New era in dark matter searches the dawn of the (nuclear) clocks

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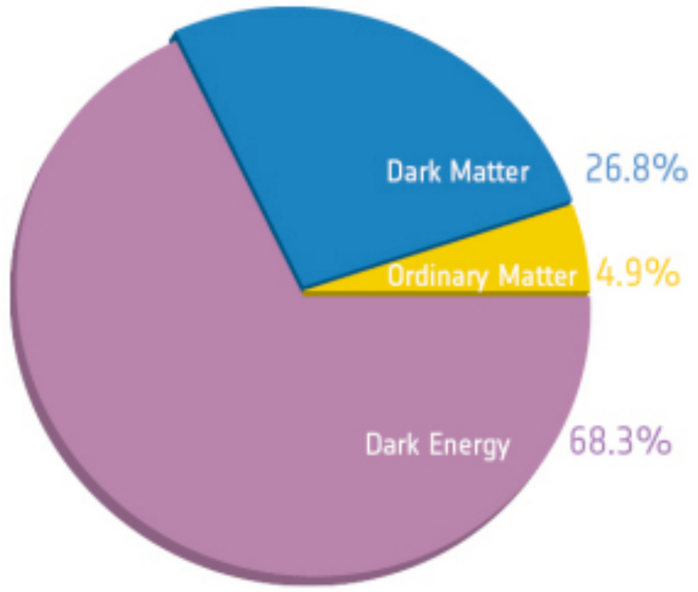
Outline

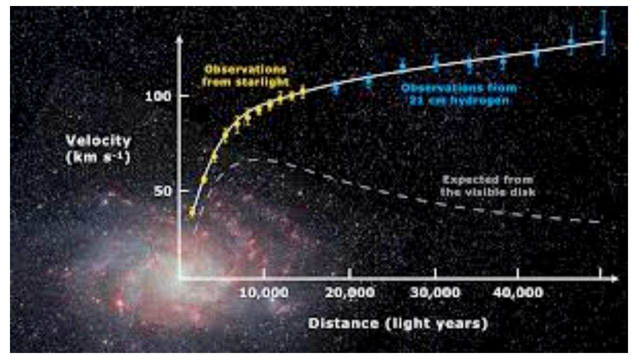
- Intro. (spin-0) ultralight dark-matter (UDM)
- Current status, UDM searches
- Nuclear clock (news, robustness & sensitivity)
- Summary

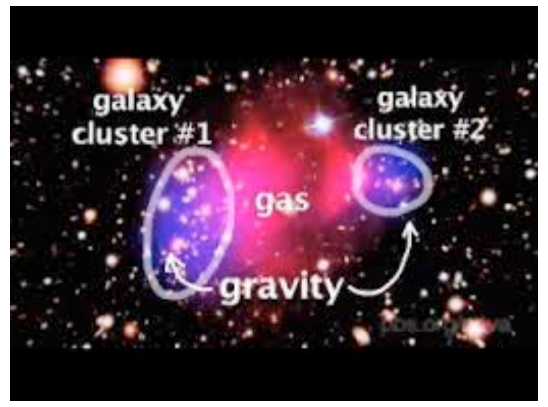
Usually in this part we discuss:

- **Unseen Mass**: The dark matter (DM) constitutes about 85% of the total mass of the universe

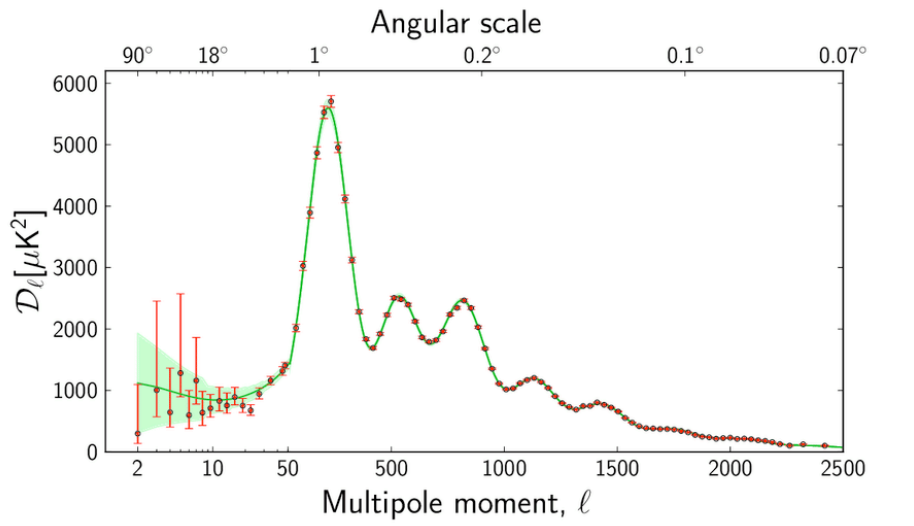


- **Galaxy Formation & rotation curves**: The gravitational influence of DM plays vital role in formation and evolution of galaxies & motions of stars





- **Cosmic Microwave Background (CMB)**: Observations of the temperature fluctuations shows excellent agreement with the ΛCDM model



Instead we'll take a different path following a theorist perspective

If you study the literature you'd find $\mathcal{O}(10^4)$ papers of model building of dark matter

Showing 1–50 of 11,662 results

Search v0.5.6 released 2020-

Query: order: -announced_date_first; size: 50; classification: Physics (grp_physics)::High Energy Physics - Phenomenology (hep-ph); include_cross_list: True; terms: AND abstract=model; AND abstract=dark; AND abstract=matter

Refine query | New search

50 results per page. Sort results by Announcement date (newest first) Go

1 2 3 4 5 … Next

1. arXiv:2404.03963 [pdf, other] hep-ph astro-ph.CO

   Composite Dark Matter with Forbidden Annihilation

   Authors: Tomohiro Abe, Ryosuke Sato, Takumu Yamanaka

   Abstract: A **dark matter model** based on QCD-like $SU(N_c)$ gauge theory with electroweakly interacting **dark** quarks is discussed. Assuming the **dark** quark mass m is smaller than the dynamical scale… ▽ More

   Submitted 5 April, 2024; **originally announced** April 2024.

   Comments: 30 pages, 11 figures

   Report number: OU-HET-1219

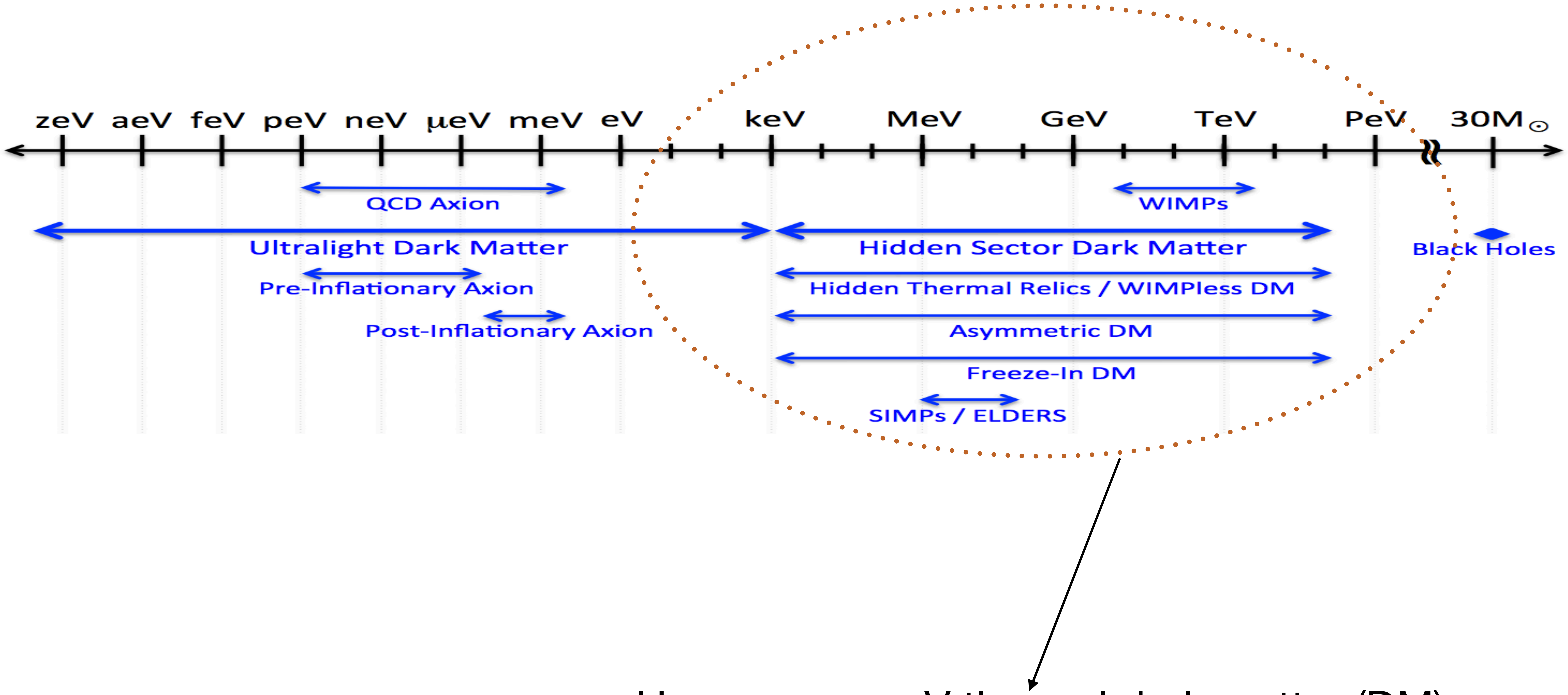
2. arXiv:2404.03666 [pdf, other] hep-ph

   Exploring the Frontiers: Challenges and Theories Beyond the Standard Model

   Authors: Dhananjay Saikumar

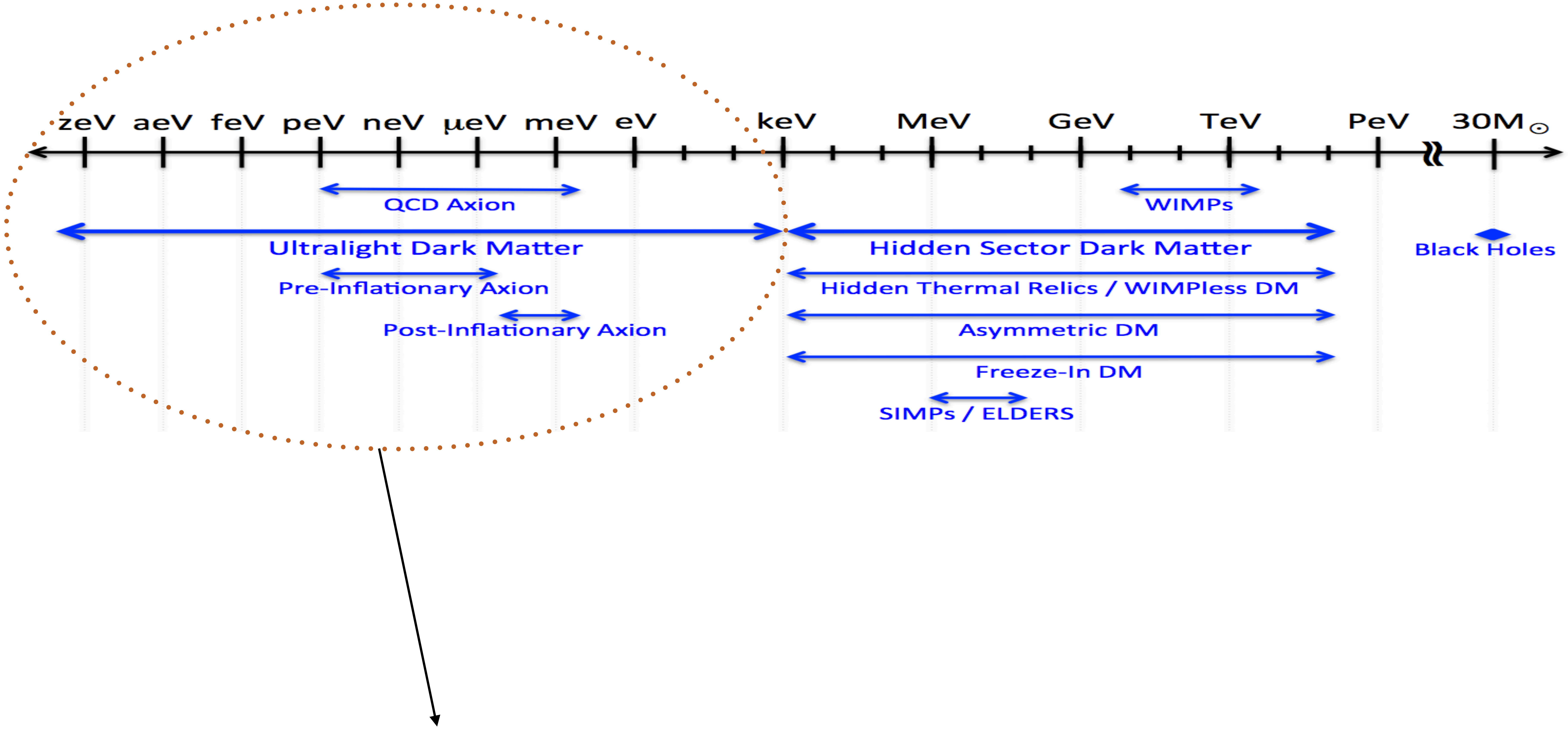
   Abstract: Quantum Field Theory (QFT) forms the bedrock of the Standard **Model** (SM) of particle

The space of possible theories is vast, but some of it is rather involved …



Heavy, super-eV thermal dark matter (DM)
behaves as gas of individual quanta
indep. of initial conditions (thermal)
however, viable models are non-minimal

The space of possible theories is vast, but some of it is rather involved …



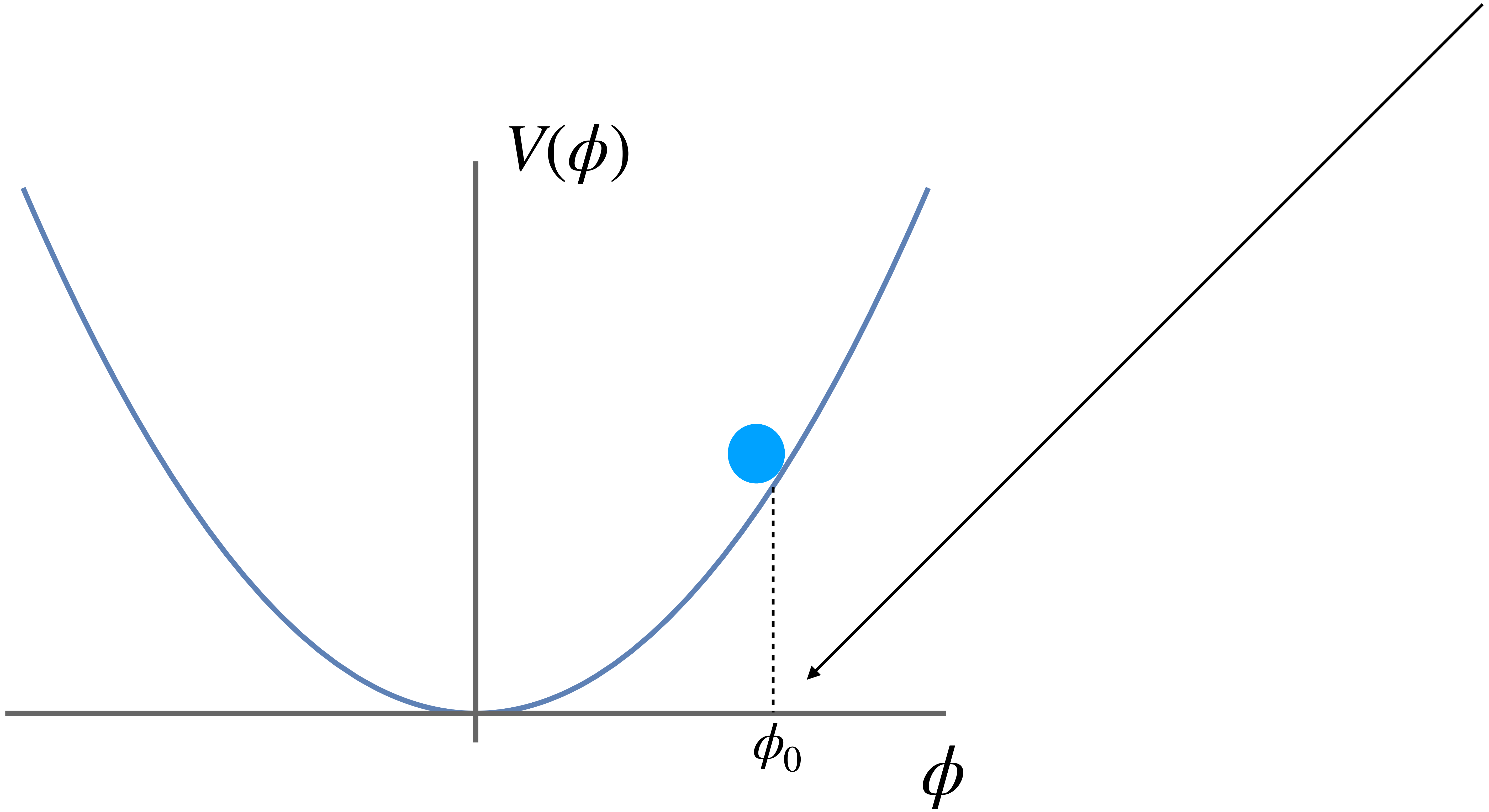
<u>Ultralight sub-eV DM (UDM)</u>

DM behaves as homogenous classical field
initial condition dependent (non-thermal)
viable very simple models, but hard to probe

