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

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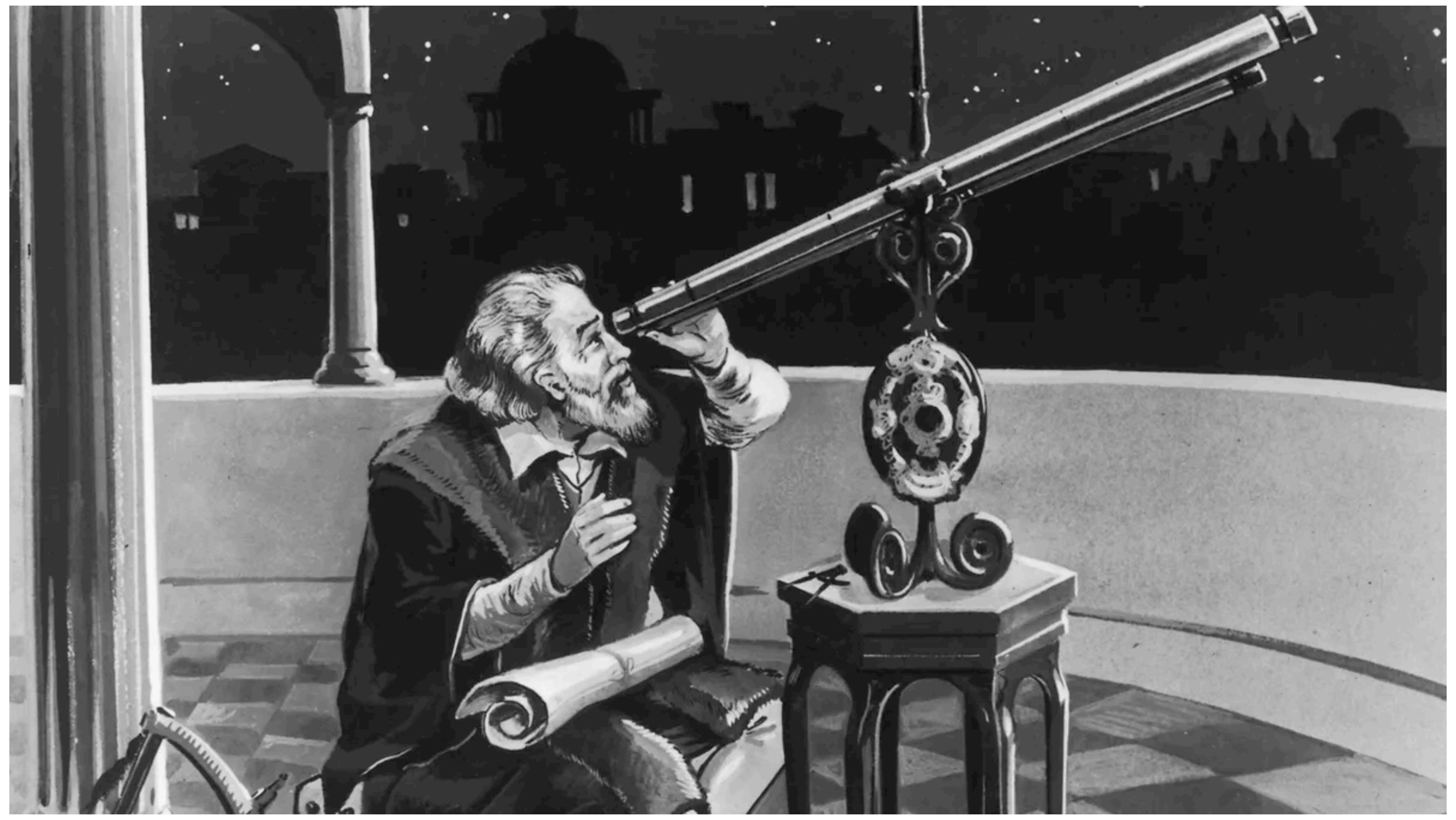
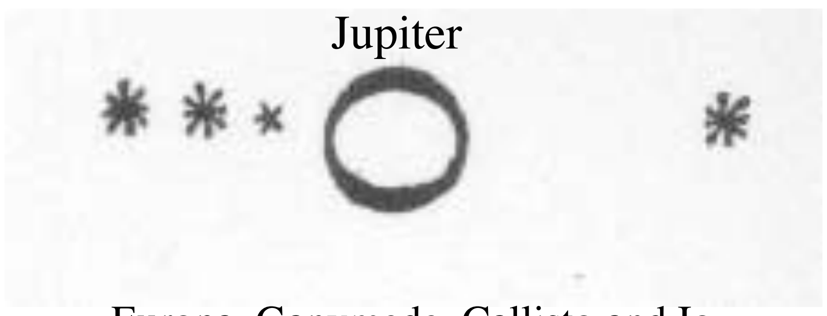
MAX-PLANCK-INSTITUT FÜR PHYSIK

Prologue





Th-239 progression of precision in isomeric-line's $\delta f/f$:

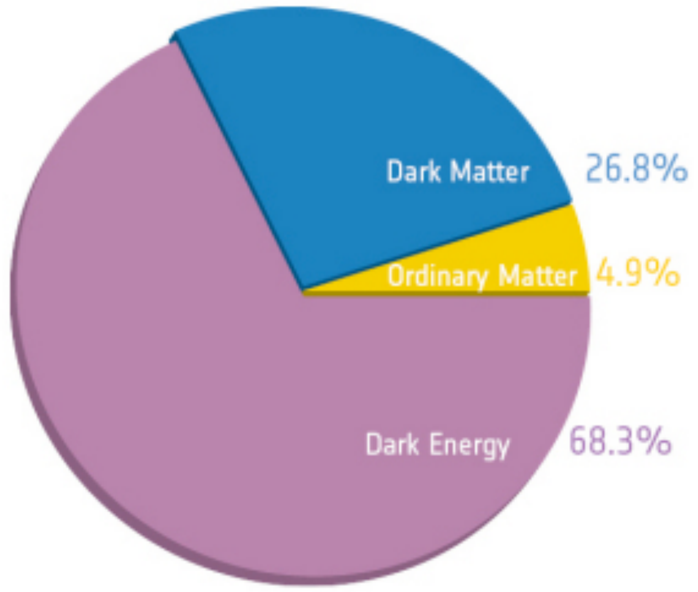
0.1 (2020) => 0.001 (2022) => $1{:}10^6$ (Mar/Apr/24) => $1{:}10^{11}$ (Jun/24)

Outline

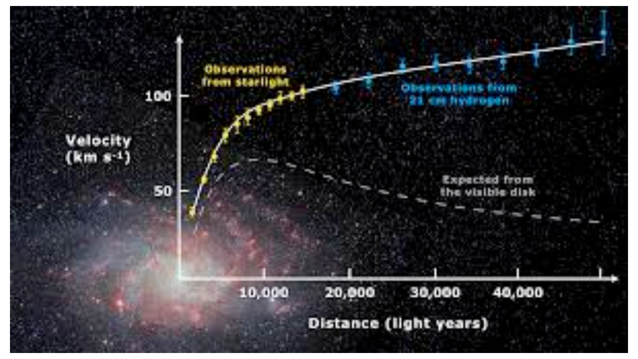
- Intro. (spin-0) ultralight dark-matter (UDM)
- Current status, UDM searches
- Laser excitation of Th-229 (news, sensitivity & robustness)
- Summary

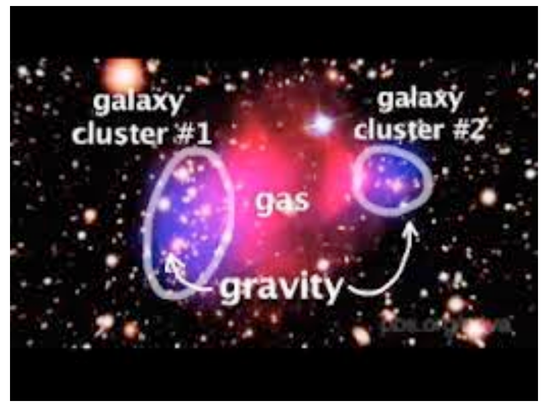
Usually in this part we discuss:

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

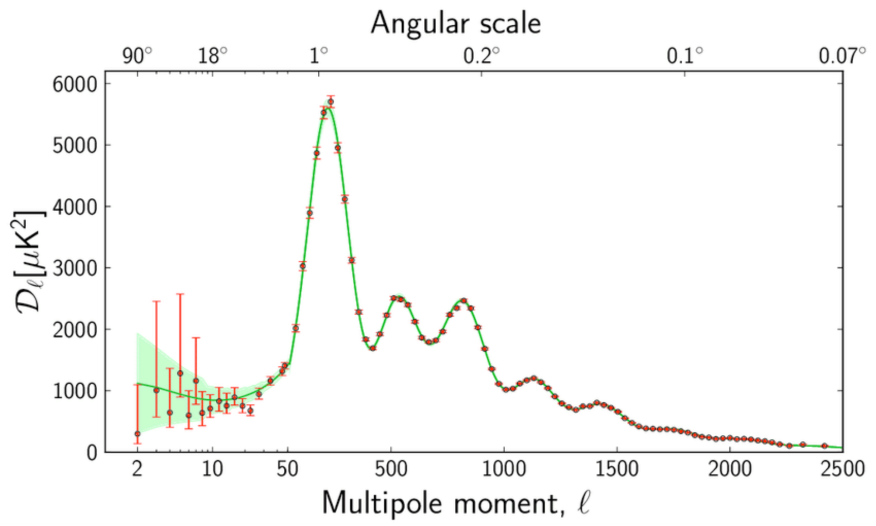


- **Galaxy Formation & rotation curves**: The gravitational influence of DM plays vital role in formation and evolution of galaxies & motions of stars





