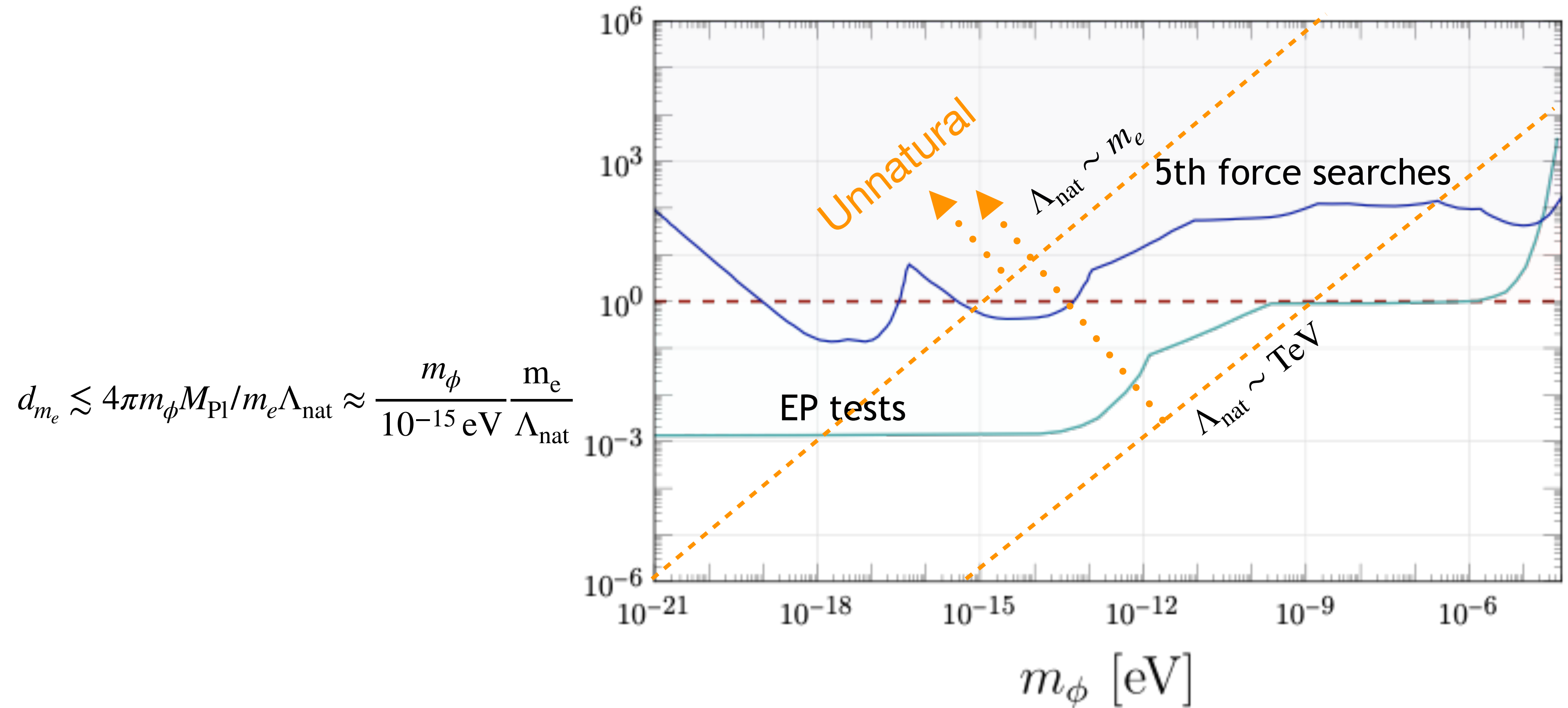
$$\mathcal{L}_{\text{axion}}^{\text{eff}} \in 10^{-3} \theta^2(t) m_N \bar{n} n$$

Can time correlate 2 clocks
to get rid of white noise,
extract the stochastic signal



Important to search for “heavyish” UDM
with mass above Hz (10^{-15} eV)