Our focus today

The simplest ever model of ultralight dark matter

- Just free (pseudo-) scalar light field, $\mathscr{L} \in m_\phi^2 \phi^2$, with some initial homogenous condition, $\phi_{\rm init} = \phi_0$

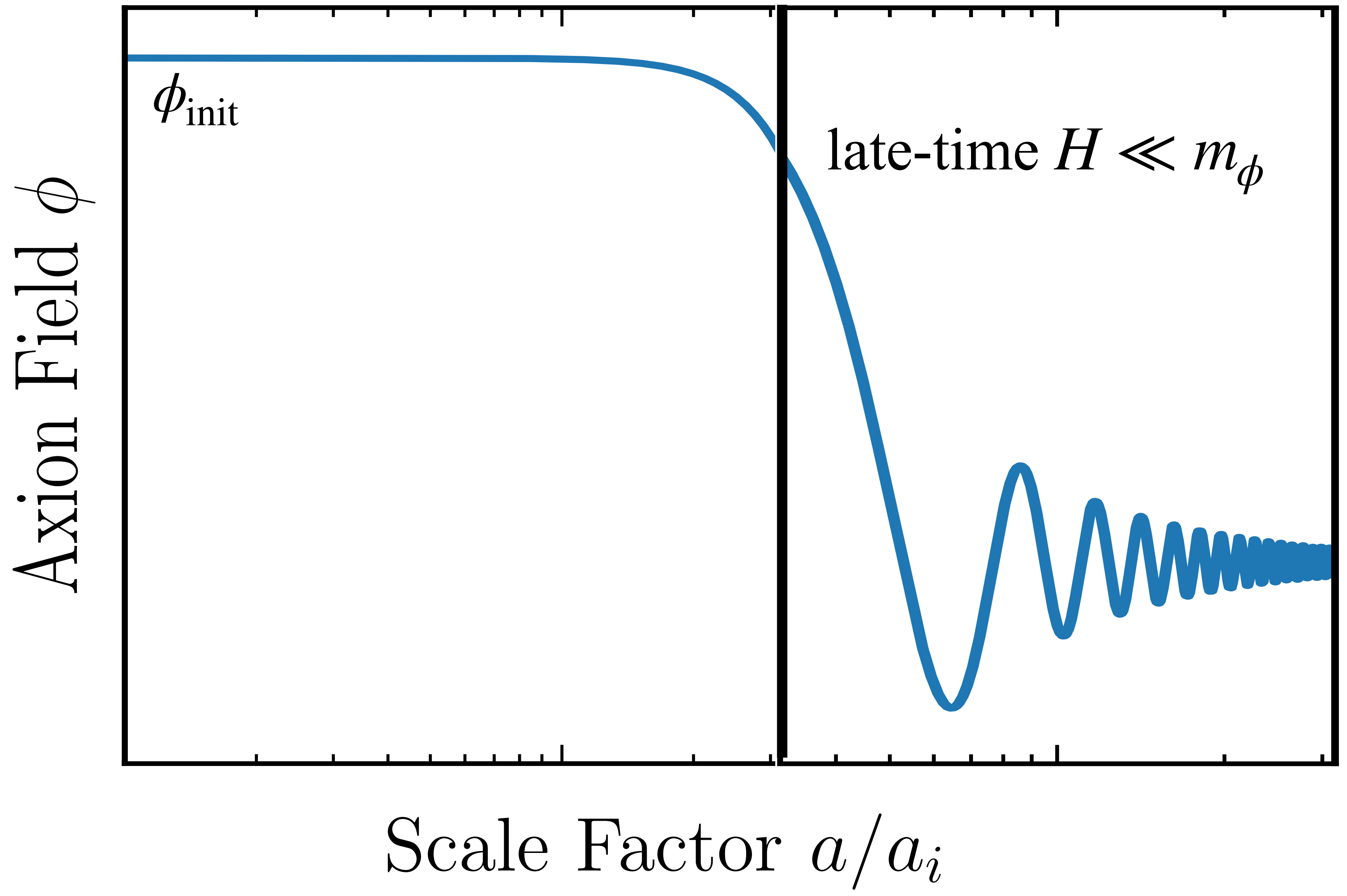


- What would be the cosmological evolution of such a field (assume $H \ll m_\phi$) ?

Late time evolution of scalar field, approximate oscillatory

- Just free (pseudo-) scalar light field, $\mathscr{L} \in m_\phi^2 \phi^2$, with some initial homogenous condition, $\phi_{\rm init} = \phi_0$

- The field oscillates around the minimum with late-time solution looks like:



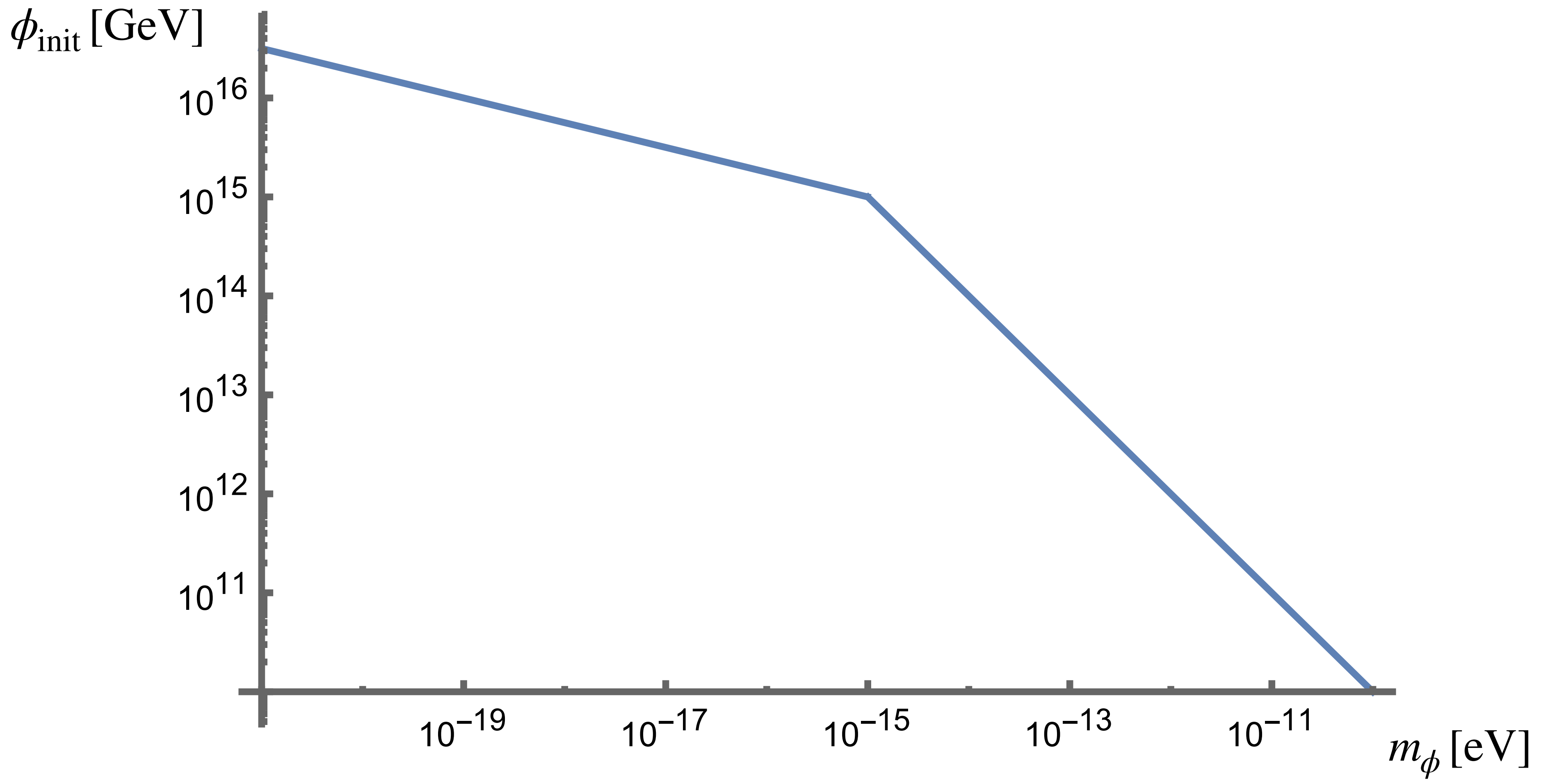
$$\phi(t) \approx \phi_0 \left(\frac{a_i}{a}\right)^{\frac{3}{2}} \cos(m_\phi t)$$

Implication for ultralight dark matter (UDM) cosmology

- What is the impact of the scalar field behavior $[\phi(t) \approx \phi_0 \left(\frac{a_i}{a}\right)^{\frac{3}{2}} \cos(m_\phi t)]$ on the cosmology:

  (i) The EOS satisfies $w_\phi = p_\phi/\rho_\phi = 0,$ and the energy density scales as $\rho_\phi \propto a^{-3}$ <=> ordinary matter

  (ii) The density goes like amplitude square, $\rho_\phi \sim \phi_0^2 \left(\frac{a}{a_{\rm osc}}\right)^{-3}$ => the DM density is mapped to initial value, ϕ_0 :



$$\phi_{\rm init} \equiv \theta f\,(f_{\rm min}) = \begin{cases} 10^{18}\,{\rm GeV} \left(\frac{10^{-27}\,{\rm eV}}{m_\phi}\right)^{\frac{1}{4}} & m_\phi \lesssim 10^{-15}\,{\rm eV} \\ 10^{15}\,{\rm GeV} \left(\frac{10^{-15}\,{\rm eV}}{m_\phi}\right) & m_\phi \gtrsim 10^{-15}\,{\rm eV} \end{cases}$$

[assuming ("best case") MeV reheating]

  (iii) Can be it considered as a classical field? $N_\phi^{\rm occup} \sim 10^3 \times \left(\frac{\rm eV}{m}\right)^4$ => sub-eV UDM behaves classically

Ultralight scalar => simplest dark matter (DM) model

- A sub-eV misaligned homogeneous scalar field => viable DM model
- Its amplitude oscillates with frequency equal to its mass, $w \sim \mathrm{Hz} \times \frac{m_\phi}{10^{-15}\,\mathrm{eV}}$
- However, this field has no coupling to us (apart from gravitational), how can we search for it?
- A minimal plausible assumption is that it'd couple to us suppressed by some very high scale (Planck suppressed?), which are extremely weak, for instance:

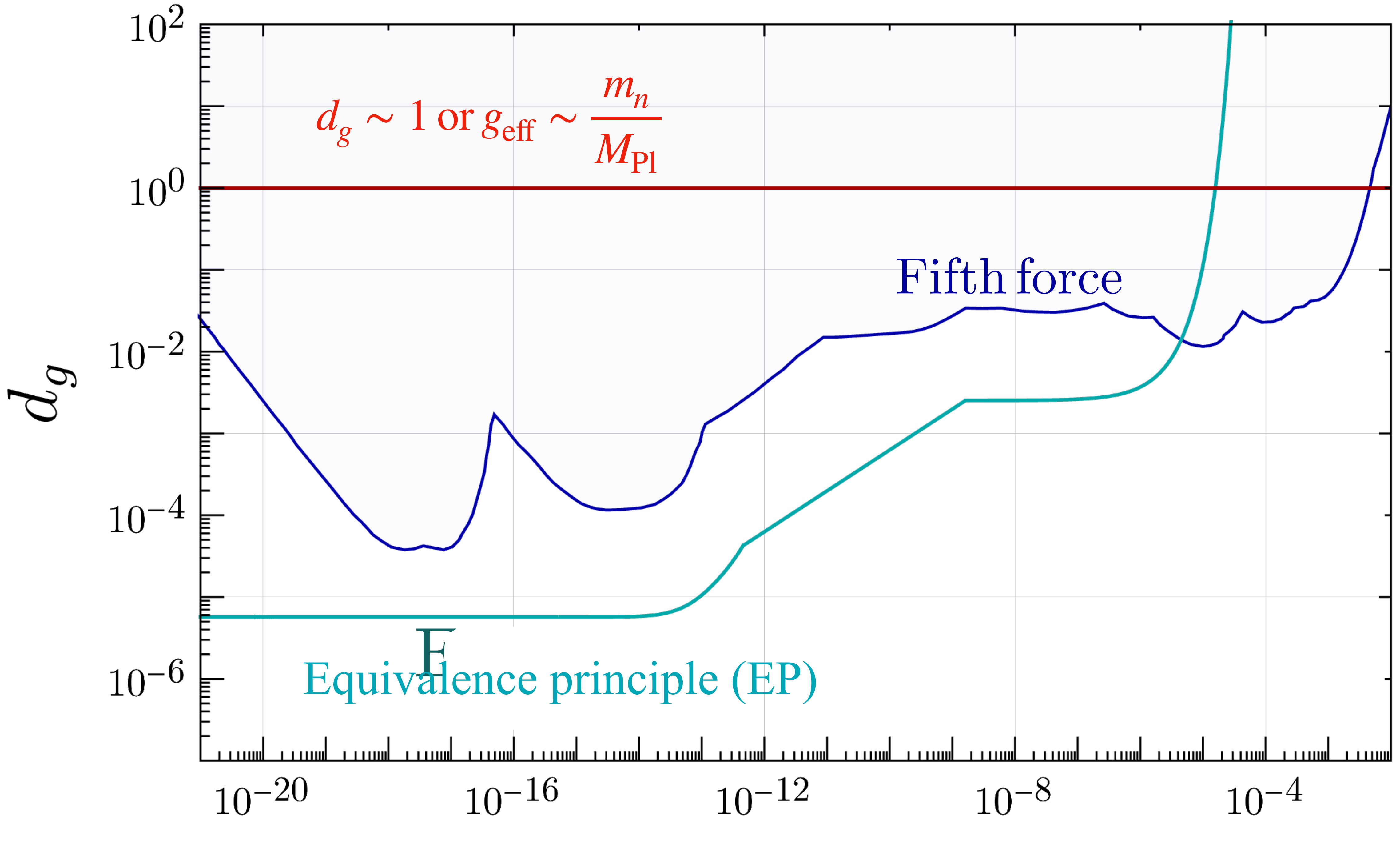
scalar coupling effecting energy levels

pseudo-scalar axial coupling magnetic/spin-observables

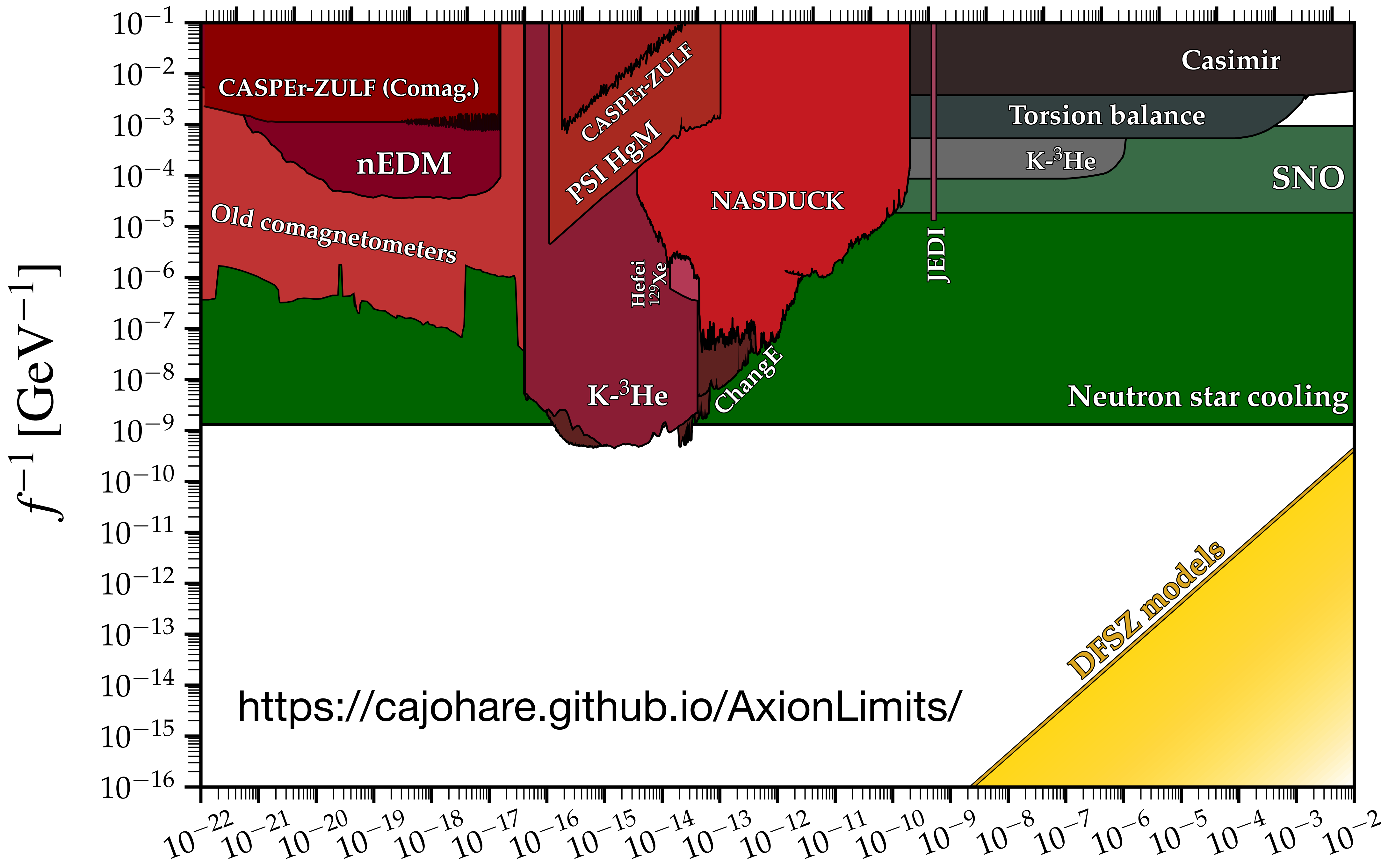
$$\mathscr{L}_{\mathrm{Pl}} \in d_g \frac{\alpha_s}{\pi} \frac{\phi}{M_{\mathrm{Pl}}} GG + \frac{a}{32\pi^2 f} G\tilde{G} \implies d_g \frac{m_n}{M_{\mathrm{Pl}}} \phi\, \bar{n} n + \frac{m_n}{f} a\, \bar{n}\gamma_5 n$$

Scalar coupling vs/ pseudo-scalar axial coupling

$$\mathscr{L}_{\rm Pl} \in d_g \frac{\phi}{M_{\rm Pl}} \frac{\alpha_s}{\pi} GG \implies d_g \frac{m_n}{M_{\rm Pl}} \phi\, \bar{n} n$$



$$\mathscr{L}_{\rm axion} \in \frac{a}{32\pi^2 f} G\tilde{G} \implies \frac{m_n}{f} a\, \bar{n}\gamma_5 n$$

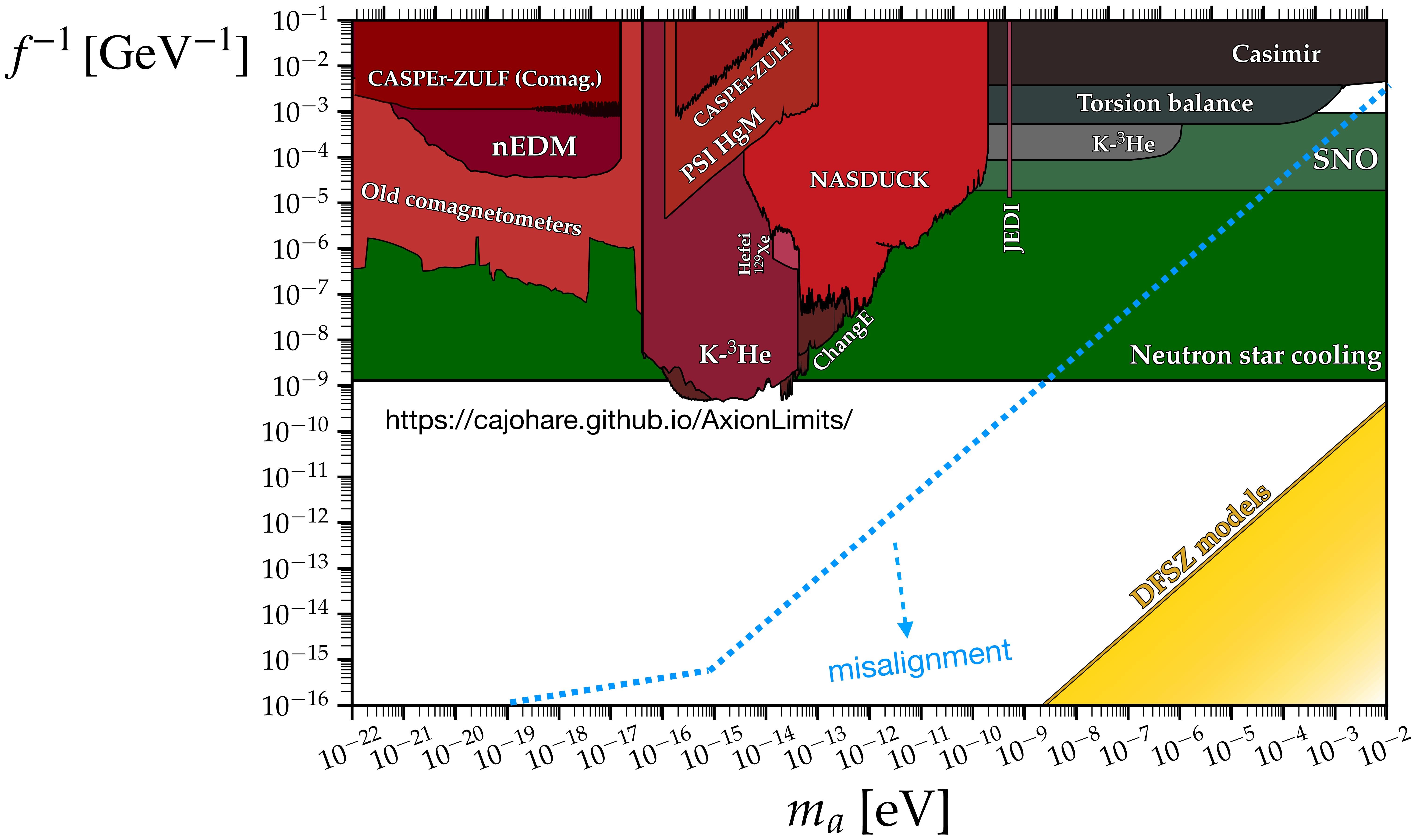


EP: Planck suppressed operators excluded for $m_\phi \lesssim 10^{-5}$ eV
5th force: operators are excluded for $m_\phi \lesssim 10^{-3}$ eV

Bounds only constrain coupling that are $\sim 10^{12}$ weaker than the Planck scale

Status of ultralight dark matter (UDM) pseudoe-scalar axial coupling

$$\mathscr{L}_{\text{axion}} \in \frac{a}{32\pi^2 f} G\tilde{G}$$



Bounds are significantly weaker than scalar ones & in most regions far from probing minimal misalignment ULDM models

Axion - the scalar way, the power of clocks #1

- Maybe should accept that probing axions is work in progress (new proposals)
- The sensitivity to scalar interaction is **10^{12}** stronger, can we use it?
- Axion models do predict quadratic scalar coupling that are suppressed however by m_a^2/f^2 => hopeless to probe

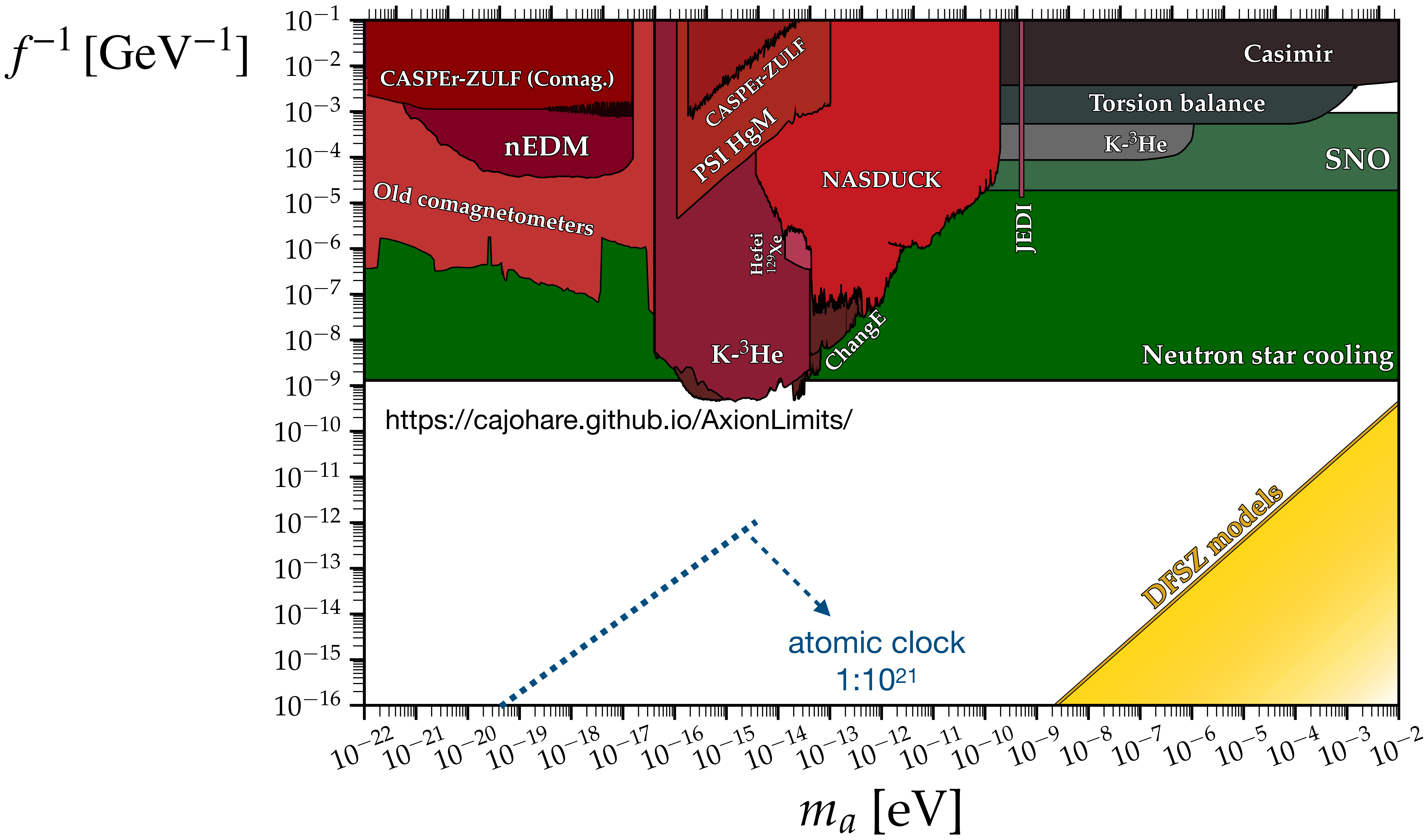
Banerjee, GP, Safronova, Savoray & Shalit (22)

- Yet, in the case of QCD-like-axion only suppressed by $\frac{\partial \ln m_\pi}{\partial \theta^2} \sim \frac{m_{u,d}}{\Lambda_{\mathrm{QCD}}}\,, \quad \theta = a/f$
- Target for clocks $\mathrm{MeV} \times \theta^2 \bar{n}n \Rightarrow \frac{\delta f}{f} \sim \frac{\delta m_N}{m_N} \sim 10^{-16} \times \cos(2m_a) \times \left(\frac{10^{-15}\,\mathrm{eV}}{m_\phi} \frac{10^9\,\mathrm{GeV}}{f} \right)^2$

Kim & GP (22)

Axion - the scalar way, the power of clocks #1

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



Naively: clocks can efficiently search for the oscillating signal of a light QCD-like-axion

Axion - the scalar way, the power of clocks #2, stochasticity

- Due to velocity dispersion, $\theta^2(t)$ => sharp resonance + continuum at lower frequencies

Masia-Roig et. al (23)

- To understand qualitatively, let's consider first linear coupling, say that changes α:

$$\delta E(t) \leftrightarrow m_e \alpha^2 (1 + \theta(t)) \propto \frac{\sqrt{\rho_{\rm DM}}}{m_a} \cos wt \,,\text{ with } w \approx m_a \left(1 + \frac{v^2}{2}\right), \text{ and } P(v) \propto \exp\left(\frac{-v^2}{\sigma^2}\right), \text{ with } \sigma \sim 10^{-3}$$

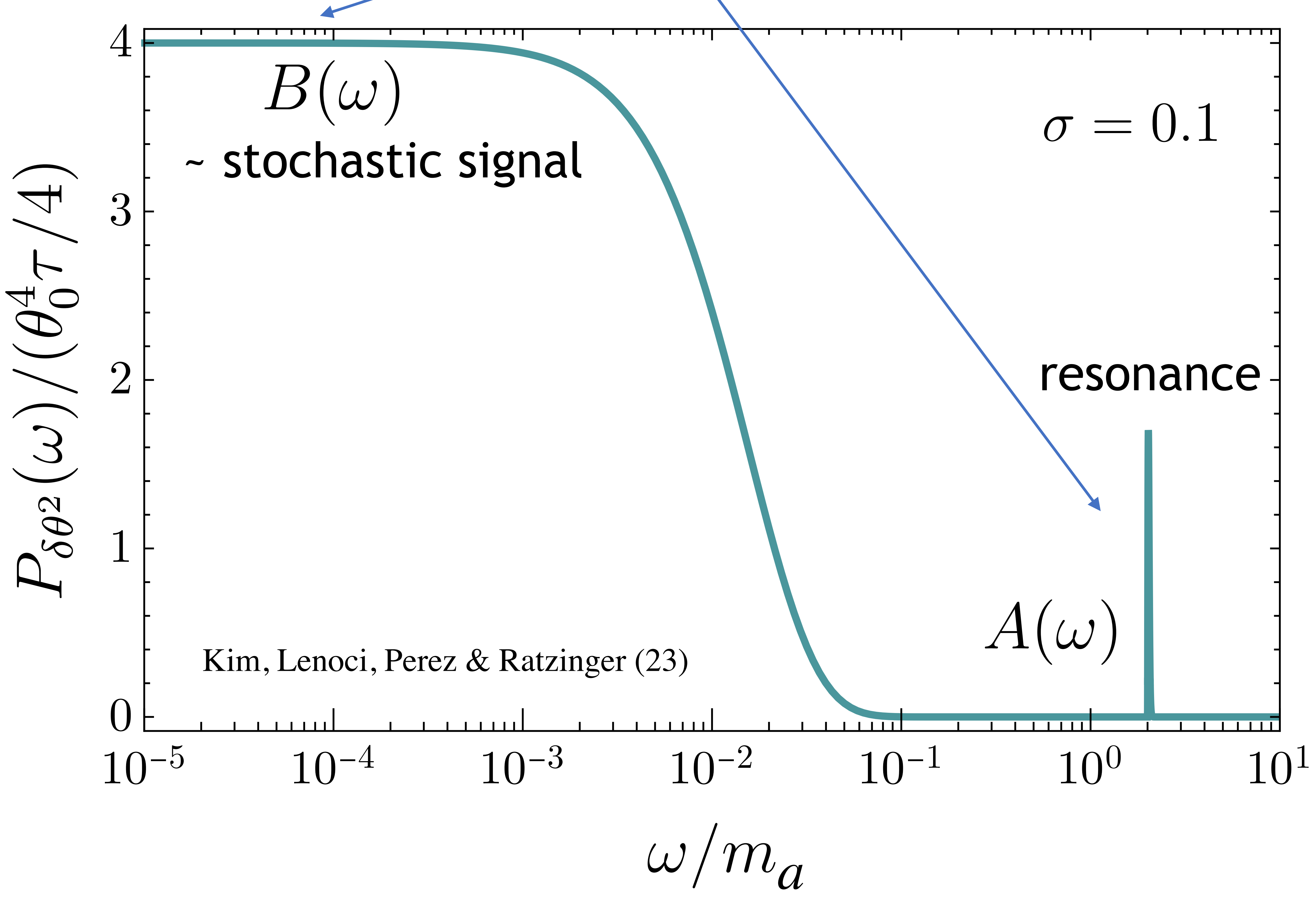
- Frequency transformed: it would result in a sharp signal at $\omega \sim m_a$ with width of $O\left(10^{-6}\right)$