- **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

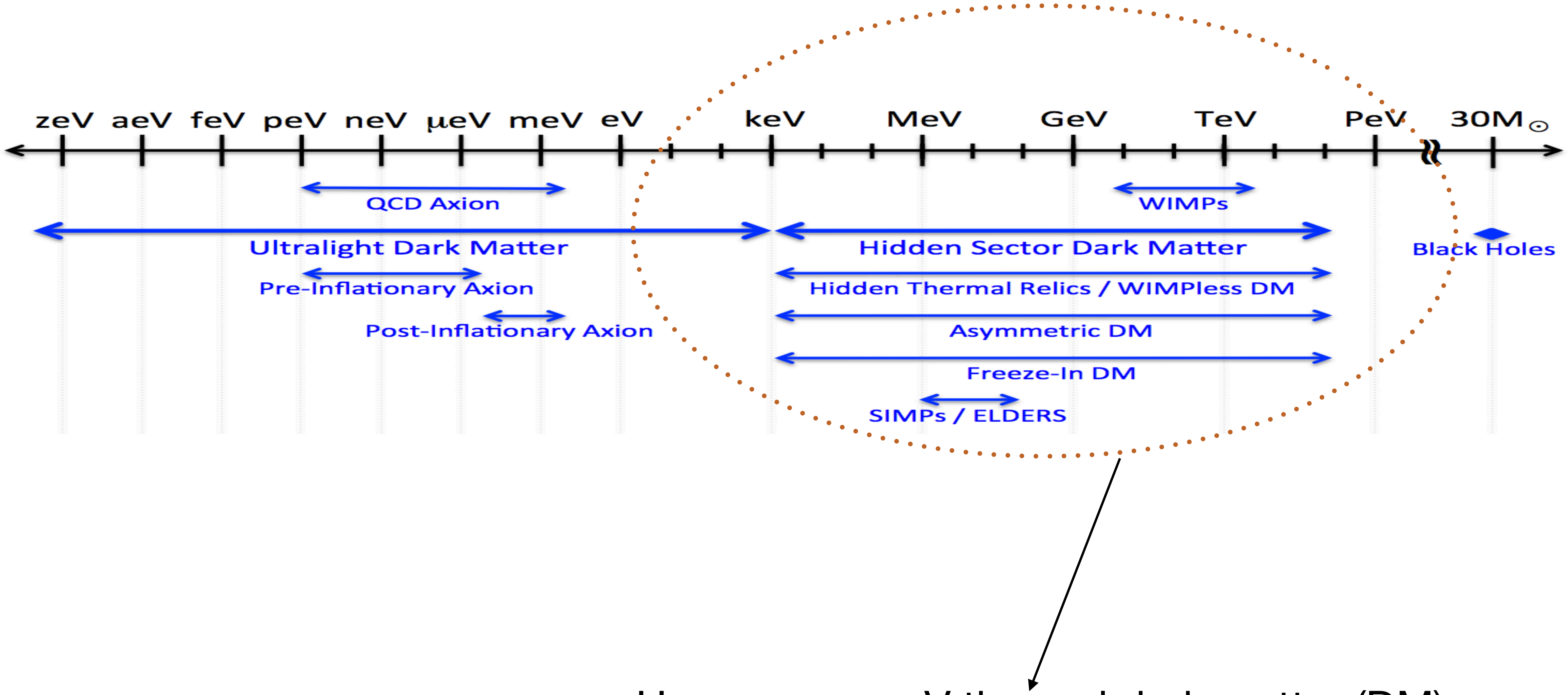
2. arXiv:2404.03666 [pdf, other] hep-ph

Exploring the Frontiers: Challenges and Theories Beyond the Standard Model

Authors: Dhananjay Saikumar

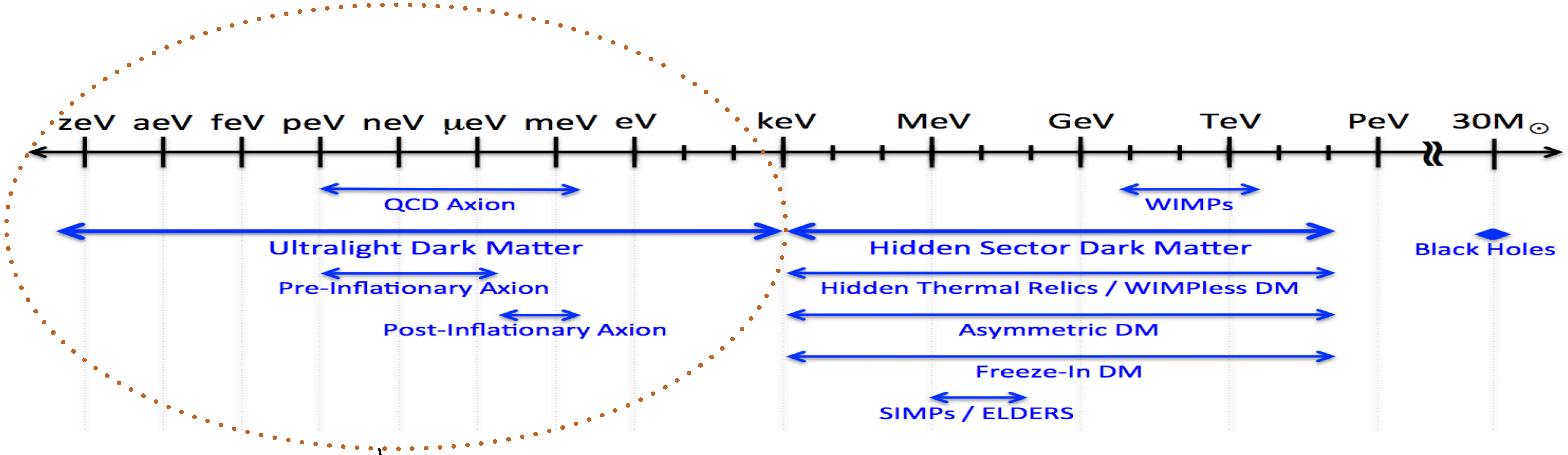
Abstract: Quantum Field Theory (QFT) forms the bedrock of the Standard **Model** (SM) of particle

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



<u>Heavy, super-eV thermal dark matter (DM)</u>
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 …



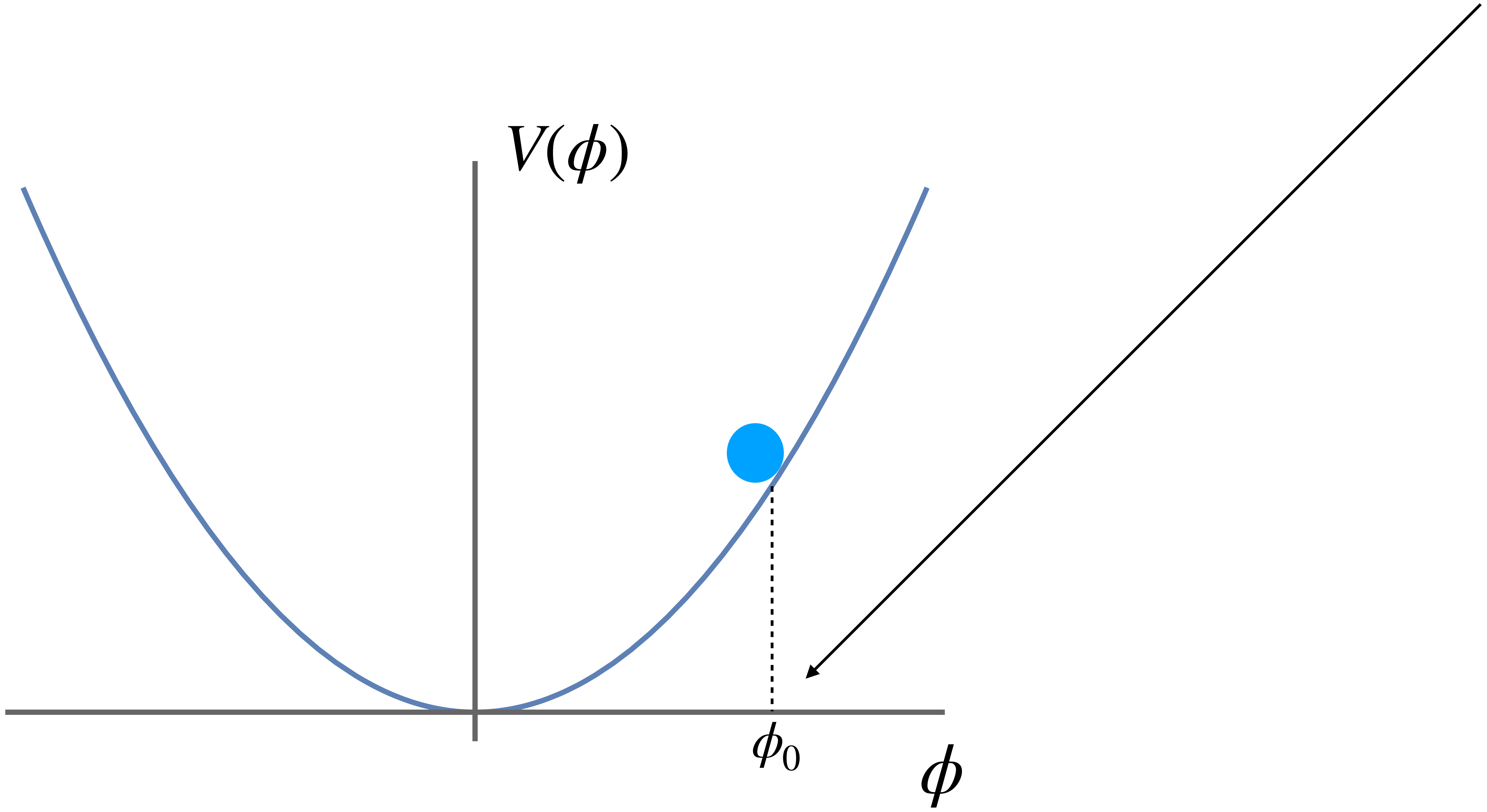
Ultralight sub-eV DM (UDM)

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, $\phi_{\rm init} = \phi_0$