Naturalness



Linear coupling seems to also be seriously challenged by naturalness

Oscillations of energy levels induced by QCD-axion-like DM

Kim & GP (22)

- Consider axion model w $(\alpha_s/8) (a/f) G\tilde{G}$ coupling, usually searched by magnetometers

- However, spectrum depends on $\theta^2 = (a(t)/f)^2$: $m_\pi^2(\theta) = B \sqrt{m_u^2 + m_d^2 + 2m_u m_d \cos \theta}$
Brower, ChandrasekharanC, Negele & Wiese (03)

$$\text{MeV} \times \theta^2 \bar{n}n \Rightarrow \frac{\delta f}{f} \sim \frac{\delta m_N}{m_N} \sim 10^{-16} \times \cos(2m_a) \times \left(\frac{10^{-15} \text{ eV}}{m_\phi} \frac{10^9 \text{ GeV}}{f} \right)^2 \quad \text{vs} \quad m_N \frac{a}{f} \bar{n} \gamma^5 n \Rightarrow (f \gtrsim 10^9 \text{ GeV})_{\text{SN}}$$

It's exciting as clocks (& EP tests) are much more precise than magnetometers
They can sense oscillation of energy level due to change of mass of the
electron or QCD masses to precision of better than $1:10^{18}$!

Axion - the scalar way, the power of clocks

- Maybe should accept that probing axions is work in progress (new proposals)
- The sensitivity to scalar interaction is **10¹²** stronger, can we use it?
- Axion models do predict quadratic scalar coupling that are suppressed however by $m_a^2/f^2 \Rightarrow$ hopeless to probe Banerjee, GP, Safronova, Savoray & Shalit (22)
- Yet, in the case of QCD-like-axion only suppressed by $\frac{\partial \ln m_\pi}{\partial \theta^2} \sim \frac{m_{u,d}}{\Lambda_{\text{QCD}}}$, $\theta = a/f$
- Target for clocks $\text{MeV} \times \theta^2 \bar{n}n \Rightarrow \frac{\delta f}{f} \sim \frac{\delta m_N}{m_N} \sim 10^{-16} \times \cos(2m_a t) \times \left(\frac{10^{-15} \text{ eV}}{m_a} \frac{10^9 \text{ GeV}}{f} \right)^2$ Kim & GP (22)

Why probing the strong sector w clocks is challenging ?

Why is nuclear clock going is a game changer ?

To understand let's talk about how clocks probe DM

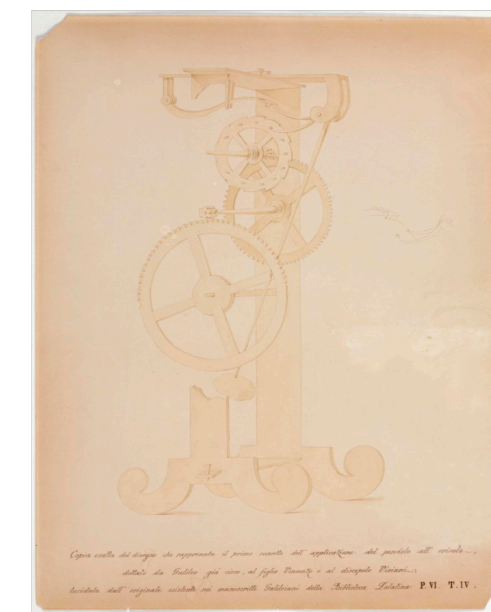
(theorist's perspective - simplified version)