- However our signal is quadratic $\delta E(w) \propto \int \delta E(t)\, e^{iwt}\, \theta(t)^2 dt \sim \delta(w - 2m_a) + F(w, m_a, \sigma)$

$$F(w, m_a, \sigma) \propto \int e^{iwt}\, P(v_1)\, P(v_2)\, \cos\left[m_a\left(\frac{v_1^2 - v_2^2}{2}\right)t\right]\, dt\, d\vec{v}_1\, d\vec{v}_2$$

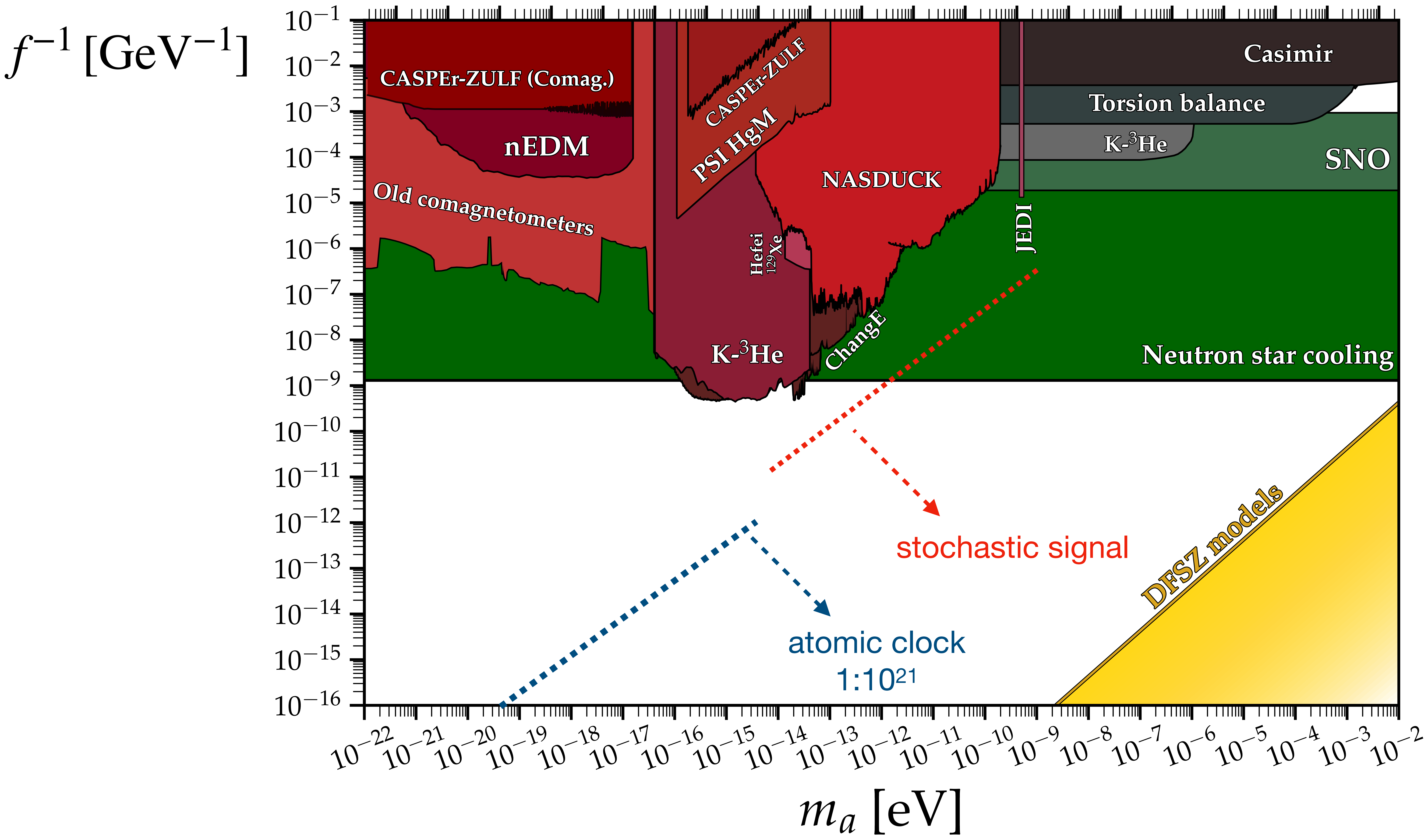
Power spectrum of quadratic (axion) UDM

$$\delta E(w) \propto \delta(w - 2m_a) + F(w, m_a, \sigma)$$



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

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



Naively: clocks can efficiently search for the oscillating signal of a light QCD-like-axion

Searching for scalar coupling to the strong/nuclear sector - a key for progress - large class of UDM models

- QCD axion models: $\frac{a}{f} G\tilde{G} \quad \Rightarrow \quad \left(\frac{a}{f}\right)^2 \bar{n}n$

- Dilaton: $d_g \frac{\alpha_s}{\pi} \frac{\phi}{M_{\rm Pl}} GG \quad \Rightarrow \quad d_g \frac{\phi}{M_{\rm Pl}} \frac{m_N}{M_{\rm Pl}} \bar{n}n$

  see however Hubisz, Ironi, GP & Rosenfeld (24)

- Higgs-mixing / relaxion: $\sin\theta_{H\phi} \frac{\alpha_s}{4\pi v} H\,GG \quad \Rightarrow \quad \sin\theta_{H\phi} \frac{\phi}{v} m_N \bar{n}n$

  Piazza and M. Pospelov (10); Banerjee, Kim & GP (19)

- Nelson-Barr UDM: $\left(\epsilon_{\rm NB} = \frac{y_s^2 V_{us}^2}{16\pi^2}\right) \frac{\phi}{f} m_u \bar{u}u \quad \Rightarrow \quad \epsilon_{\rm NB} \frac{\phi}{f} m_u \bar{n}n$

  \w Dine, Ratzinger & Savoray, tomorrow?

$\vdots$

Why probing the strong sector \w clocks is challenging ?

To understand let’s talk about how clocks probe DM

(theorist’s perspective - simplified model …)

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

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

$$|\langle\psi^+(t=0)\,|\,\psi^+(t)\rangle|^2 = \cos\left(\frac{\Delta E t}{2}\right)^2 \quad \text{<=>} \quad \text{perfect pendulum}$$

Clocks and ultralight DM (UDM) search?

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

- 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 couples to F^2 or to the electron would induce oscillatory component: $\Delta E \propto \left[\text{const} + \frac{\sqrt{2\rho}}{m_{\text{UDM}}}\cos\left(m_{\text{UDM}}\,t\right)\right]$ which atomic clocks can sense

Observables directly probing coupling to QCD/nuclear sector

- Regular transition are sensitive to the reduced mass:

$$\Delta E \propto m_{\text{reduced}}\,\alpha^2\,, \quad m_{\text{reduced}} \approx m_e\left(1 - \frac{m_e}{m_{\text{nuc}}}\right), \text{ however } \frac{m_e}{Am_p} \sim 10^{-5} \quad (A \text{ is number of nucleons})$$

- Hyperfine clocks via the *g*-factor, however their sensitivity is "only" 1:10^12-14

- One can use vibrational modes in molecules, scales like $\sqrt{\frac{m_e}{Am_p}} \sim 10^{-3}$

In vapor see: Oswald, Nevsky, Vogt, Schiller, Figuerora, Zhang, Tretiak, Antypas, Budker, Banerjee & GP (21) In corr. spec.: Madge, GP, Meir (last month)

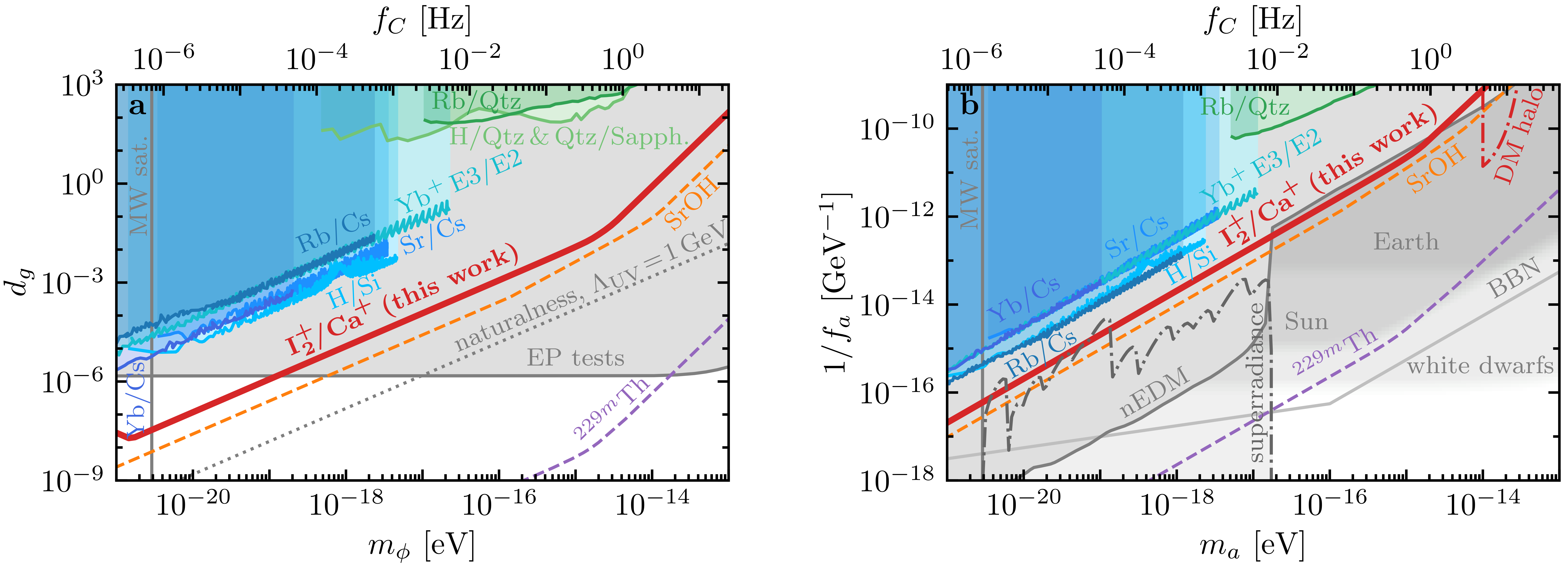
- Or charge radius effect, scales like $A^{8/3}\alpha\left(\frac{m_{\text{Bohr}}}{m_p}\right)^3$

Banerjee, Budker, Filzinger, Huntemann, Paz, GP, Porsev & Safronova (23)

All result with a suppression factor, $R_{\text{atom}} \sim 10^{3-5}$

Observables directly probing coupling to QCD/nuclear sector

Madge, GP, Meir (24)



Bottomline: accessing the nucleus is hard \w atomic clocks, sensitivity suppressed by $R_{\text{atom}} \sim 10^{3-5}$

Why all of this is about to change by potentially improving the sensitivity by a factor of $10^{8\text{-}10}$?

Laser excitation of the Th-229 nucleus

(*i*) on the sensitivity and its robustness

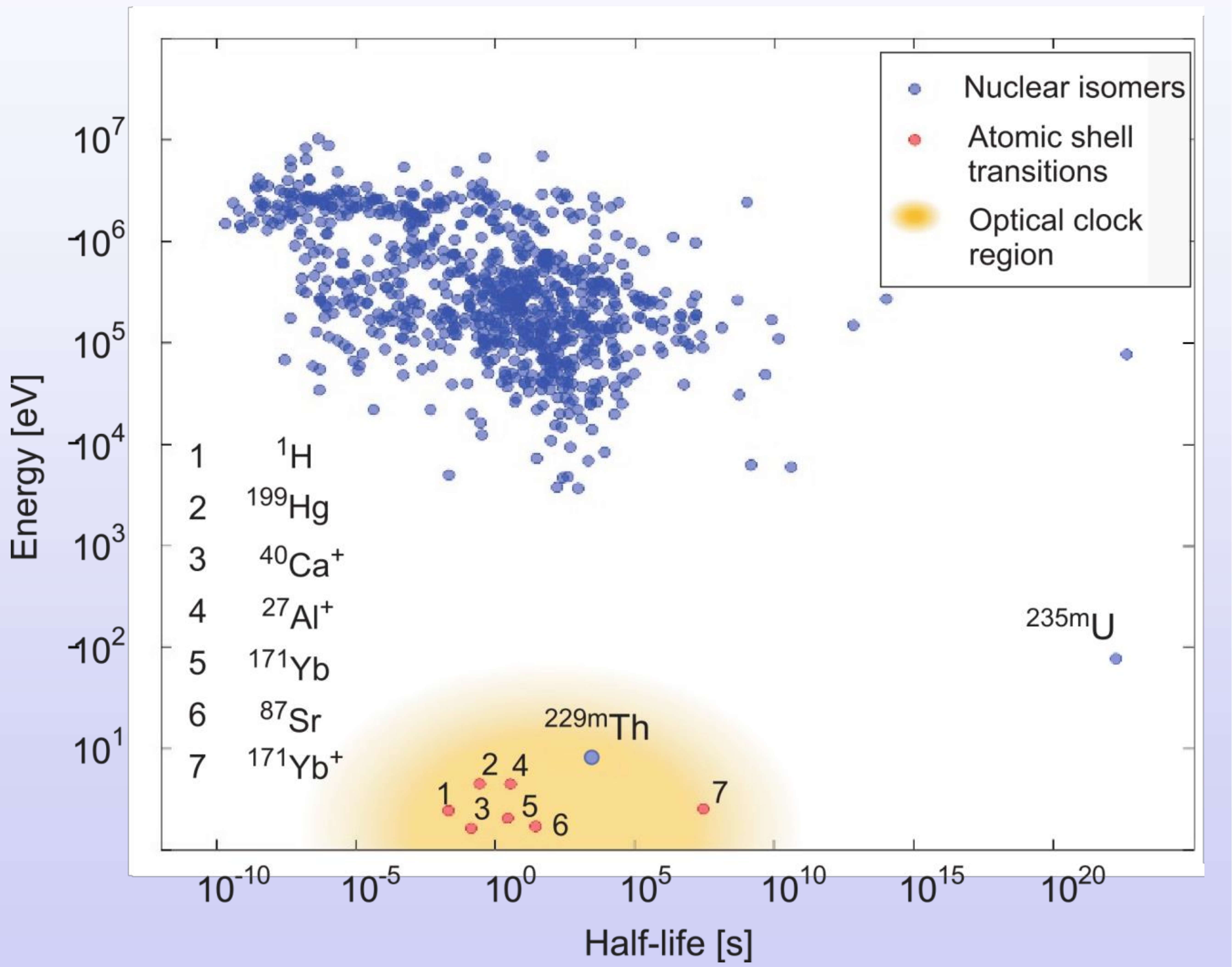
with: Doron Gazit, Joachim Kopp , Gil Paz & Konstantin Springmann …