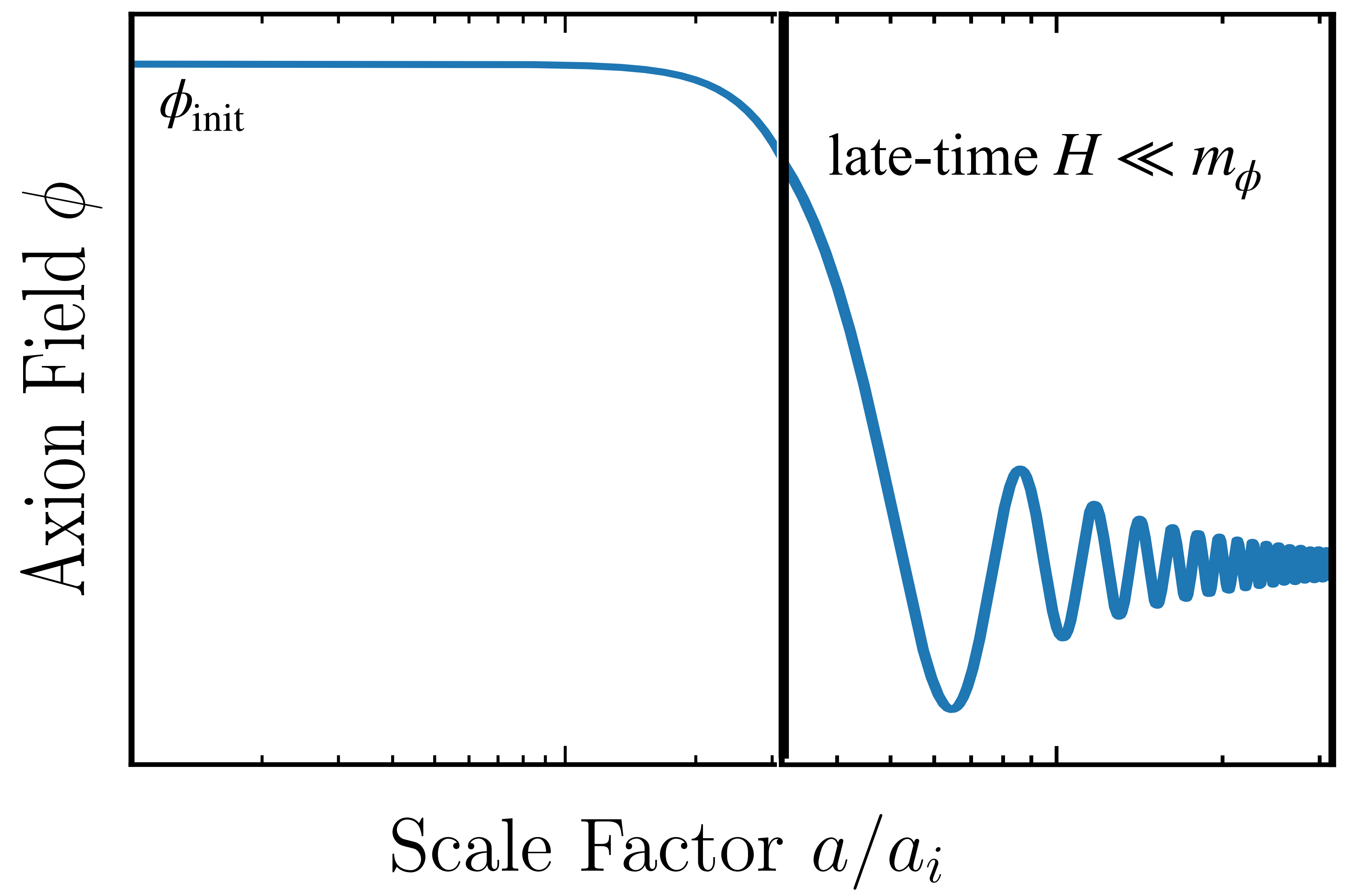


- What would be the cosmological evolution of such a field (assume $H \ll m_\phi$) ?

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:



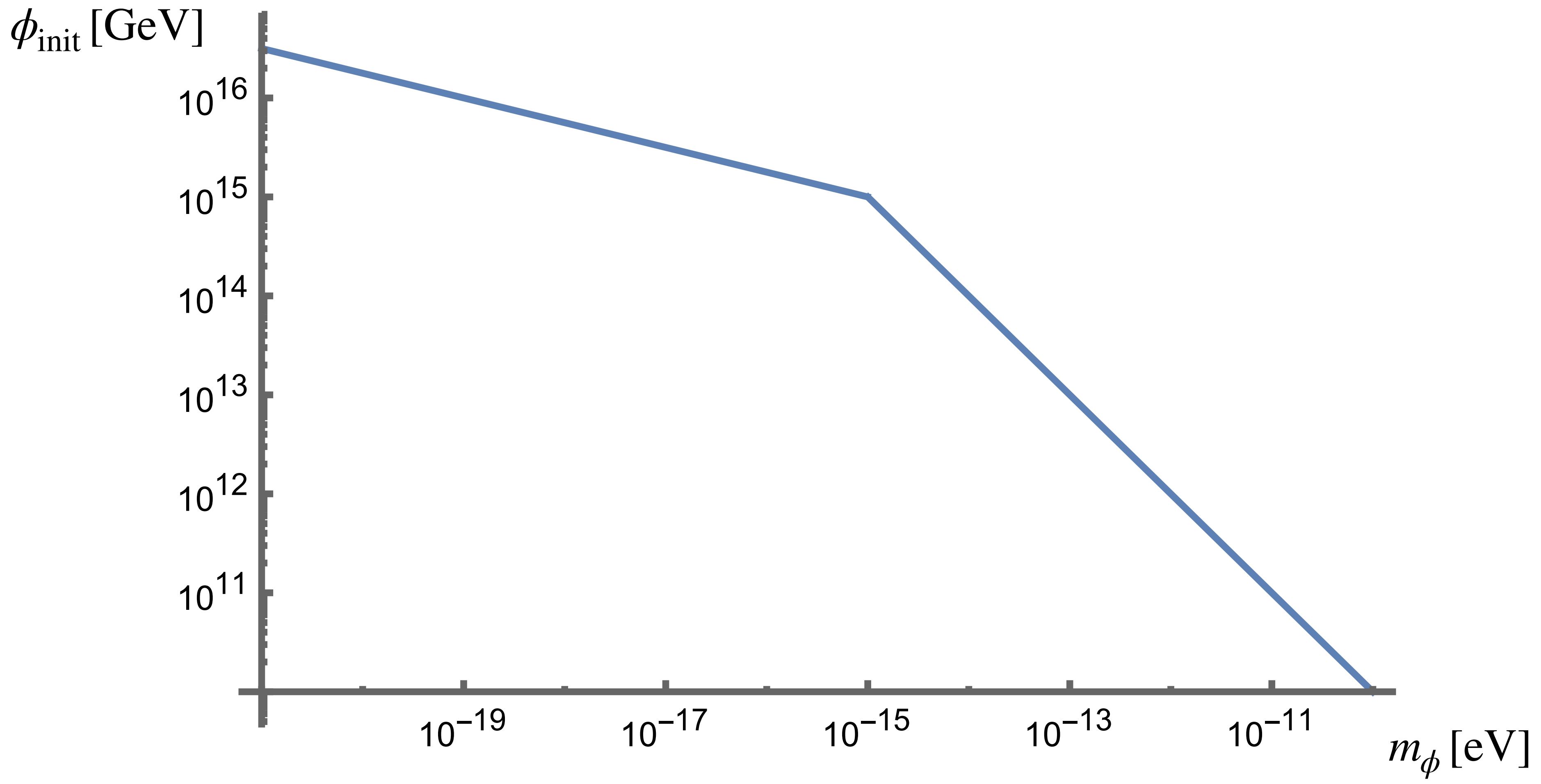
$$\phi(t) \approx \phi_0 \left(\frac{a_i}{a}\right)^{\frac{3}{2}} \cos(m_\phi t)$$

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, $w \sim \mathrm{Hz} \times \dfrac{m_\phi}{10^{-15}\,\mathrm{eV}}$
- 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:

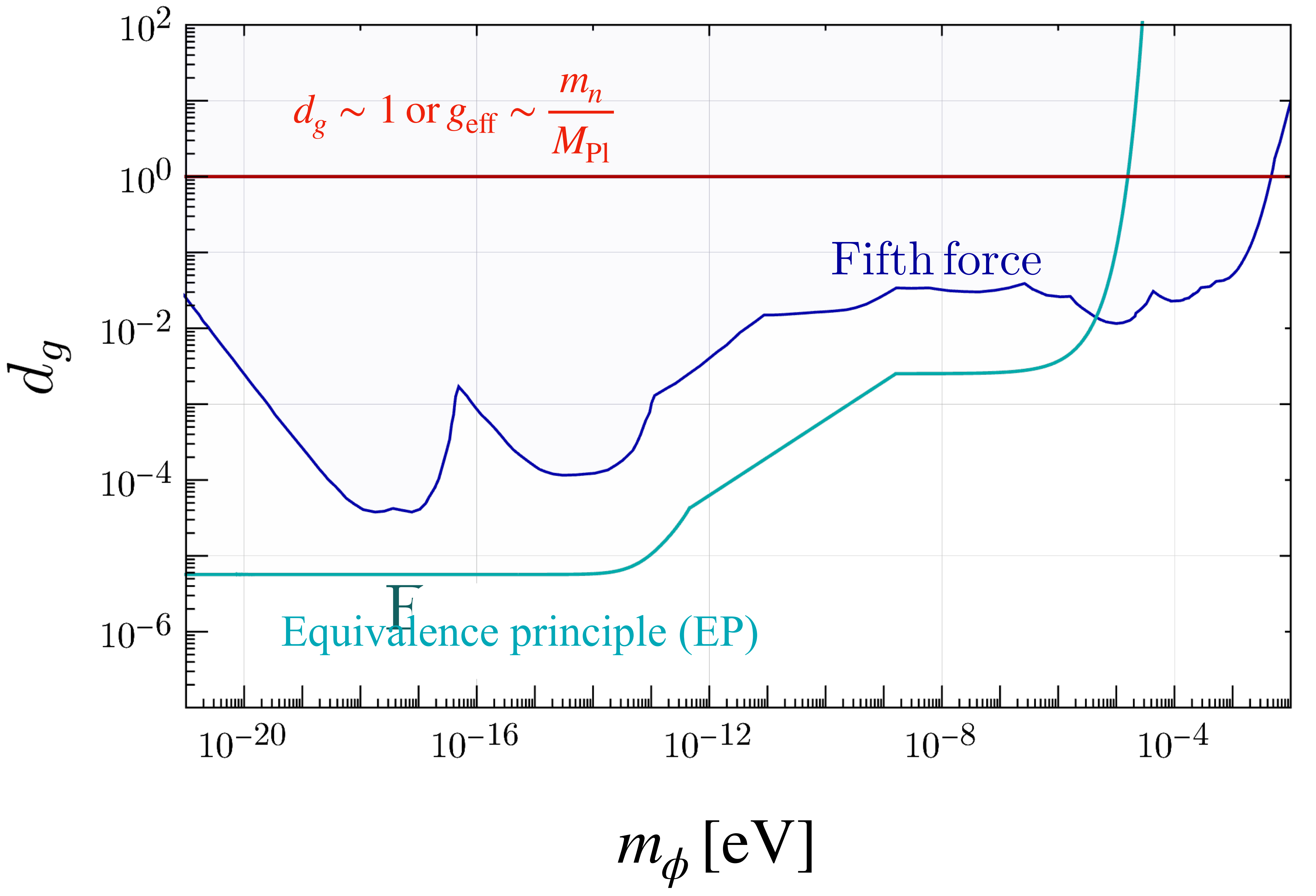
scalar coupling effecting energy levels

pseudo-scalar axial coupling magnetic/spin-observables

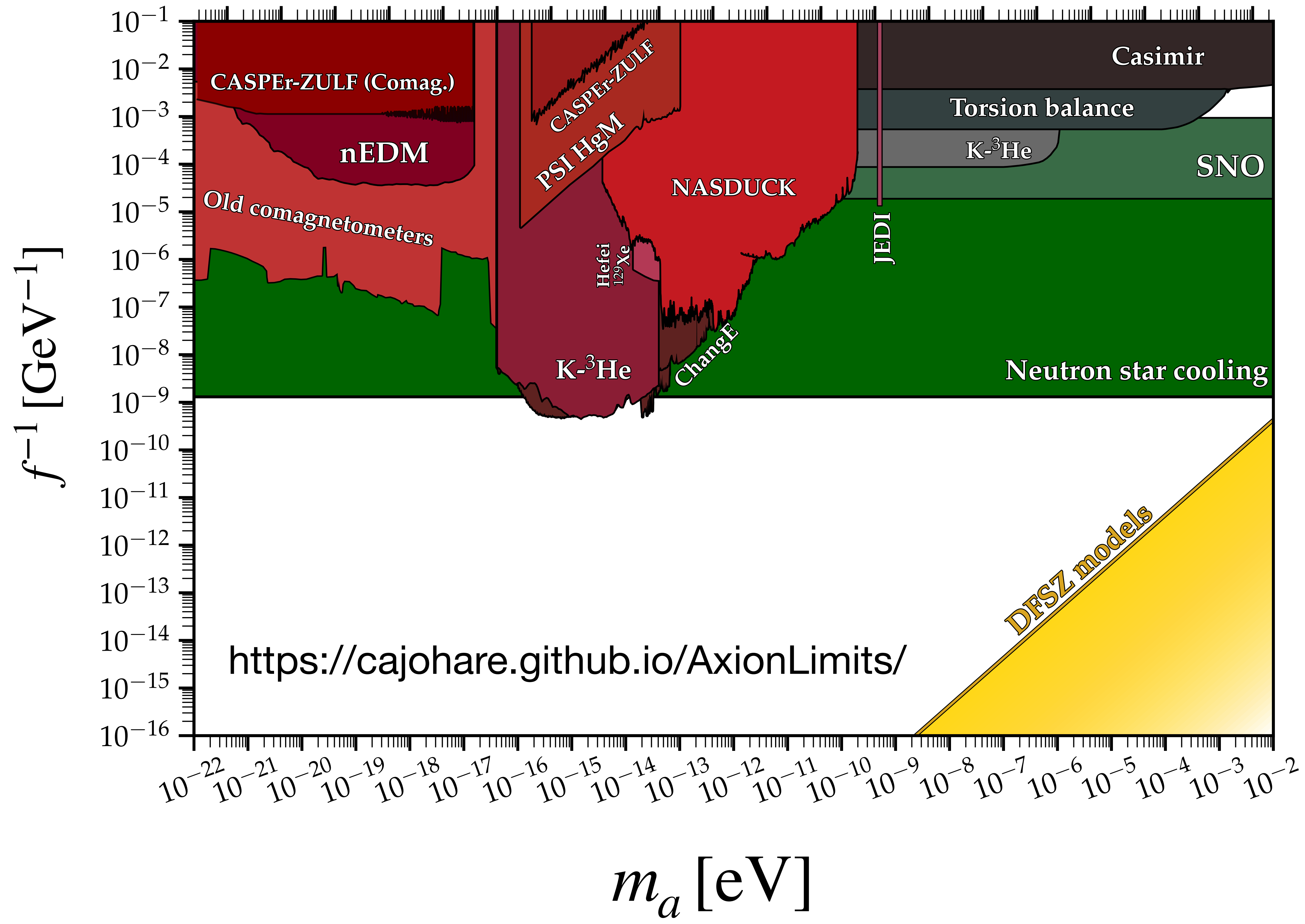
$$\mathscr{L}_{\mathrm{Pl}} \in d_g \frac{\alpha_s}{\pi} \frac{\phi}{M_{\mathrm{Pl}}} GG + \frac{a}{32\pi^2 f} G\tilde{G} \quad \Longrightarrow \quad d_g \frac{m_n}{M_{\mathrm{Pl}}} \phi\, \bar{n}n + \frac{m_n}{f} a\, \bar{n}\gamma_5 n$$

Scalar coupling vs/ pseudo-scalar axial coupling

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



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

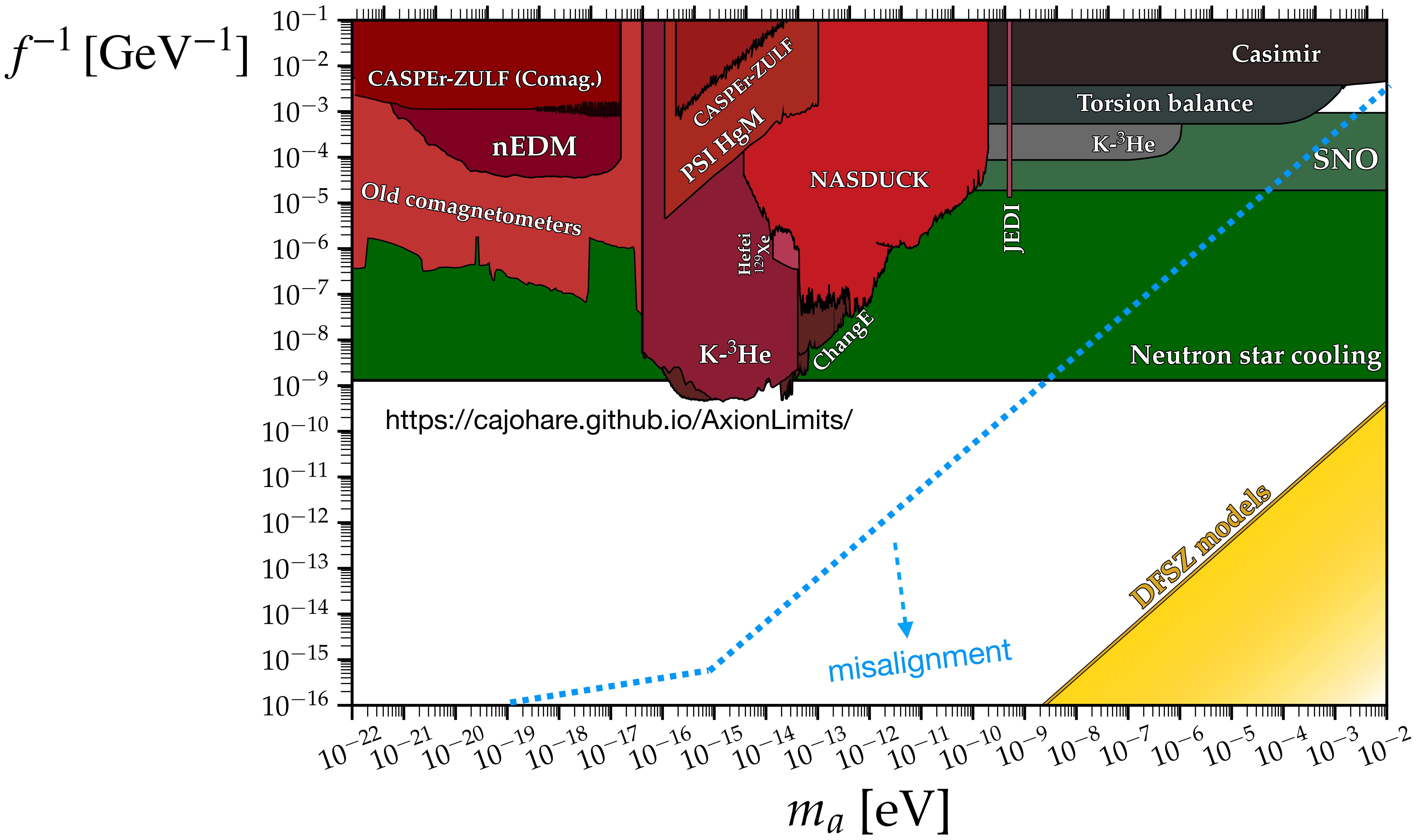


EP: Planck suppressed operators excluded for $m_\phi \lesssim 10^{-5}$ eV
5th force: operators are excluded for $m_\phi \lesssim 10^{-3}$ eV

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)