Atomic clock in 1-slide

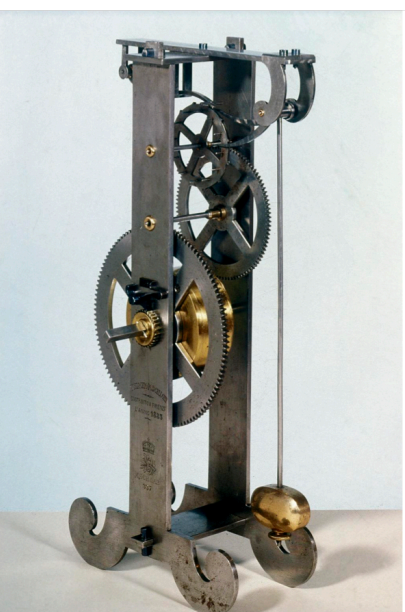
- A clock requires an apparatus that repeat itself in a very precise manner
- Atomic clocks are based on cases where there are electronic transitions between stable 2-level system, $H \approx \Delta E \times \sigma_z$
- In the experiment, via laser, one prepare a linear combination of these levels

$$\psi^+(t=0) \sim \frac{|0\rangle + |1\rangle}{\sqrt{2}} \implies \psi(t)^+ \propto \frac{|0\rangle + \exp(i\Delta Et) |1\rangle}{\sqrt{2}}$$

$$|\langle \psi^+(t=0) | \psi^+(t) \rangle|^2 = \cos^2\left(\frac{\Delta Et}{2}\right) \iff \text{perfect pendulum}$$



Florence



Clocks and ultralight DM (UDM) search?

- Established that clock is a perfect oscillator: $|\langle \psi^+(t=0) | \psi^+(t) \rangle|^2 = \cos^2 \left(\frac{\Delta E t}{2} \right)$

- Why is it an excellent ultralight DM (UDM) detector?

For electronic transitions: $\Delta E \propto m_{\text{reduced}} \alpha^2$, with $m_{\text{reduced}} \approx m_e \left(1 - \frac{m_e}{m_{\text{nuc}}} \right)$

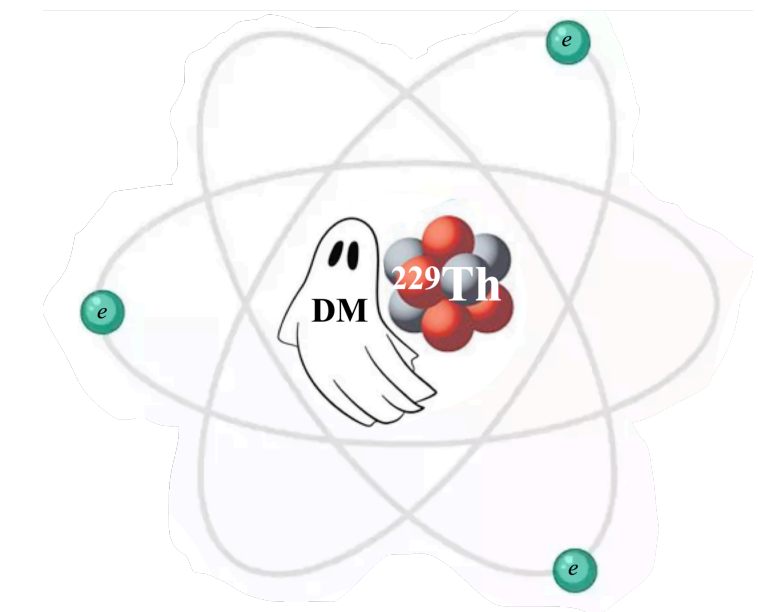
- Scalar DM could couple to F^2 or to the electron would induce oscillatory

component: $\Delta E \propto \left[\text{const} + \frac{\sqrt{2\rho}}{m_{\text{UDM}}} \cos(m_{\text{UDM}} t) \right]$ which atomic clocks can sense

Searching for ULDM coupling to nuclear sector is challenging

- Motivated UDM dominantly couples to nuclear sector sensitivity of atomic probes
- It creates major challenge, just saw it discussing clocks that probes the EM sector:

$$\Delta E \propto m_{\text{reduced}} \alpha^2, \quad \text{with} \quad m_{\text{reduced}} \approx m_e \left(1 - \frac{m_e}{m_{\text{nuc}}} \right) \quad \longleftrightarrow$$



Typically results with suppressed sensitivity by a factor of $R_{\text{nuc}}^{\text{atom}} \sim 10^{3-5}$