(*ii*) BSM implications

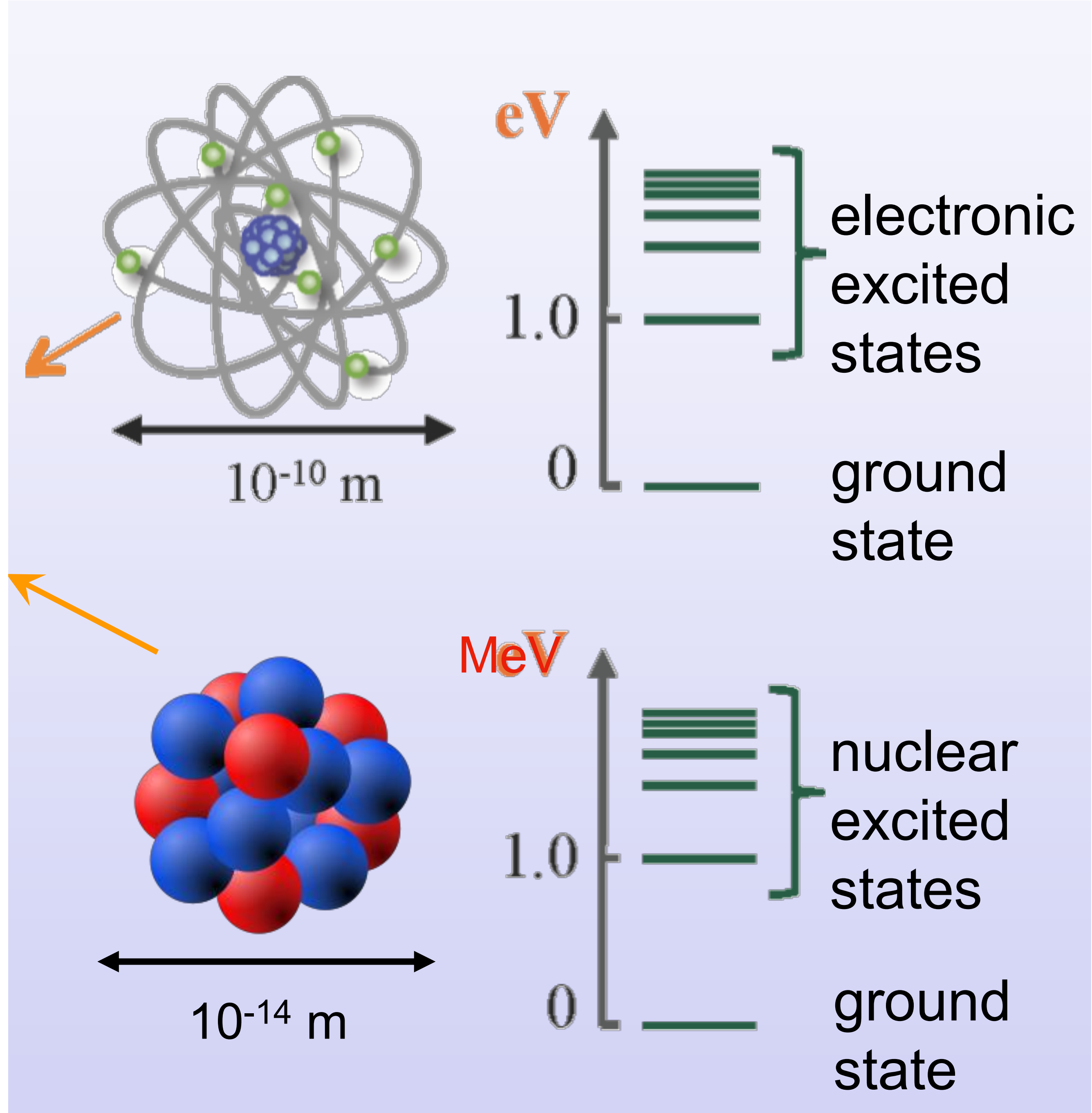
with: Elina Fuchs, Fiona Kirk, Eric Madge, Chaitanya Paranjape, Ekkehard Peik & Wolfram Ratzinger

Natural fine tuning, Th-229 isomeric excitation

Peter G. Thirolf: MIAPbP Workshop: Quantum Sensors, Garching, 28.8.-8.9.2

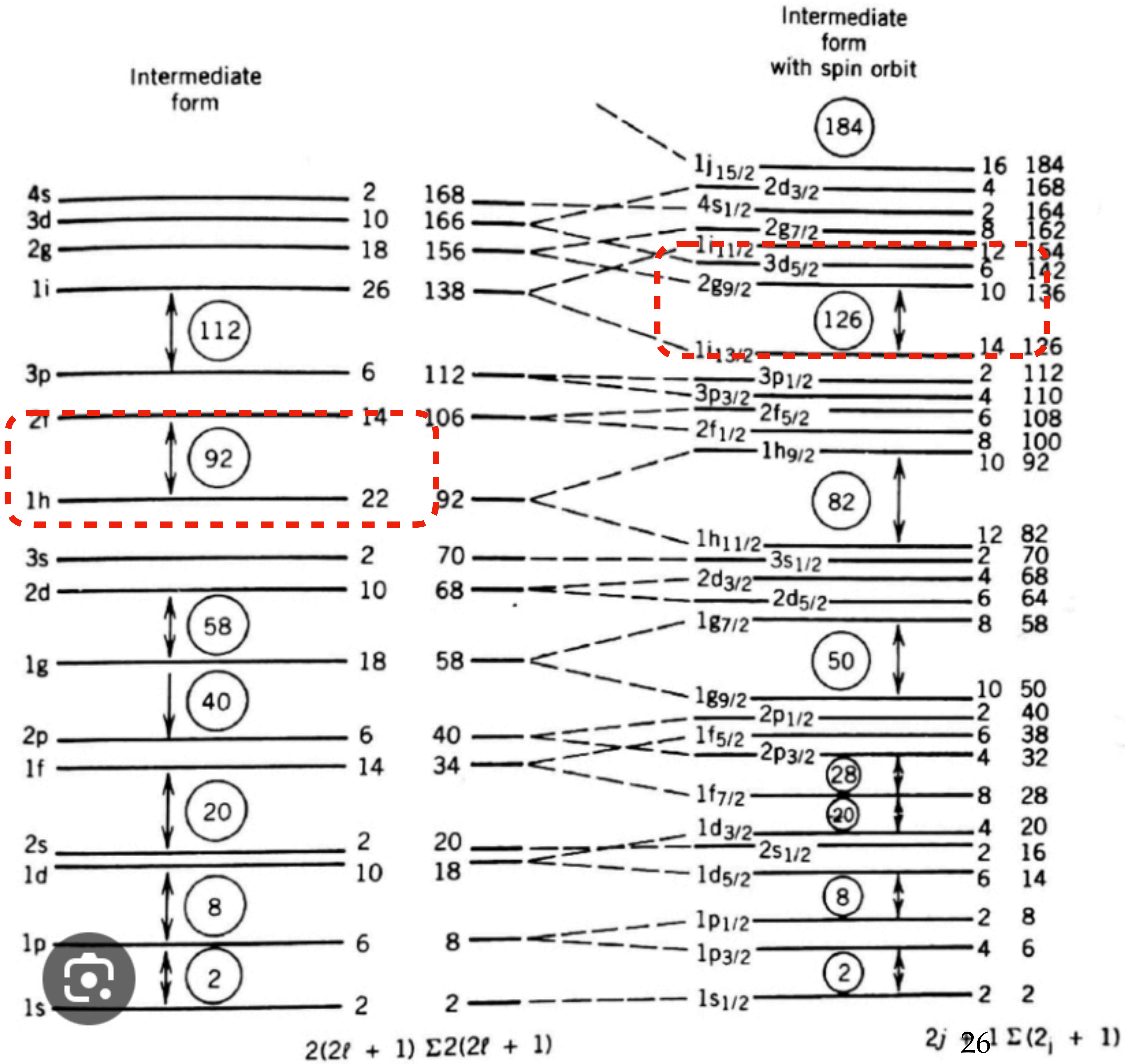


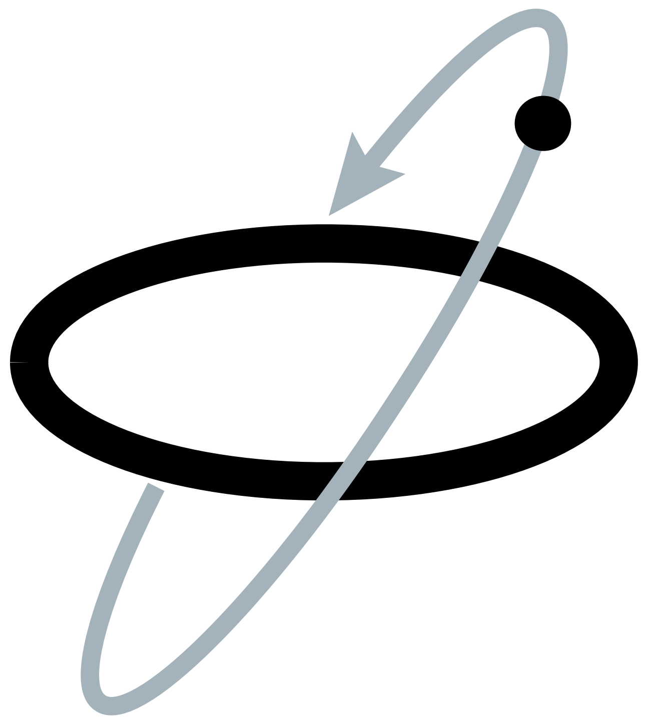
lowest E* of all ca. 186000 presently known nuclear excited states



Th-229 shell's structure, one unpaired neutron, the transition

90 *protons*, 139 *neutrons*

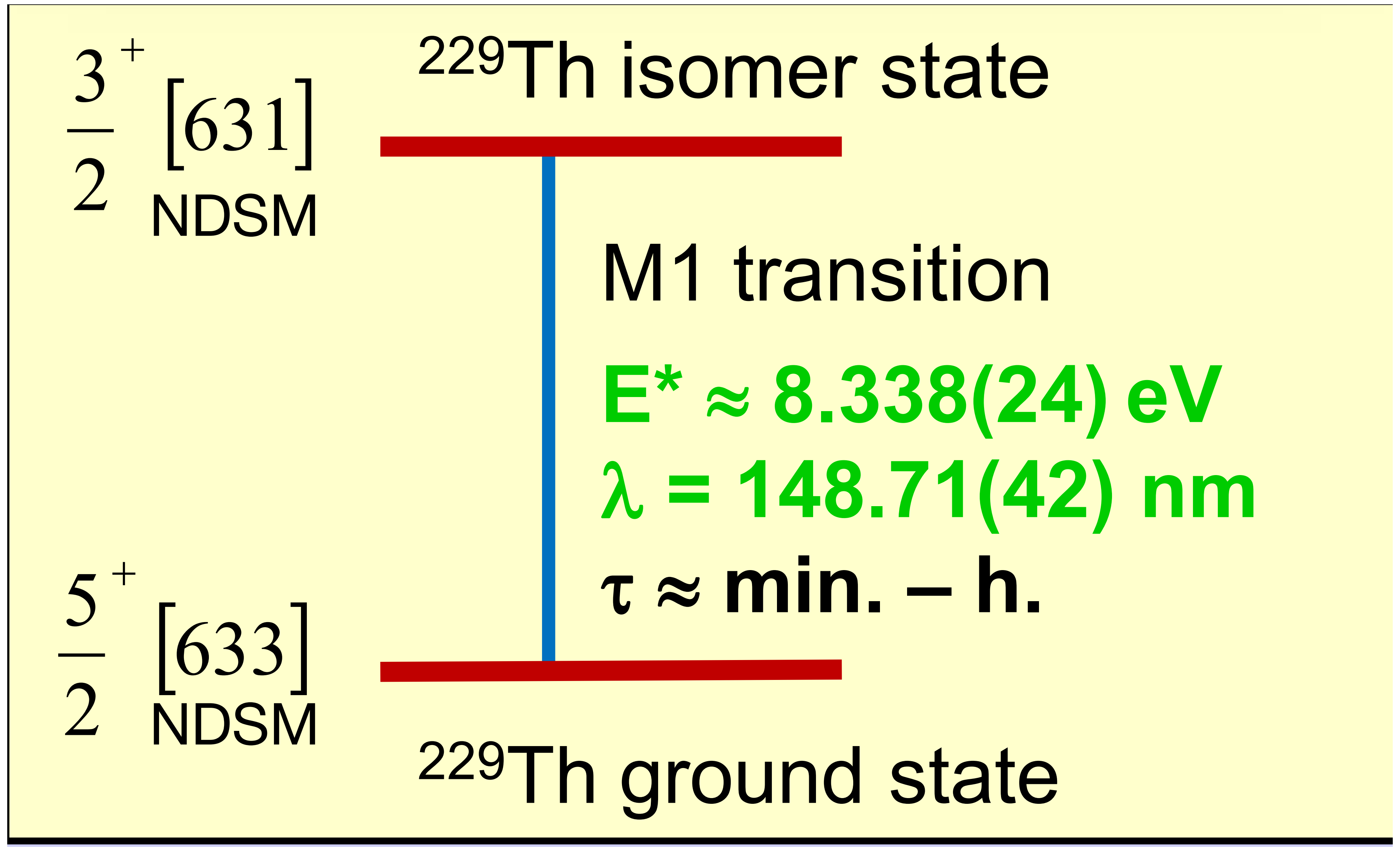




The nuclear level structure "can be described"

in terms of an elliptic core and an unpaired neutron

Beeks et al: Nat. Rev. (21)



The (other) April revolution?

Laser Excitation of the Th-229 Nucleus

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(Received 5 February 2024; revised 12 March 2024; accepted 14 March 2024; published 29 April 2024)

The 8.4 eV nuclear isomer state in Th-229 is resonantly excited in Th-doped CaF_2 crystals using a tabletop tunable laser system. A resonance fluorescence signal is observed in two crystals with different Th-229 dopant concentrations, while it is absent in a control experiment using Th-232. The nuclear resonance for the Th^{4+} ions in Th:CaF_2 is measured at the wavelength 148.3821(5) nm, frequency 2020.409(7) THz, and the fluorescence lifetime in the crystal is 630(15) s, corresponding to an isomer half-life of 1740(50) s for a nucleus isolated in vacuum. These results pave the way toward Th-229 nuclear laser spectroscopy and realizing optical nuclear clocks.

April Revolution

Protesters during the April Revolution

Date	April 11–26, 1960
Location	South Korea
Caused by	• Oppression by Syngman Rhee's government • Electoral fraud

Laser excitation of the ^{229}Th nuclear isomeric transition in a solid-state host

R. Elwell,[1] Christian Schneider,[1] Justin Jeet,[1] J. E. S. Terhune,[1] H. W. T. Morgan,[2]
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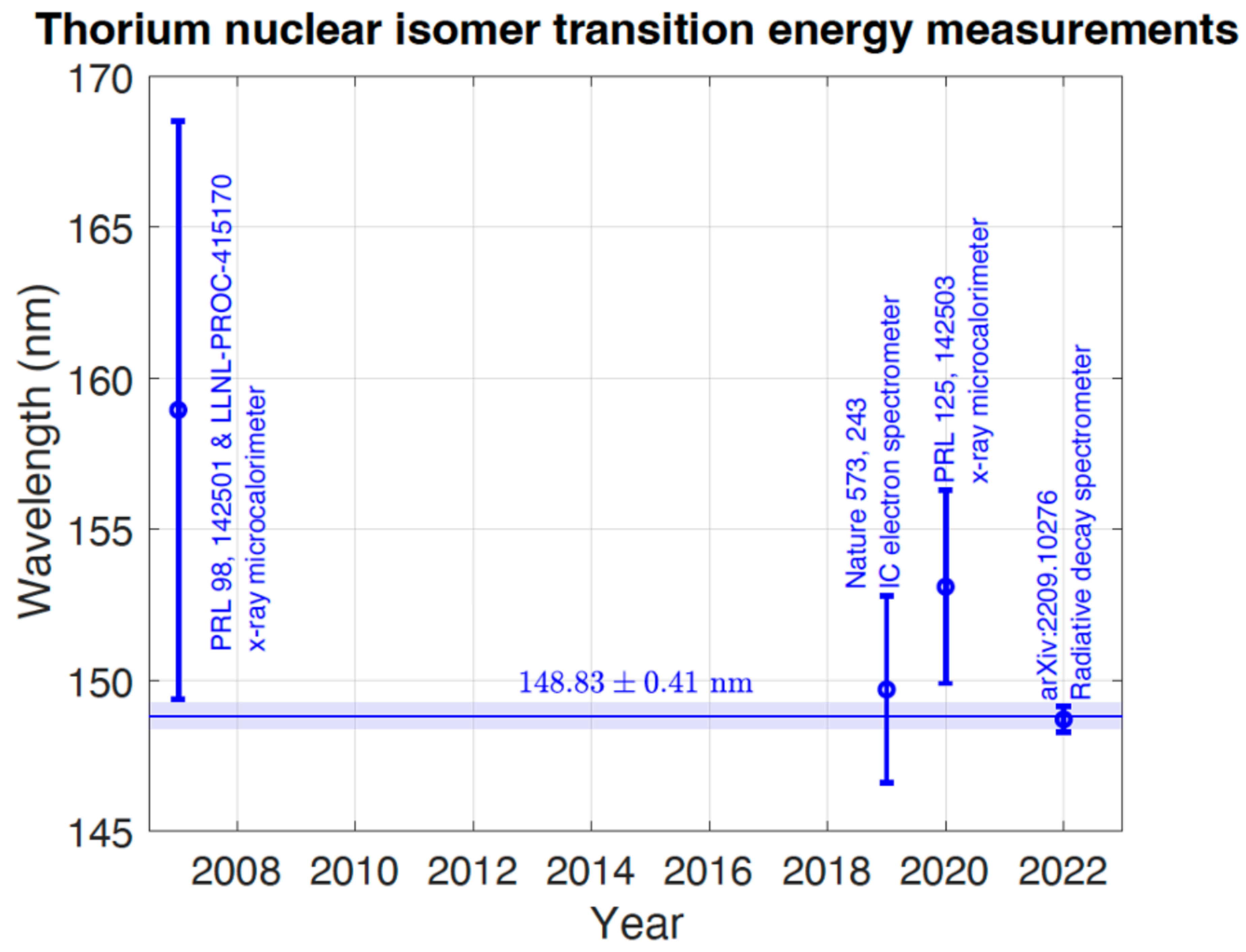
[6] *Center for Quantum Science and Engineering, University of California Los Angeles, Los Angeles, CA, USA*
(Dated: April 19, 2024)

$LiSrAlF_6$ crystals doped with ^{229}Th are used in a laser-based search for the nuclear isomeric transition. Two spectroscopic features near the nuclear transition energy are observed. The first is a broad excitation feature that produces red-shifted fluorescence that decays with a timescale of a few seconds. The second is a narrow, laser-linewidth-limited spectral feature at $148.38219(4)_{stat}(20)_{sys}$ nm ($2020407.3(5)_{stat}(30)_{sys}$ GHz) that decays with a lifetime of $568(13)_{stat}(20)_{sys}$ s. This feature is assigned to the excitation of the ^{229}Th nuclear isomeric state, whose energy is found to be $8.355733(2)_{stat}(10)_{sys}$ eV in ^{229}Th:$LiSrAlF_6$.