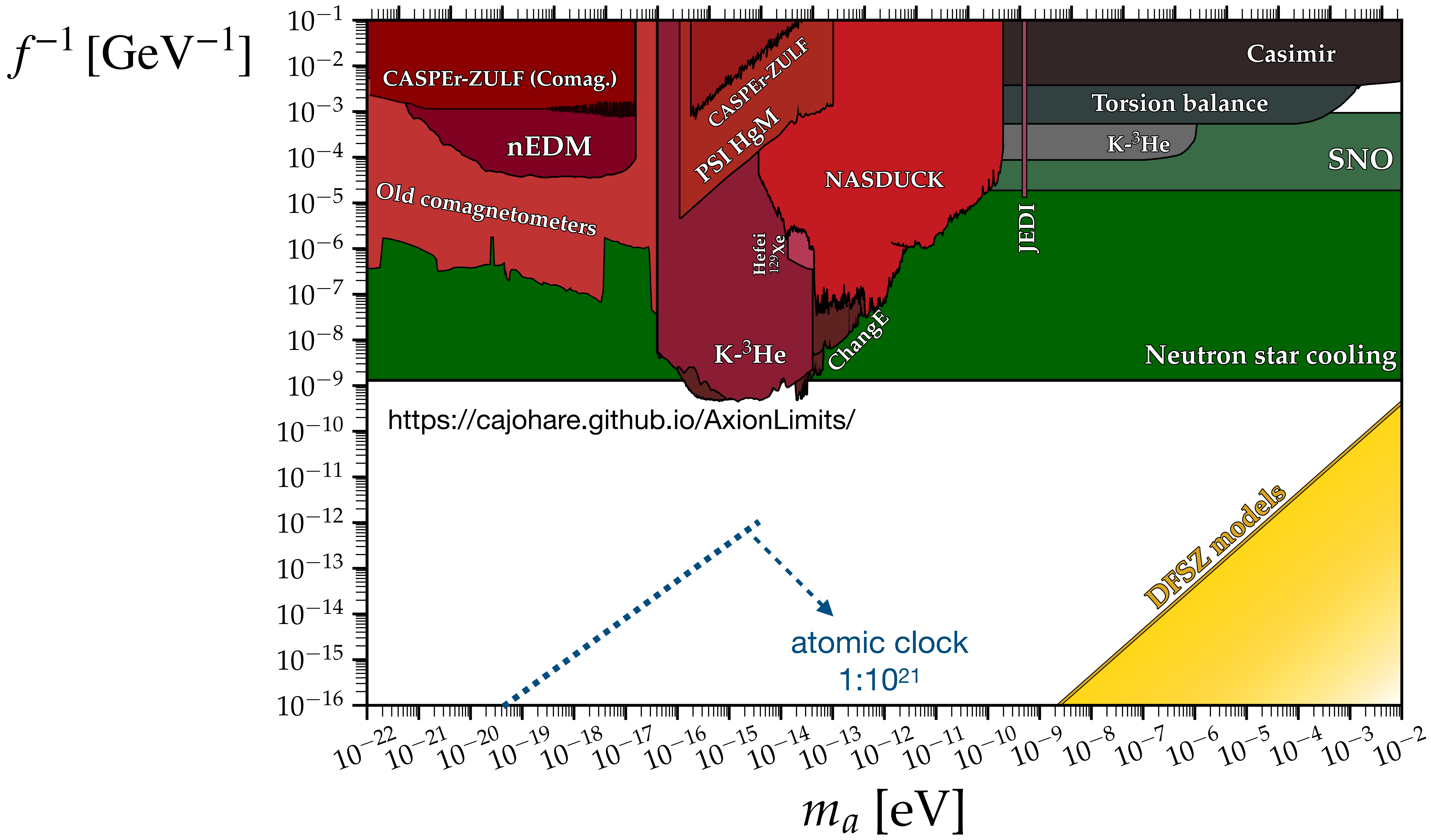
- Yet, in the case of QCD-like-axion only suppressed by $\frac{\partial \ln m_\pi}{\partial \theta^2} \sim \frac{m_{u,d}}{\Lambda_{\rm QCD}}\,, \quad \theta = a/f$

- Target for clocks $\quad {\rm MeV} \times \theta^2 \bar{n} n \Rightarrow \frac{\delta f}{f} \sim \frac{\delta m_N}{m_N} \sim 10^{-16} \times \cos(2m_a) \times \left(\frac{10^{-15}\,{\rm eV}}{m_\phi}\frac{10^9\,{\rm GeV}}{f}\right)^2$

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:

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

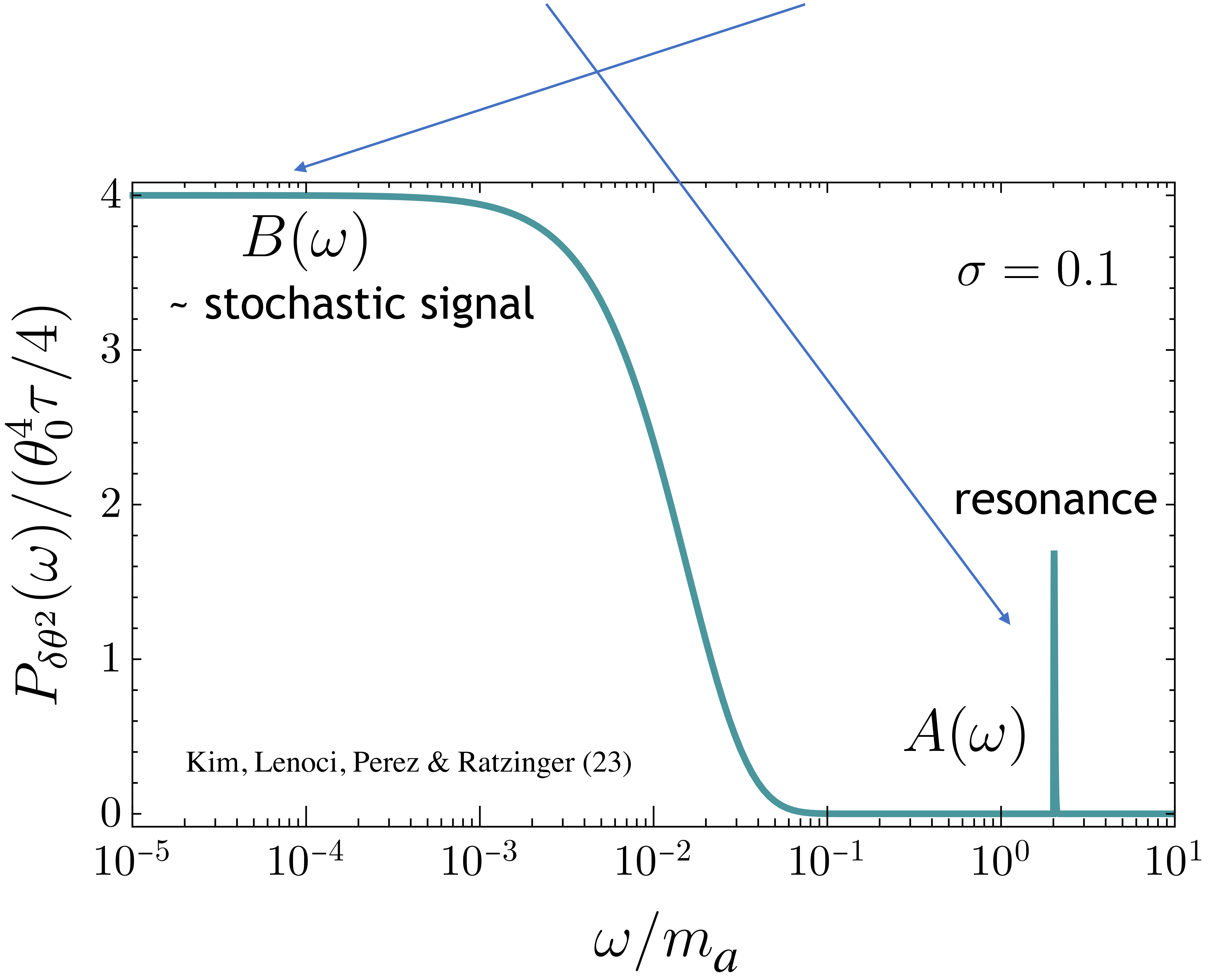
- Frequency transformed: it would result in a sharp signal at $\omega \sim m_a$ with width of $O\left(10^{-6}\right)$

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

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

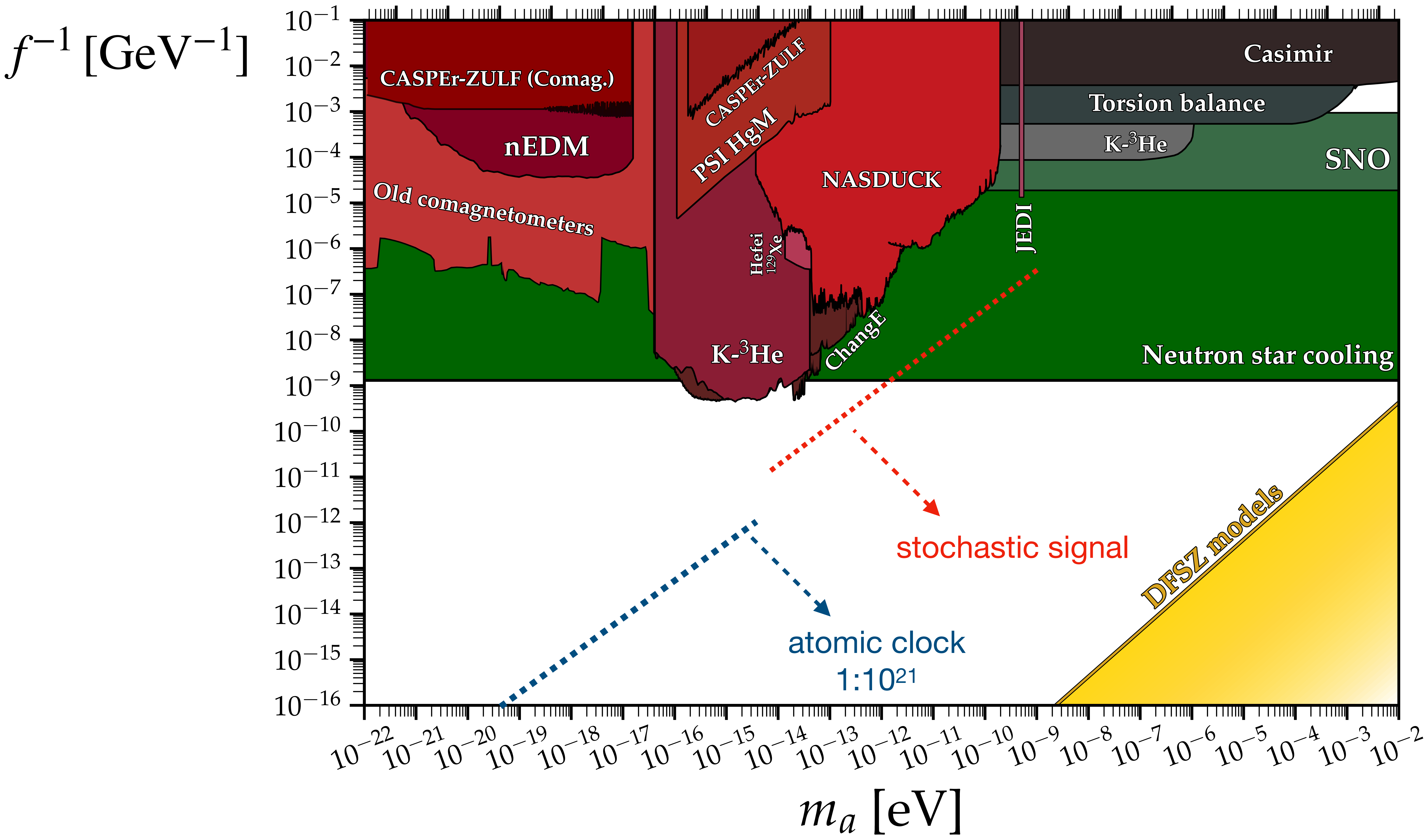
Power spectrum of quadratic (axion) UDM

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



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

  Dine, GP, Ratzinger & Savoray (24)

⋮

Why probing the strong sector \w clocks is challenging ?

To understand let's talk about how clocks probe DM

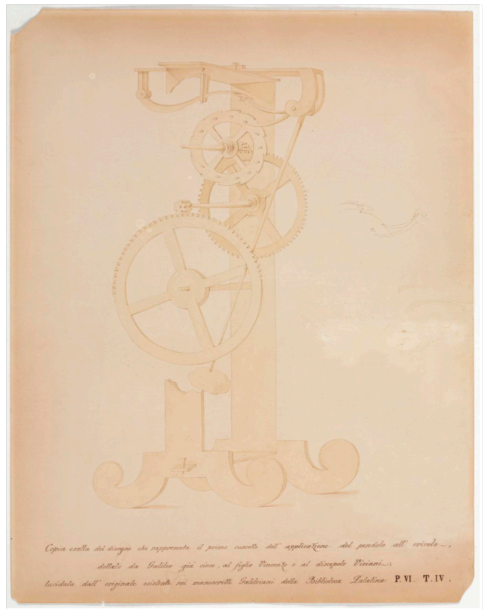
(theorist's perspective - simplified model …)

Atomic clock in 1-slide

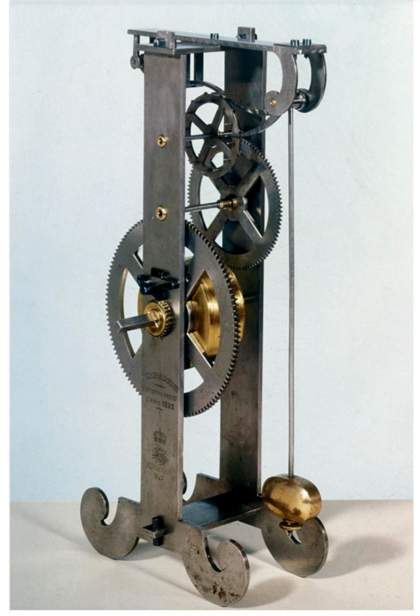
- A clock requires an apparatus that repeat itself in a very precise manner
- Atomic clocks are based on cases where there are electronic transitions between stable 2-level system, $H \approx \Delta E \times \sigma_Z$
- In the experiment, via laser, one prepare a linear combination of these levels

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

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



Florence



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:

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

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

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

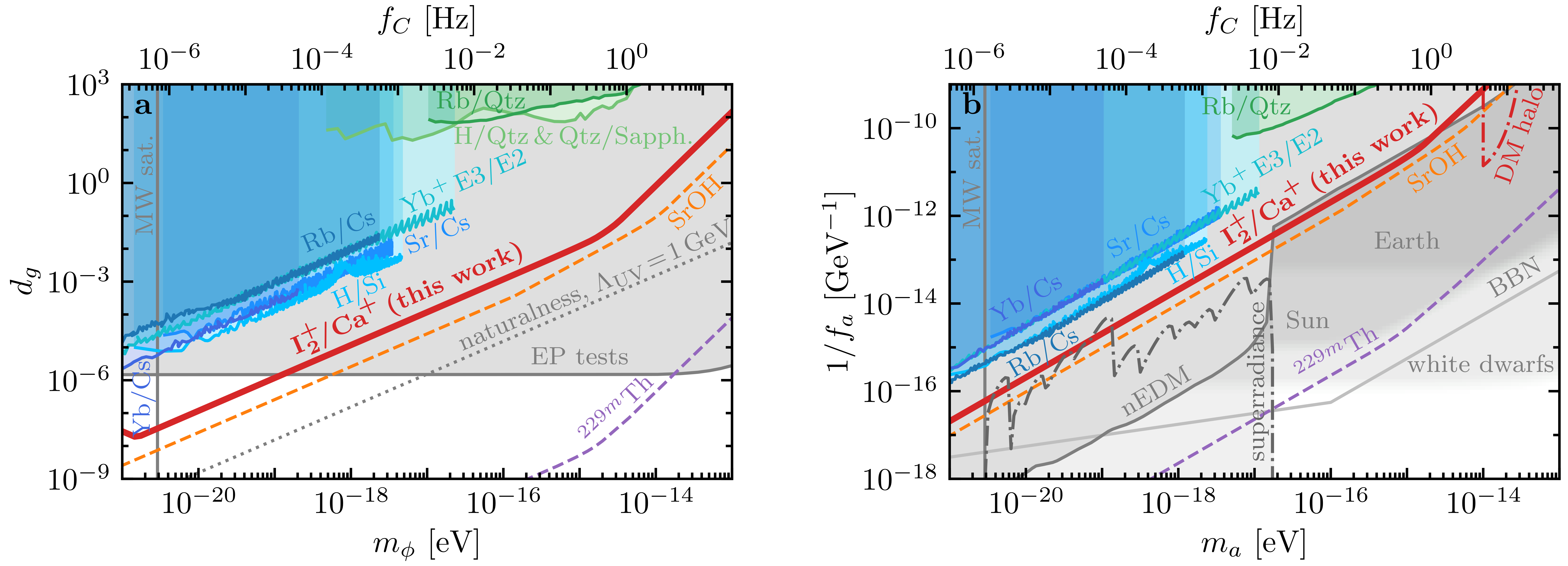
In vapor see: Oswald, Nevsky, Vogt, Schiller, Figuerora, Zhang, Tretiak, Antypas, Budker, Banerjee & GP (21) In corr. spec.: Madge, GP, Meir (24)

- Or charge radius effect, scales like $A^{8/3}\alpha\left(\frac{m_{\rm Bohr}}{m_p}\right)^3$ Banerjee, Budker, Filzinger, Huntemann, Paz, GP, Porsev & Safronova (23)

Result \w a suppression factor: $R_{\rm atom} \sim 10^{3-5}$

Observables directly probing coupling to QCD/nuclear sector

Madge, GP, Meir (24)



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

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

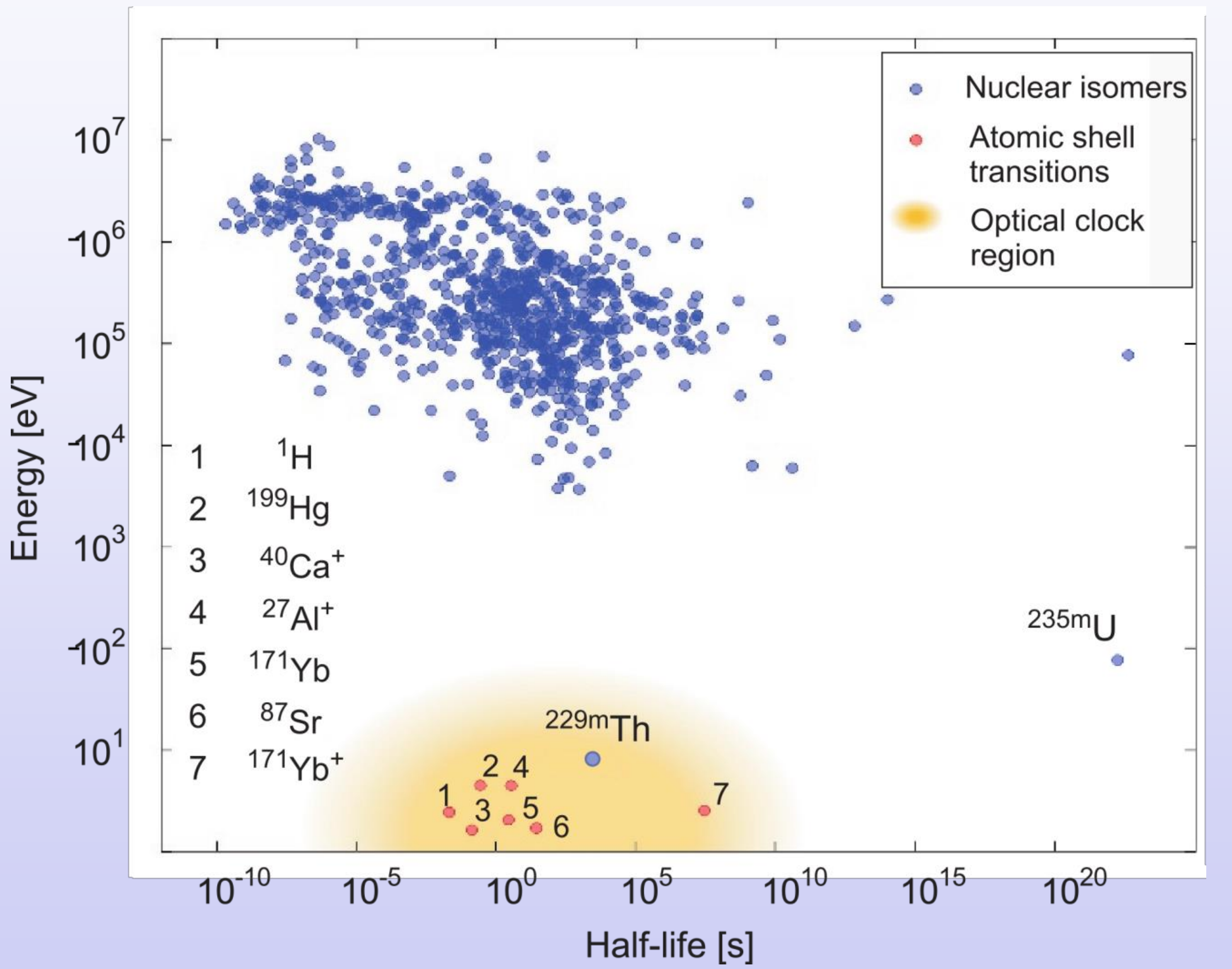
with: Andrea Caputo, Doron Gazit, Hans Werner Hammer, Joachim Kopp , Gil Paz & Konstantin Springmann