Moore's law - quantum sensors

The situation prior to this months' publications:



Peter G. Thirolf: MIAPbP Workshop: Quantum Sensors, Garching, 28.8.-8.9.2

Over the last 2 yrs error on $\delta f/f$ has been reduced to:

0.1 (2020) => 0.001 (2022) => 0.000001 (Apr/24)

Enhanced sensitivity, ^{229}Th

- How to estimate the sensitivity say of UDM that couples only to the QCD sector?
- Let's break the energy difference according to nucl' & Coulomb parts, following the lore:

$$\Delta E_{\rm nu-clock} \sim \Delta E_{\rm nu} - \Delta E_{\rm EM} \sim 8\,{\rm eV} \ll \Delta E_{\rm nu} \sim \Delta E_{\rm EM} \sim \frac{Z^2\,\alpha}{\Lambda_{\rm QCD}\,A^{1/3} \times A} \sim {\rm MeV}$$

Therefore the lore says: $K_{\rm canc} = \Delta E_{\rm nu}/\Delta E_{\rm nu-clock} \sim 10^5 \gg 1$

- Now let's assume that we have a UDM couples only to the QCD sector:

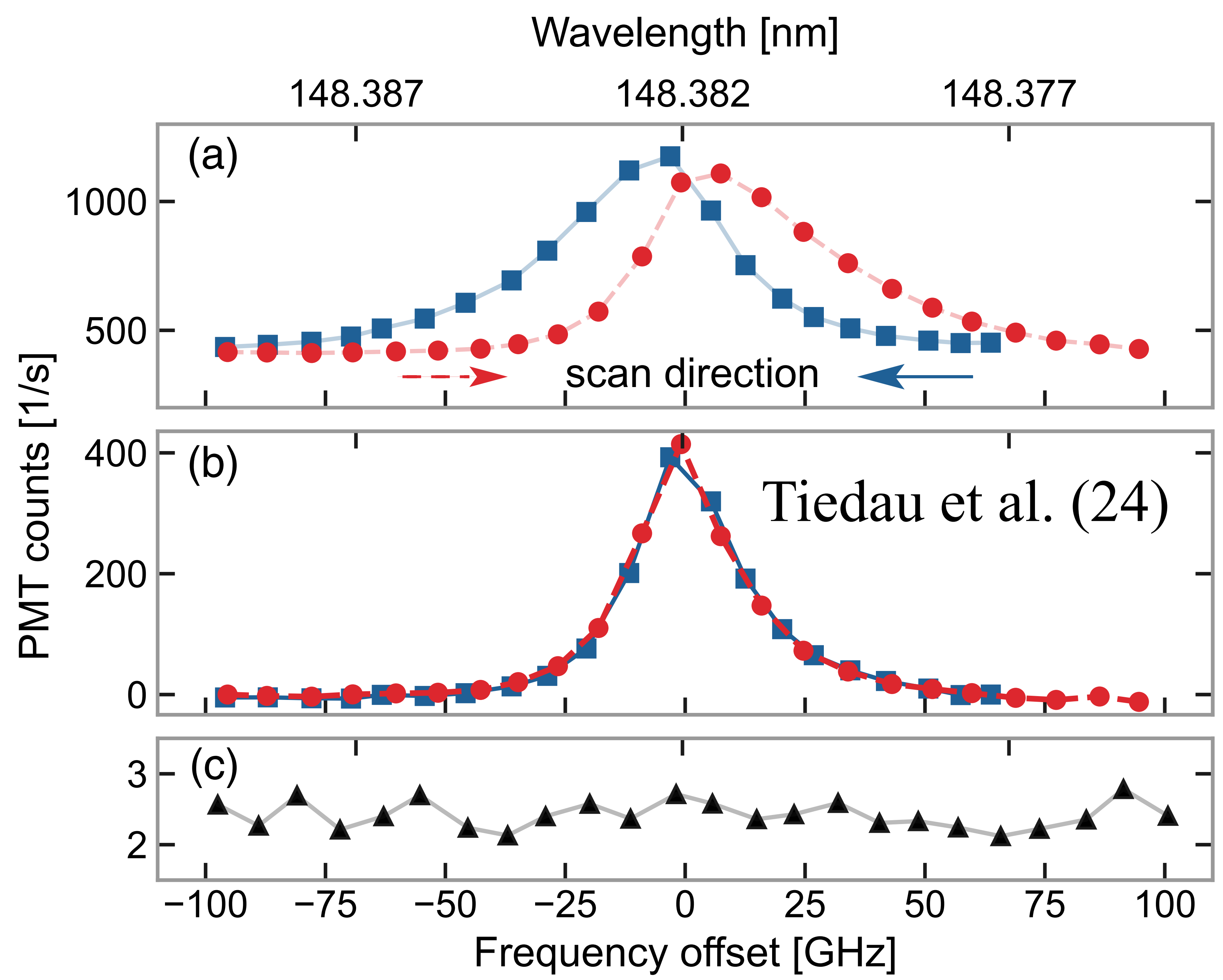
$$\frac{\delta_{\rm UDM}(\Delta E_{\rm nu-clock})}{\Delta E_{\rm nu-clock}} = \frac{\Delta E_{\rm nu}(t) - \Delta E_{\rm EM}}{\Delta E_{\rm nu-clock}} \Rightarrow \frac{\Delta E_{\rm nu}(t)}{\Delta E_{\rm nu-clock}} \sim \frac{\Delta E_{\rm nu}}{\Delta E_{\rm nu-clock}} \times d_g \frac{m_N}{M_{\rm Pl}} \cos(m_\phi t) \sim 10^5 \times d_g \frac{m_N}{M_{\rm Pl}} \cos(m_\phi t)$$

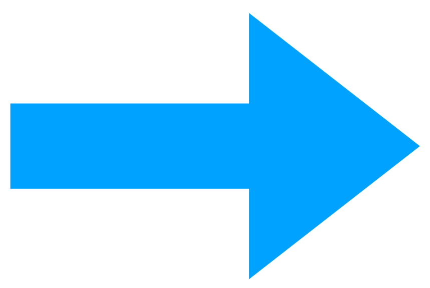
enhancement of $R_{\rm atom} \times K_{\rm canc} \sim 10^{8\text{-}10}$ relative to existing probes of QCD!

What was measured ?

- Used a super broad super powerful laser ~ few GHz to shine on a 229-Th lattice

- Scan the frequencies (width of 10^{-5} to cover region of 0.1 eV!), then after ~ 1000 s got back fluorescence at a specific frequency equal to: 2020.409(3-7) THz resulting with





$$\frac{\delta f}{f} \sim 10^{-6}$$

Present and future implications

with: Elina Fuchs, Fiona Kirk, Eric Madge, Chaitanya Paranjape, Ekkehard Peik & Wolfram Ratzinger

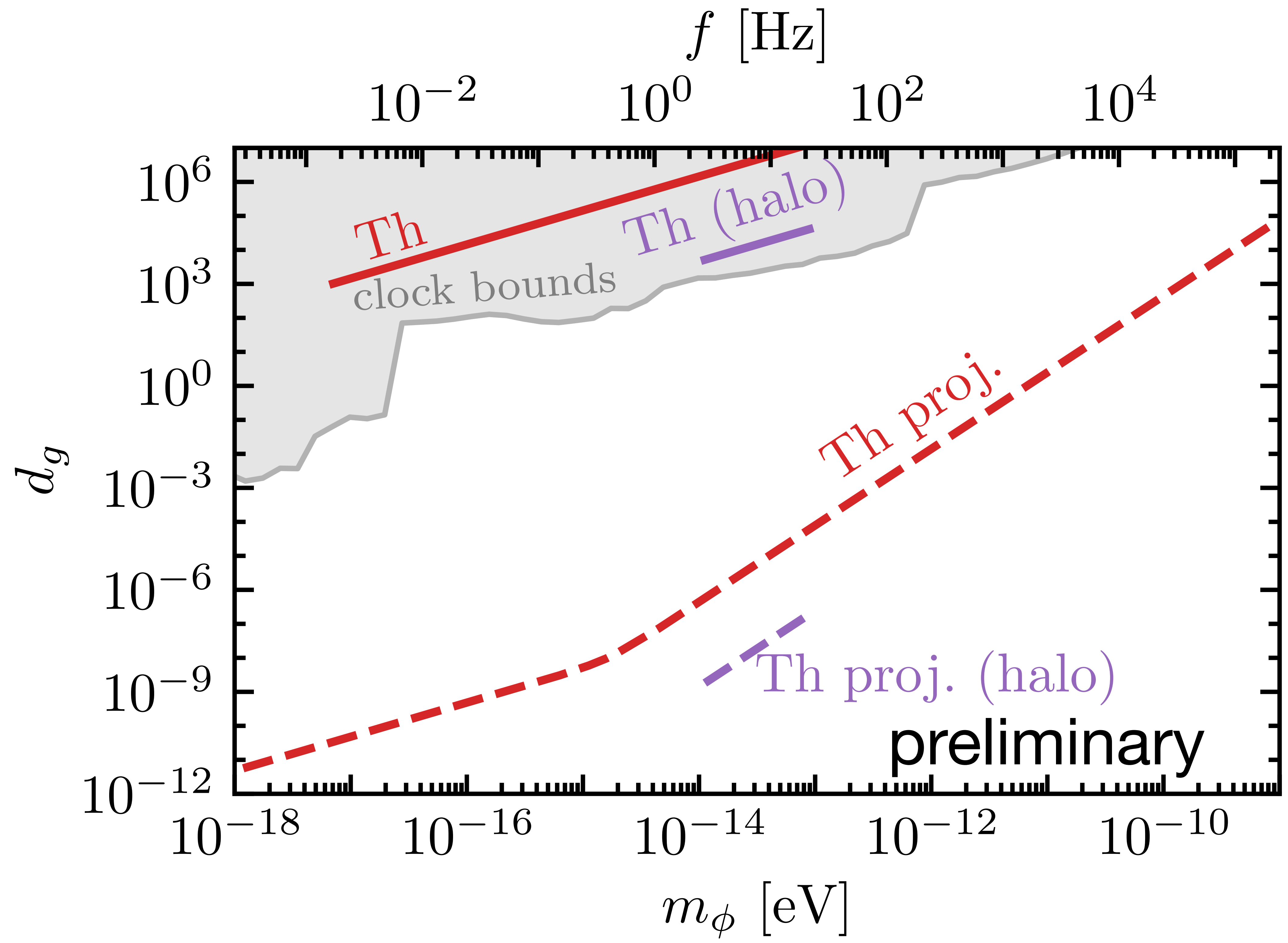
- We have now $\frac{\delta f}{f} \sim 10^{-6}$, effectively this should be translated to effective sensitivity of

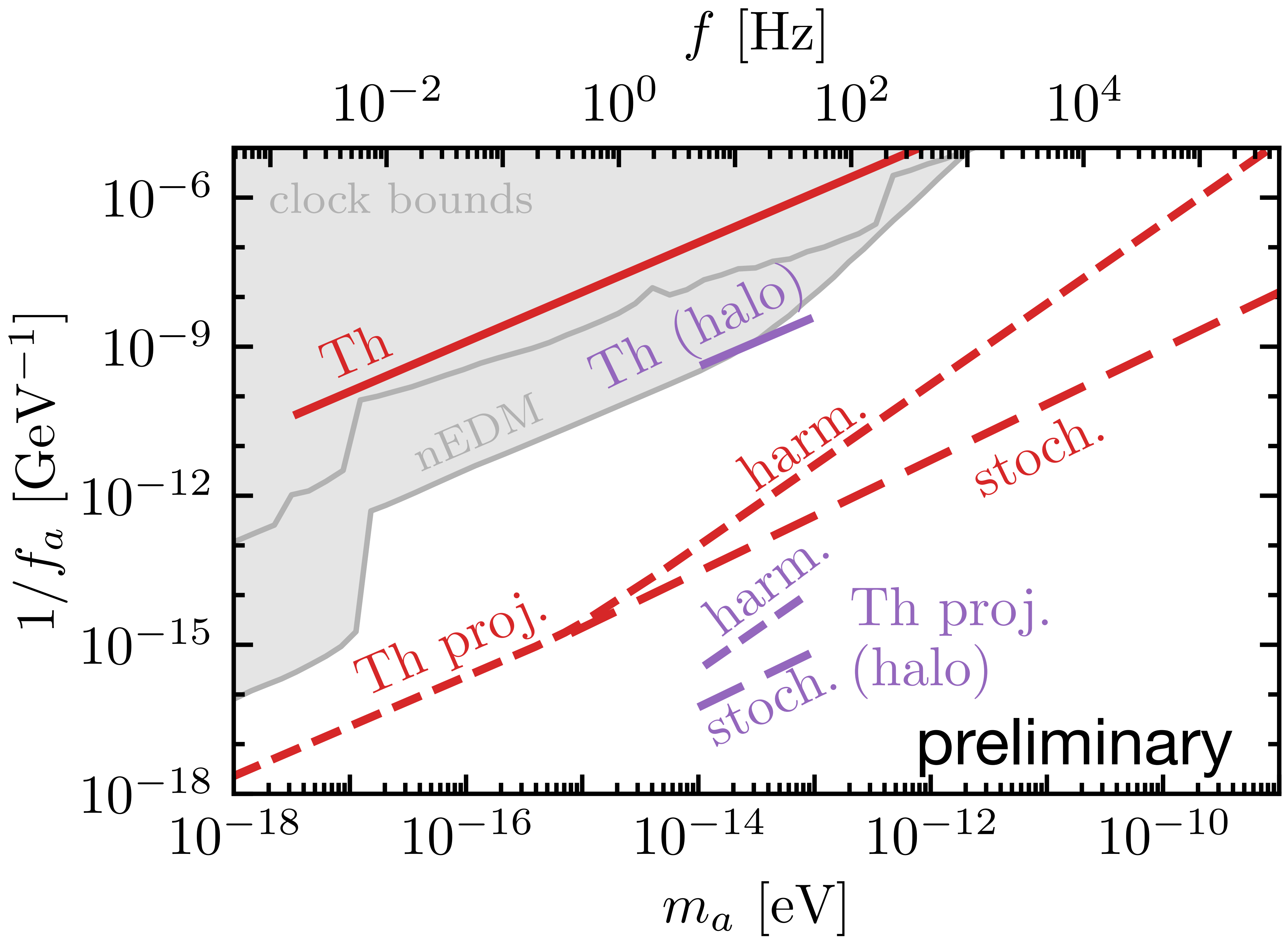
$\frac{\delta f}{f} \times R_{\text{atom}} \times K_{\text{canc}} \sim \; 10^{-14} - 10^{-16}$ of atomic clocks, only 2-3 orders of mag from the frontier

- However, how can we use the existing info?