(*ii*) BSM implications (line-shape)

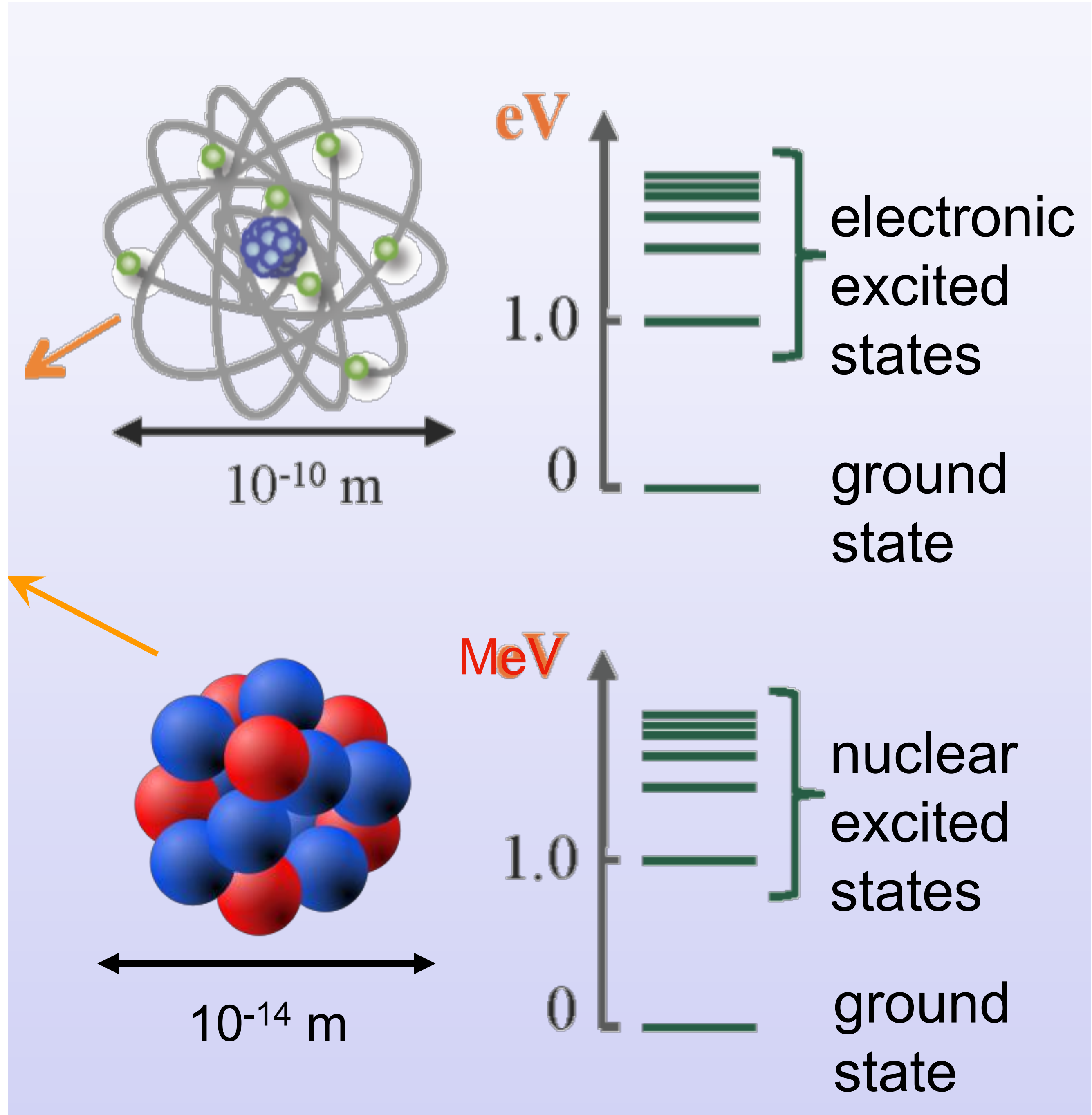
with: Elina Fuchs, Fiona Kirk, Eric Madge, Chaitanya Paranjape, Ekkehard Peik, Wolfram Ratzinger & Johannes Tiedau

Natural fine tuning, Th-229 isomeric excitation

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

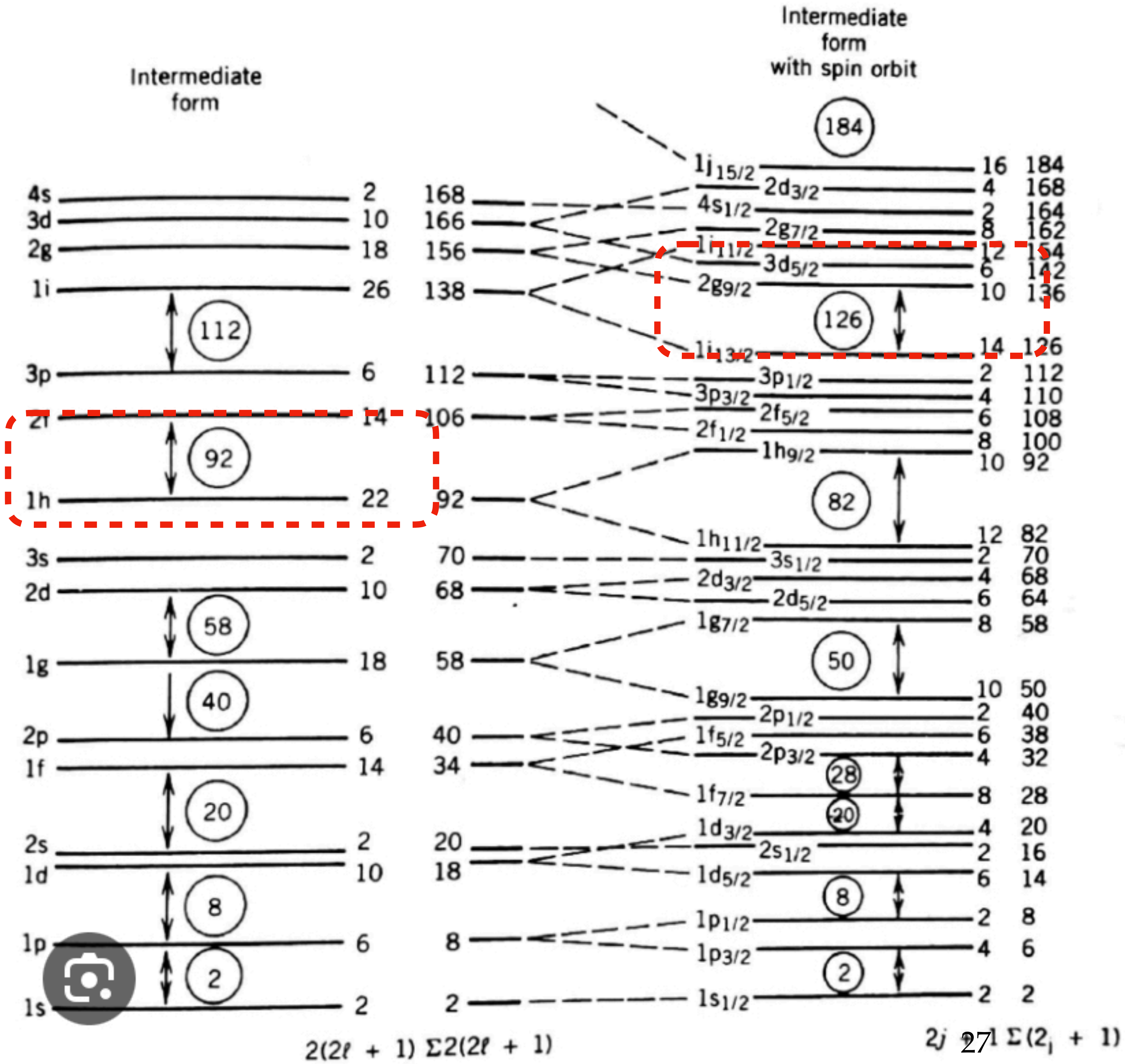


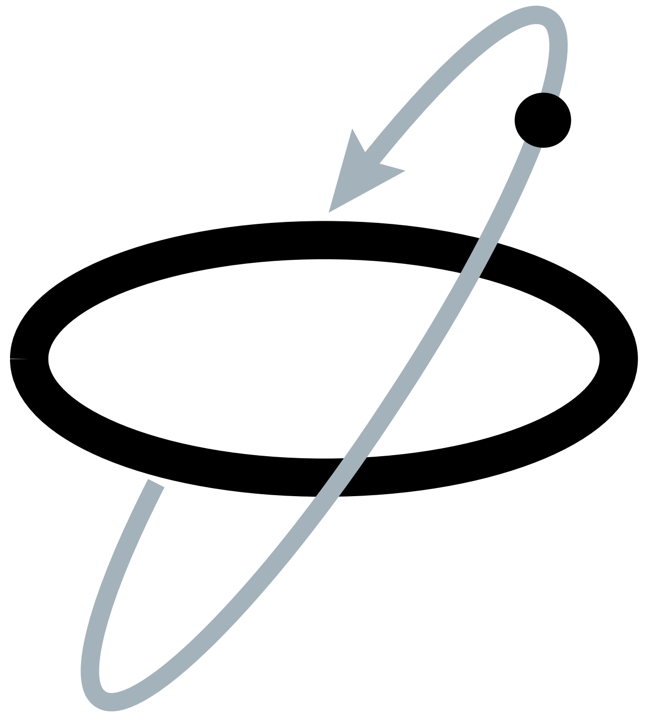
lowest E* of all ca. 186000 presently known nuclear excited states