- Line shape analysis, if the UDM oscillating faster than measurement time it'd lead to broadening of the line beyond what has been observed => new constrain (would take over soon …)

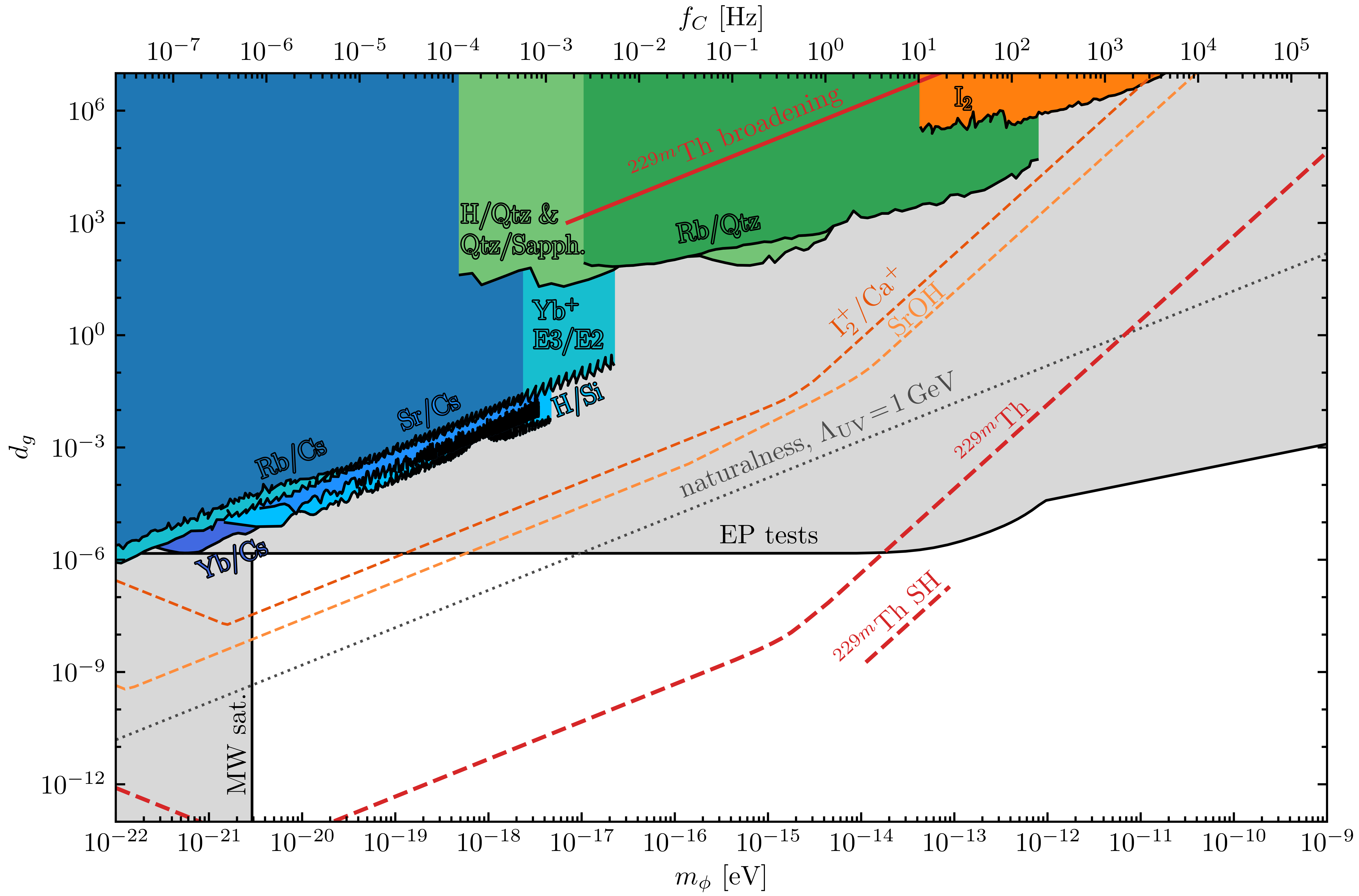
Using Th-229 to search for oscillating UDM signal





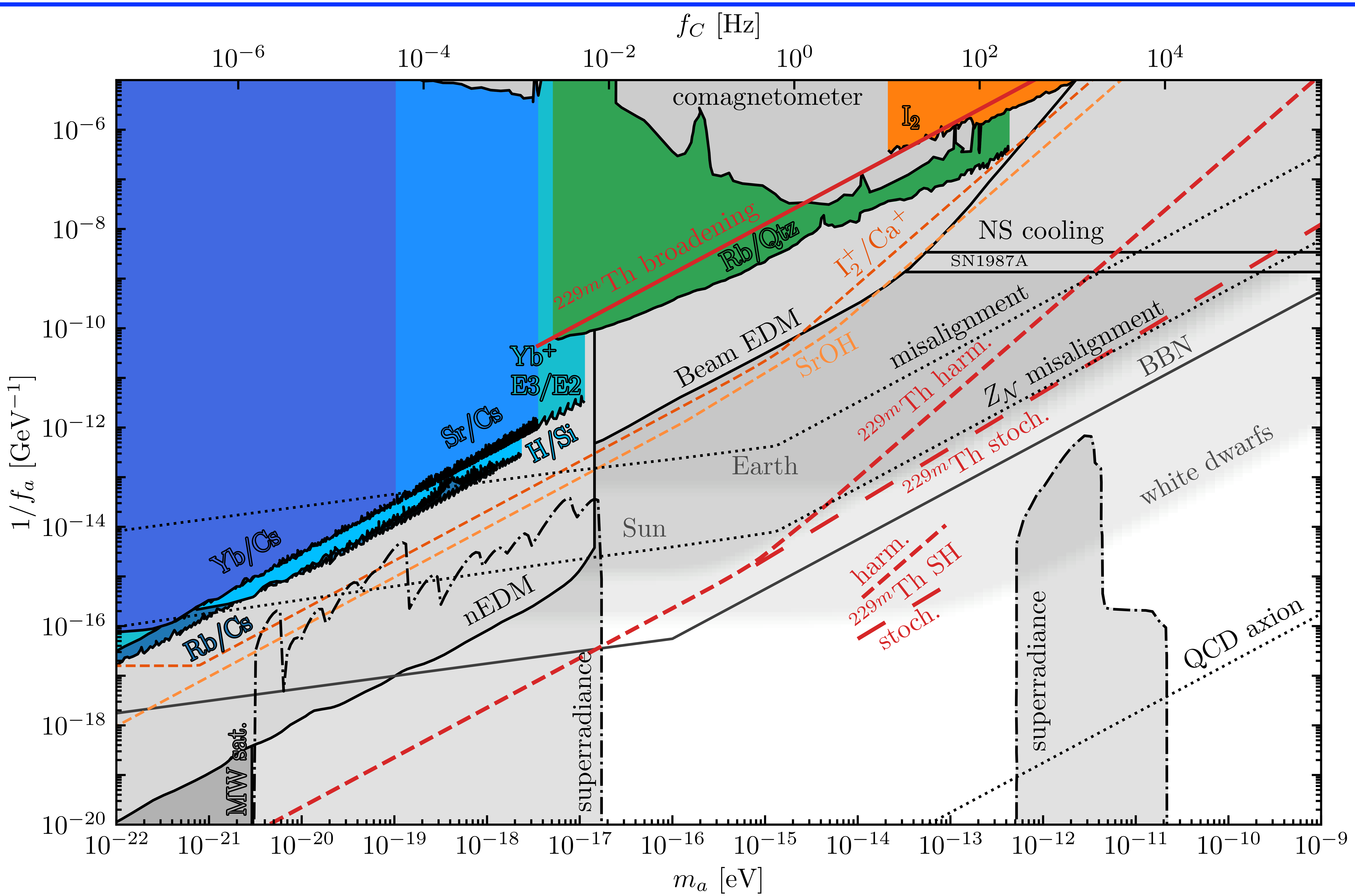
with: Elina Fuchs, Fiona Kirk, Eric Madge, Chaitanya Paranjape, Ekkehard Peik & Wolfram Ratzinger

Scalar coupling to QCD & nuclear clock



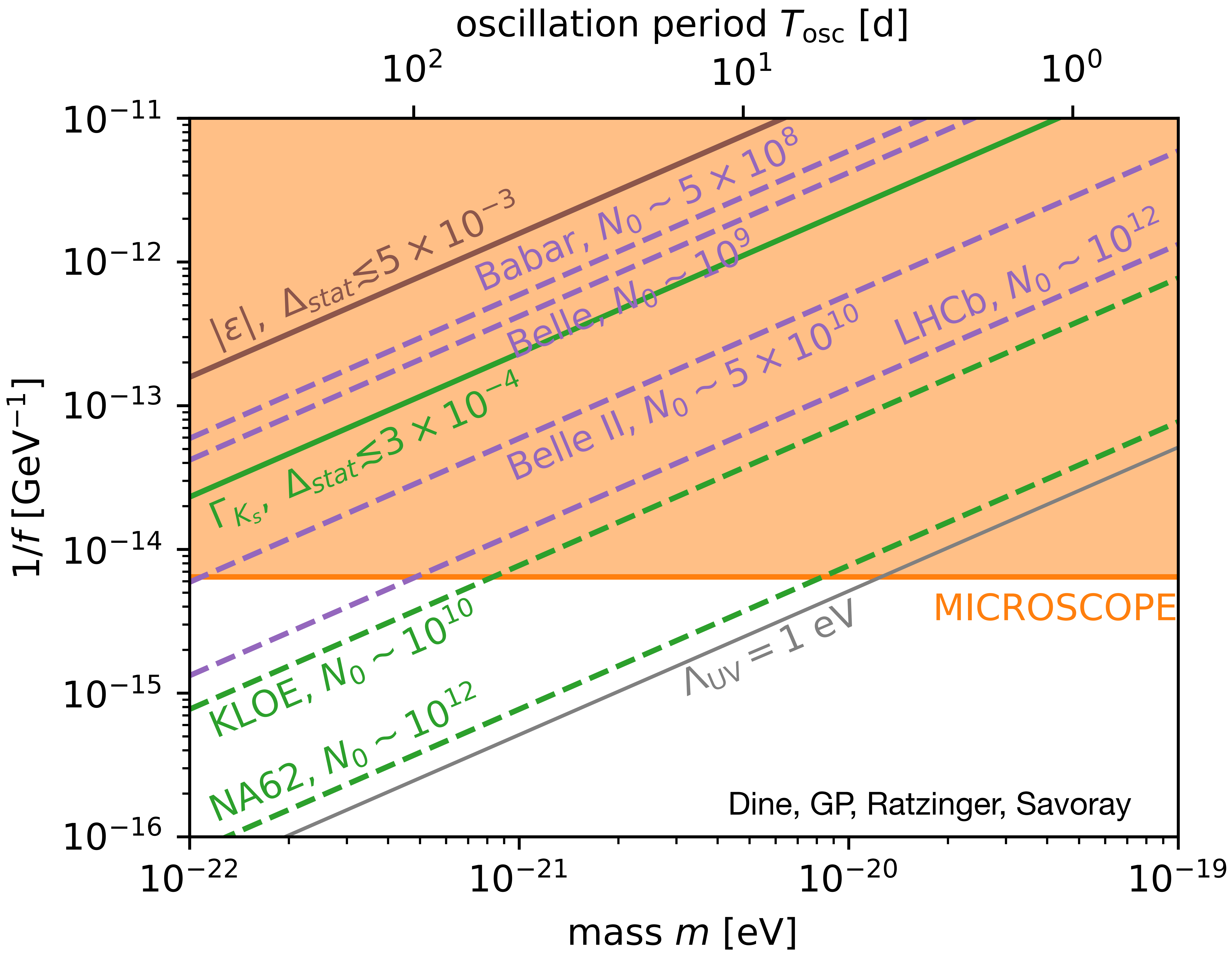
with: Elina Fuchs, Fiona Kirk, Eric Madge, Chaitanya Paranjape, Ekkehard Peik & Wolfram Ratzinger

QCD-axion-like & nuclear clock

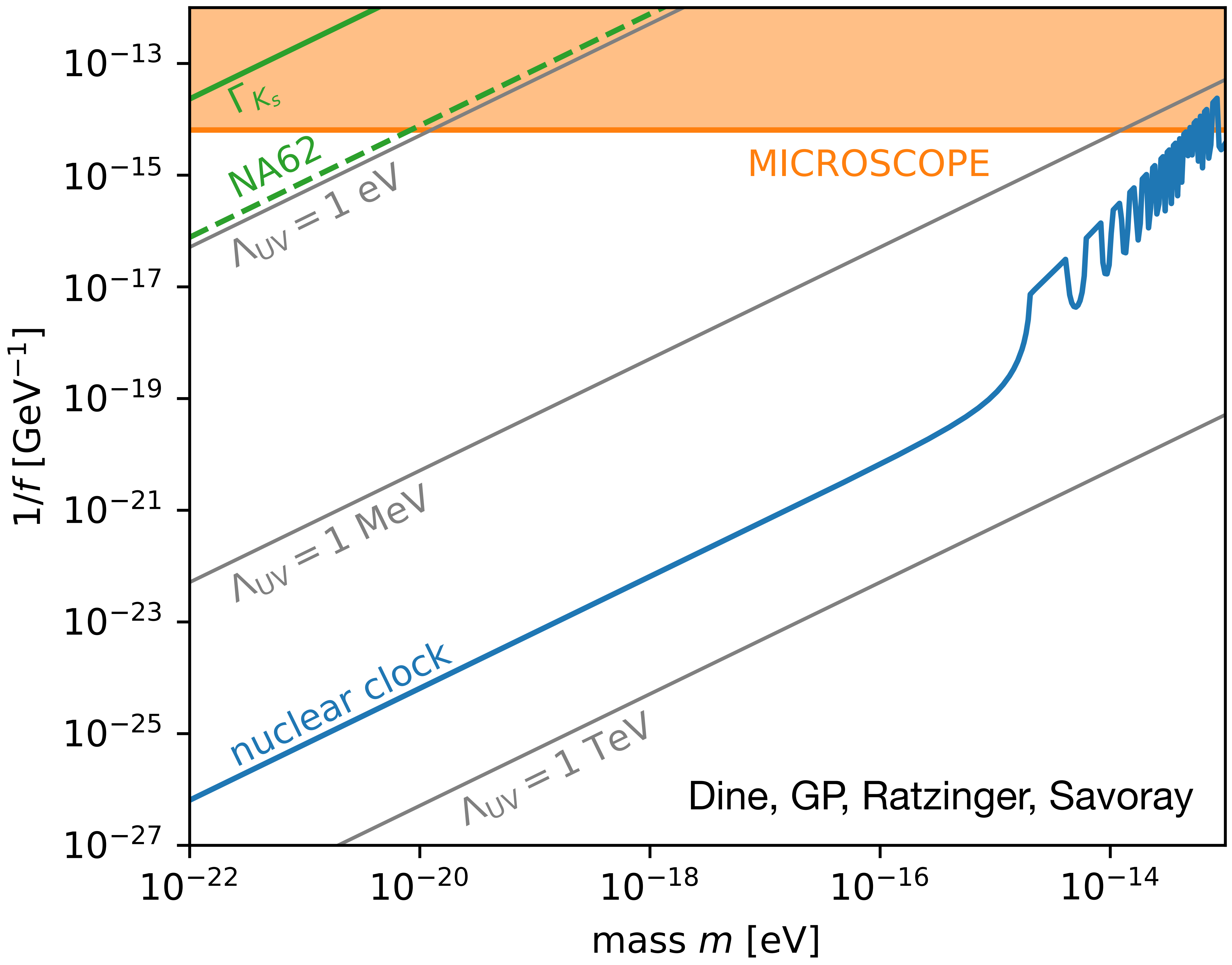


with: Elina Fuchs, Fiona Kirk, Eric Madge, Chaitanya Paranjape, Ekkehard Peik & Wolfram Ratzinger

Nelson-Barr-UDM parameter space, luminosity exp.



Nelson-Barr-UDM & nuclear clock



How robust is the sensitivity factor?

with: Doron Gazit, Joachim Kopp , Gil Paz & Konstantin Springmann …

- Can we measure or test this enhancement factor, $K_{\rm canc} = \Delta E_{\rm nu}/\Delta E_{\rm nu-clock} \sim 10^5 \gg 1$?
- Calculation of the nuclear binding energy difference is very challenging …
- Can instead consider at the electrostatic binding energy of the two states
- A crude way could be via imagining that the nuclear is a classical object
- Given the shape and charge density of both states we can evaluate $\Delta E_{\rm EM}$
- However, shape and density are hard to measure, one can use simplification assuming that the nucleus is a spheroid of a constant density

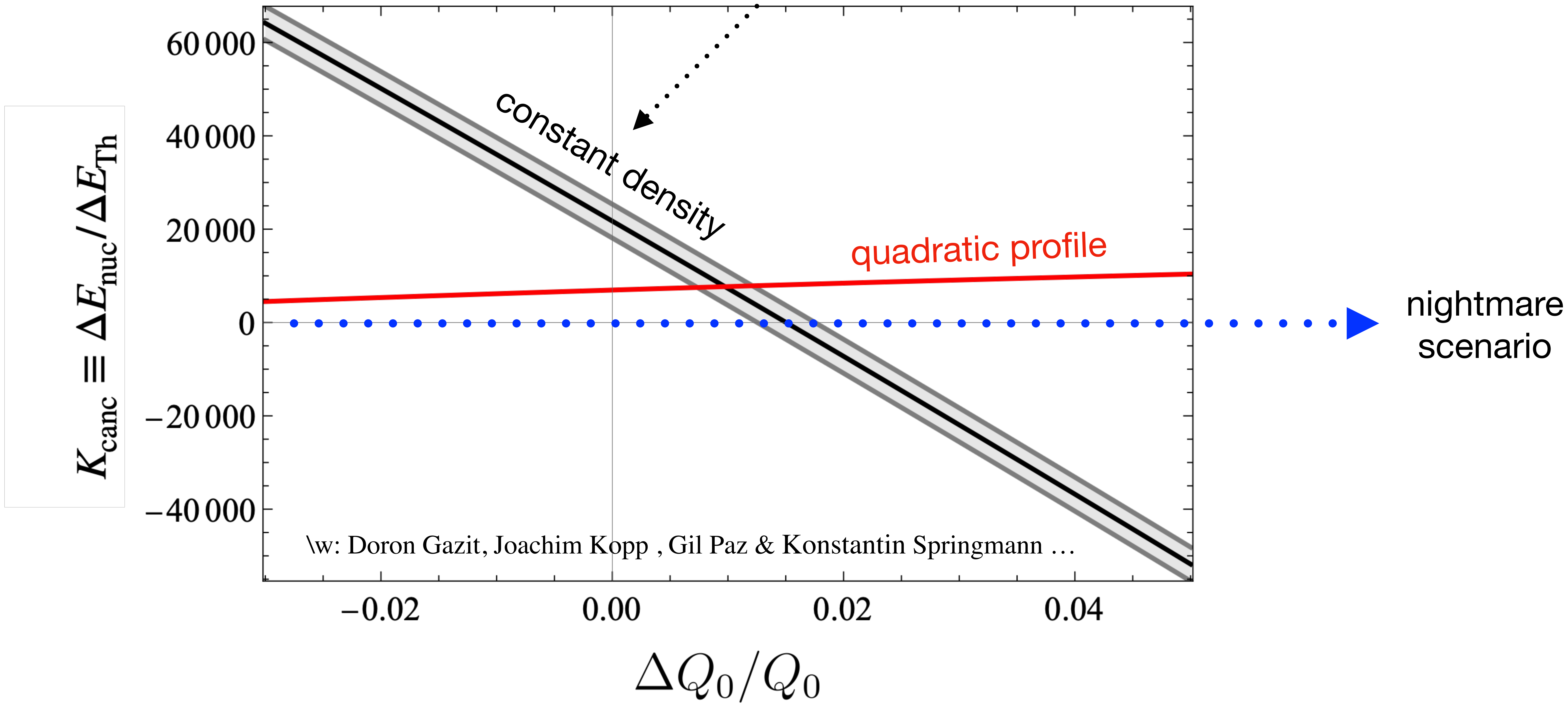
Berengut, Dzuba, Flambaum & Porsev (09); Fadeev, Berengut & Flambaum (20)

Estimating the sensitivity factor spheroid model

- In the const' density - spheroid model one finds $\Delta E_{\rm EM} \approx -485\,{\rm MeV}\,\frac{\Delta\langle r^2\rangle}{\langle r^2\rangle} + 11.6\,{\rm MeV}\frac{\Delta Q_0}{Q_0}\,,$

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

with $\langle r^2\rangle$ & Q_0 being the charge radius square, and the quadrupole moment, Δ stands for isomer-ground-state difference, \w $\Delta Q_0/Q_0 = -0.01(4)$



Conclusions

- Most well motivated models coupled to the QCD/nuclear sector, however currently we have only limited ways to probe the UDM-nuclear coupling
- Nuclear clock will change it all:

  (i) direct coupling to the nuclear parameters

  (ii) enhanced sensitivity due to the fine cancelletion
- New measurement => game changer moving to precision nuclear clock phase
- Existing measurement might already give impressive bound (but not strongest)
- Discussed robustness

Backups

NB-UDM signature & parameter space

- What is the size of the effect? $\delta a \sim \frac{\sqrt{\rho_{\rm DM}}}{m_{\rm NB} f} \cos(m_{\rm NB} t) \sim 10^{-4} \times \frac{10^{13}\,\text{GeV}}{f} \times \frac{10^{-21}\,\text{eV}}{m_{\rm NB}} \times \cos(m_{\rm NB} t)$

- How to search such signal?

(i) Luminosity frontier: oscillating CP violation + oscillating CKM angles:

$$\frac{\delta V_{us}}{V_{us}} \sim \delta a \Rightarrow \text{oscillating Kaon decay lifetime}$$

$$\frac{\delta \theta_{\rm KM}}{\theta_{\rm KM}} \sim \delta a \Rightarrow \text{oscillating CP violation}$$

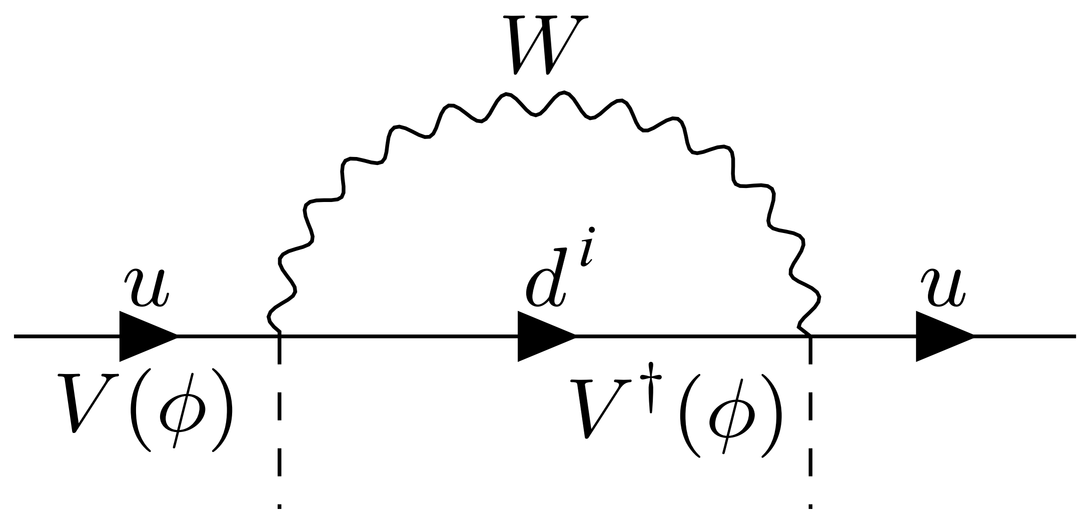
$$\frac{\delta V_{ub}}{V_{ub}} \sim \delta a \Rightarrow \text{oscillating semi inclusive } b\text{->}u \text{ decay}$$

NB-UDM signature & parameter space

- How to search such signal?

(ii) Equivalence principle (EP)+clocks, at 1-loop scalar coupling to mass is induced:

$$\frac{\Delta m_u}{m_u} \approx \frac{3}{32\pi^2} y_s^2 \, |V_{us}^{\mathrm{SM}}|^2 \frac{a}{f}$$



- EP $\Rightarrow f \gtrsim 10^{14}\,\mathrm{GeV}$

- Nuclear clock (1:10^{24}) $\Rightarrow f \gtrsim 10^{19}\,\mathrm{GeV} \times \dfrac{\mathrm{m_{NB}}}{10^{-15}\,\mathrm{eV}}$

Challenges

- Minimal misalignment DM bound, can't be satisfied: $f \gtrsim 10^{15}\,\mathrm{GeV}\left(\frac{10^{-19}\,\mathrm{eV}}{m_\phi}\right)^{\frac{1}{4}}$, but pretty close …

- Naive naturalness => currently only probing sub-MeV cutoff , $\Delta m_a \approx \frac{y_b |V_{ub}| m_u \Lambda_{\mathrm{UV}}}{16\pi^2 f}$

- Rely on NB construction, \w Z_2 and a (non-anomalous) U(1)

Two models:

$Q^{U(1)}(\Phi,\, u_1, Q_1, d_1,\, u_2, Q_2, d_1) = \;(+1,\; +1, +1, +1,\; -1, -1, -1)$

$Q^{U(1)}(\eta, \Phi, \psi, \psi^c, \bar{u}_1) = +1, +1/2, -1/2, -1/2, +1$ (η additional flavon)

Planck suppression for ultralight spin 0 field

- Let's consider some dimension 5 operators, and ask if current sensitivity reach the Planck scale (assumed linear coupling and that gravity respects parity):

Graham, Kaplan, Rajendran;
Stadnik & Flambaum;
Arvanitaki Huang & Van Tilburg (15)

$$\boxed{m_\phi = 10^{-18}\ \mathrm{eV}} \quad \text{(1/hour)}$$

operator	current bound	type of experiment
$\frac{d_e^{(1)}}{4\,M_{\rm Pl}}\phi\, F^{\mu\nu}F_{\mu\nu}$	$d_e^{(1)} \lesssim 10^{-4}$ [58]	DDM oscillations
$\frac{\tilde{d}_e^{(1)}}{M_{\rm Pl}}\phi\, F^{\mu\nu}\tilde{F}_{\mu\nu}$	$\tilde{d}_e^{(1)} \lesssim 2\times 10^{6}$ [68]	Astrophysics
$\frac{\lvert d_{m_e}^{(1)}\rvert}{M_{\rm Pl}}\phi\, m_e\psi_e\psi_e^c$	$\lvert d_{m_e}^{(1)}\rvert \lesssim 2\times 10^{-3}$ [58]	DDM Oscillations
$i\frac{\lvert \tilde{d}_{m_e}^{(1)}\rvert}{M_{\rm Pl}}\phi\, m_e\psi_e\psi_e^c$	$\lvert \tilde{d}_{m_e}^{(1)}\rvert \lesssim 7\times 10^{8}$ [63]	Astrophysics
$\frac{d_g^{(1)}\beta(g)}{2M_{\rm Pl}\, g}\phi\, G^{\mu\nu}G_{\mu\nu}$	$d_g^{(1)} \lesssim 6\times 10^{-6}$ [67]	EP test: MICROSCOPE
$\frac{\tilde{d}_g^{(1)}}{M_{\rm Pl}}\phi\, G^{\mu\nu}\tilde{G}_{\mu\nu}$	$\tilde{d}_g^{(1)} \lesssim 4$ [69]	Oscillating neutron EDM
$\frac{\lvert d_{m_N}^{(1)}\rvert}{M_{\rm Pl}}\phi\, m_N\psi_N\psi_N^c$	$\lvert d_{m_N}^{(1)}\rvert \lesssim 2\times 10^{-6}$ [67]	EP test: MICROSCOPE
$i\frac{\lvert \tilde{d}_{m_N}^{(1)}\rvert}{M_{\rm Pl}}\phi\, m_N\psi_N\psi_N^c$	$\lvert \tilde{d}_{m_N}^{(1)}\rvert \lesssim 4$ [69]	Oscillating neutron EDM

DDM = direct dark matter searches

For updated compilation see: Banerjee, Perez, Safronova, Savoray & Shalit (22)

Status of spin-0 UDM, generalized quality problem

- It seems that genially linearly-coupled models are in troubles, however:

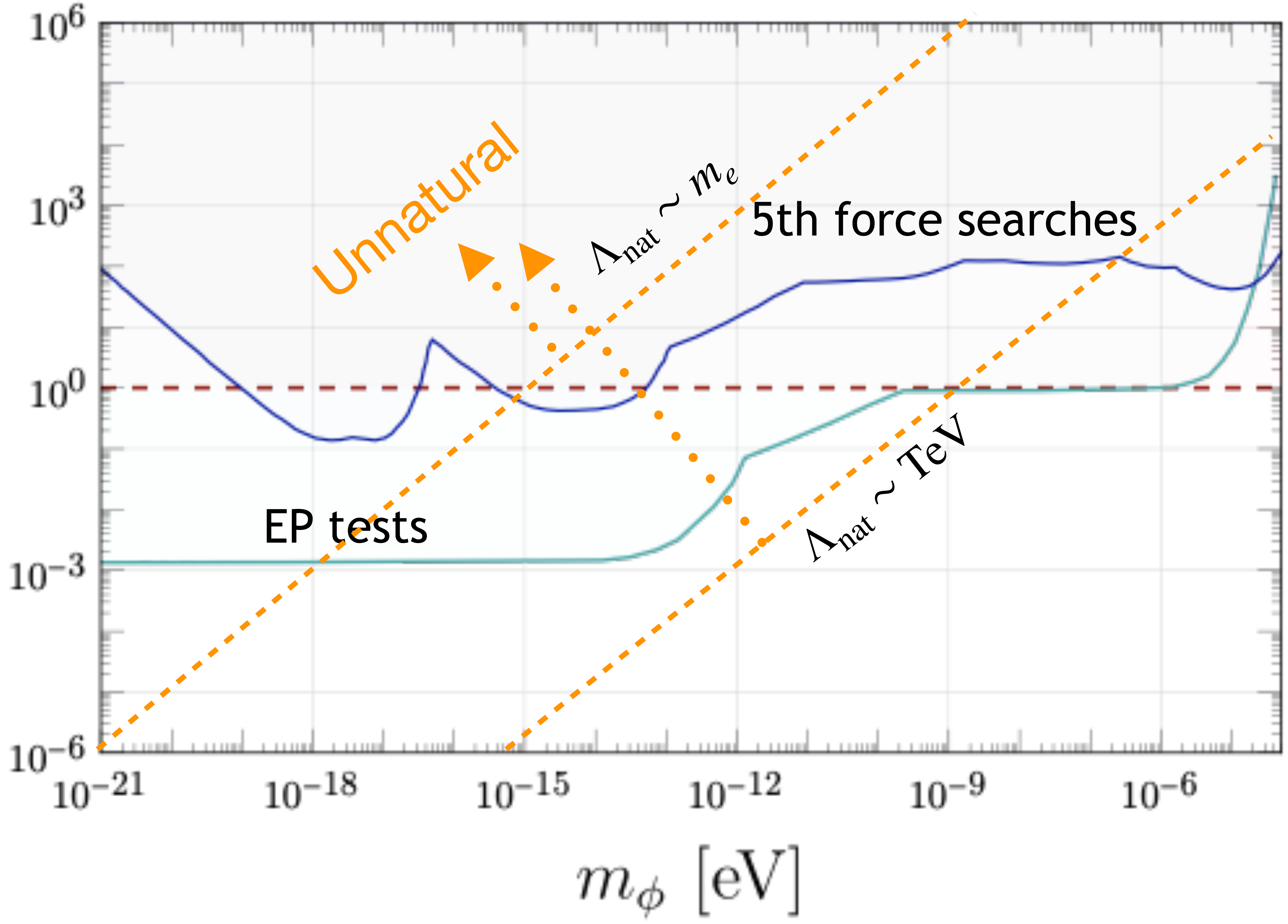
  If coupling is quadratic or more than situation is better -

$\frac{d_e^{(2)}}{8M_{\rm Pl}^2}\phi^2 F^{\mu\nu}F_{\mu\nu}$	$d_e^{(2)} \lesssim 10^{11}$ [67]	EP test: MICROSCOPE
$\frac{\left\lvert d_{m_e}^{(2)}\right\rvert}{2M_{\rm Pl}^2}\phi^2 m_e\psi_e\psi_e^c$	$\left\lvert d_{m_e}^{(2)}\right\rvert \lesssim 10^{12}$ [67]	EP test: MICROSCOPE
$\frac{d_g^{(2)}\beta_g}{4M_{\rm Pl}^2\, g}\phi^2 G^{\mu\nu}G_{\mu\nu}$	$d_g^{(2)} \lesssim 10^{11}$ [67]	EP test: MICROSCOPE.
$\frac{\left\lvert d_{m_N}^{(2)}\right\rvert}{2M_{\rm Pl}^2}\phi^2 m_N\psi_N\psi_N^c$	$\left\lvert d_{m_N}^{(2)}\right\rvert \lesssim 10^{11}$ [67]	EP test: MICROSCOPE

For updated compilation see: Banerjee, GP, Safronova, Savoray & Shalit (22)

Naturalness

$$d_{m_e} \lesssim 4\pi m_\phi M_{\rm Pl}/m_e\Lambda_{\rm nat} \approx \frac{m_\phi}{10^{-15}\,{\rm eV}}\frac{{\rm m_e}}{\Lambda_{\rm nat}}$$



Linear coupling seems to also be seriously challenged by naturalness

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

Kim & GP, last month

- 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)

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

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} !