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

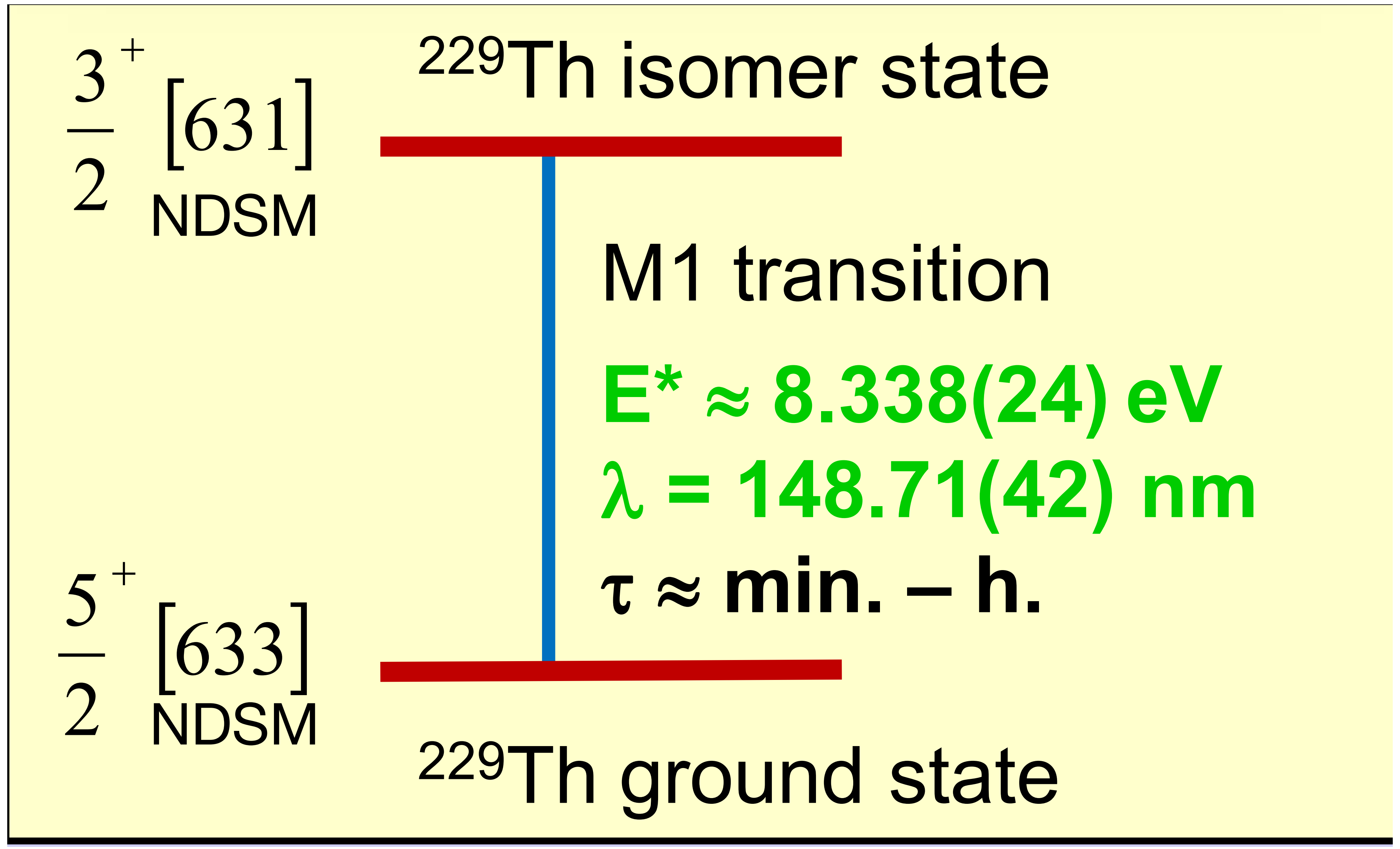
90 *protons*, 139 *neutrons*





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

[Submitted on 26 Jun 2024]

Dawn of a nuclear clock: frequency ratio of the ^{229m}Th isomeric transition and the ^{87}Sr atomic clock

Chuankun Zhang, Tian Ooi, Jacob S. Higgins, Jack F. Doyle, Lars von der Wense, Kjeld Beeks, Adrian Leitner, Georgy Kazakov, Peng Li, Peter G. Thirolf, Thorsten Schumm, Jun Ye

Optical atomic clocks[1,2] use electronic energy levels to precisely keep track of time. A clock based on nuclear energy levels promises a next-generation platform for precision metrology and fundamental physics studies. Thorium-229 nuclei exhibit a uniquely low energy nuclear transition within reach of state-of-the-art vacuum ultraviolet (VUV) laser light sources and have therefore been proposed for construction of the first nuclear clock[3,4]. However, quantum state-resolved spectroscopy of the ^{229m}Th isomer to determine the underlying nuclear structure and establish a direct frequency connection with existing atomic clocks has yet to be performed. Here, we use a VUV frequency comb to directly excite the narrow ^{229}Th nuclear clock transition in a solid-state CaF_2 host material and determine the absolute transition frequency. We stabilize the fundamental frequency comb to the JILA ^{87}Sr clock[2] and coherently upconvert the fundamental to its 7th harmonic in the VUV range using a femtosecond enhancement cavity. This VUV comb establishes a frequency link between nuclear and electronic energy levels and allows us to directly measure the frequency ratio of the ^{229}Th nuclear clock transition and the ^{87}Sr atomic clock. We also precisely measure the nuclear quadrupole splittings and extract intrinsic properties of the isomer. These results mark the start of nuclear-based solid-state optical clock and demonstrate the first comparison of nuclear and atomic clocks for fundamental physics studies. This work represents a confluence of precision metrology, ultrafast strong field physics, nuclear physics, and fundamental physics.

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

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[6] *Center for Quantum Science and Engineering, University of California Los Angeles, Los Angeles, CA, USA*
(Dated: April 19, 2024)

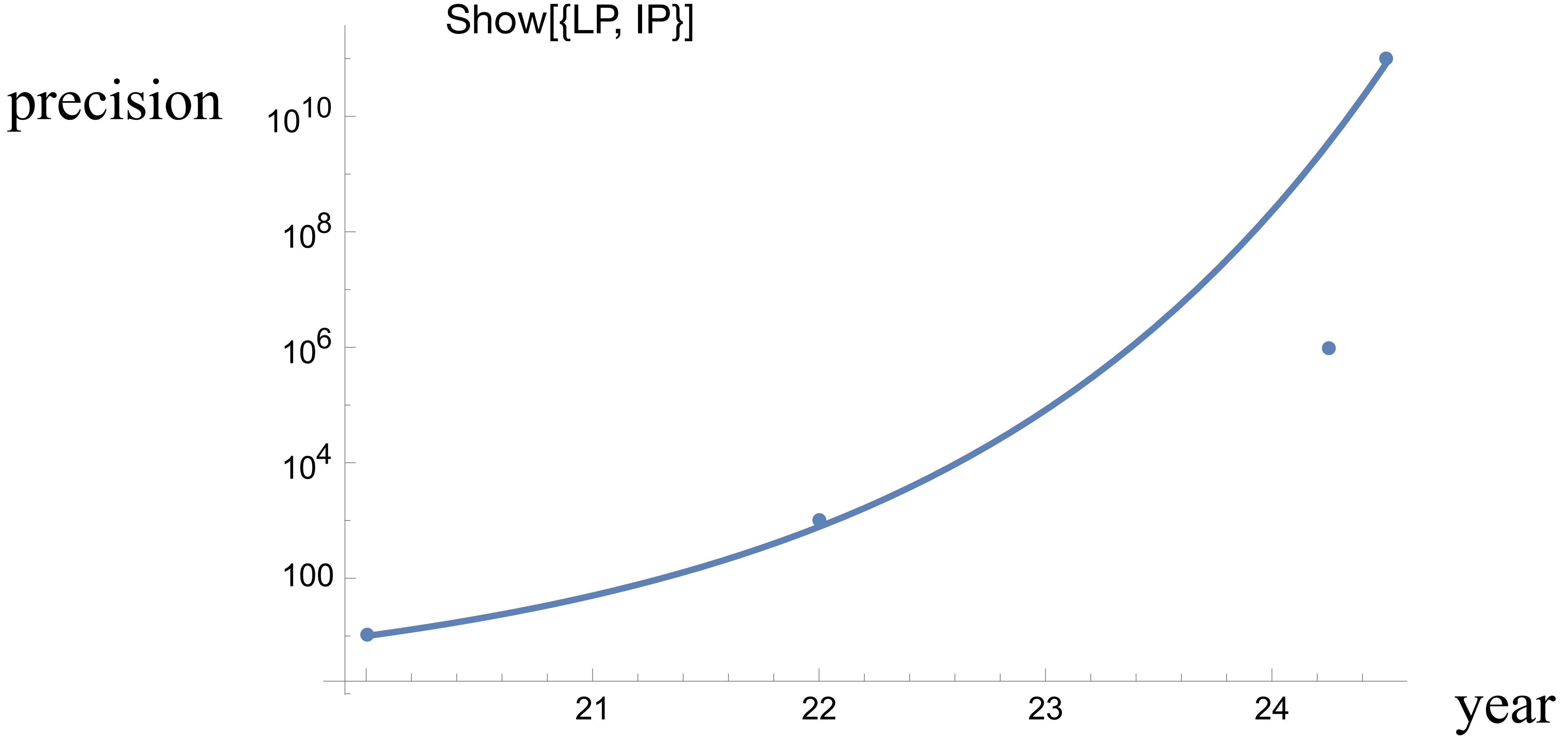
$LiSrAlF_6$ crystals doped with ^{229}Th are used in a laser-based search for the nuclear isomeric transition. Two spectroscopic features near the nuclear transition energy are observed. The first is a broad excitation feature that produces red-shifted fluorescence that decays with a timescale of a few 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 on steroids - quantum sensors

Th-239 progression of precision in isomeric-line's $\delta f/f$:

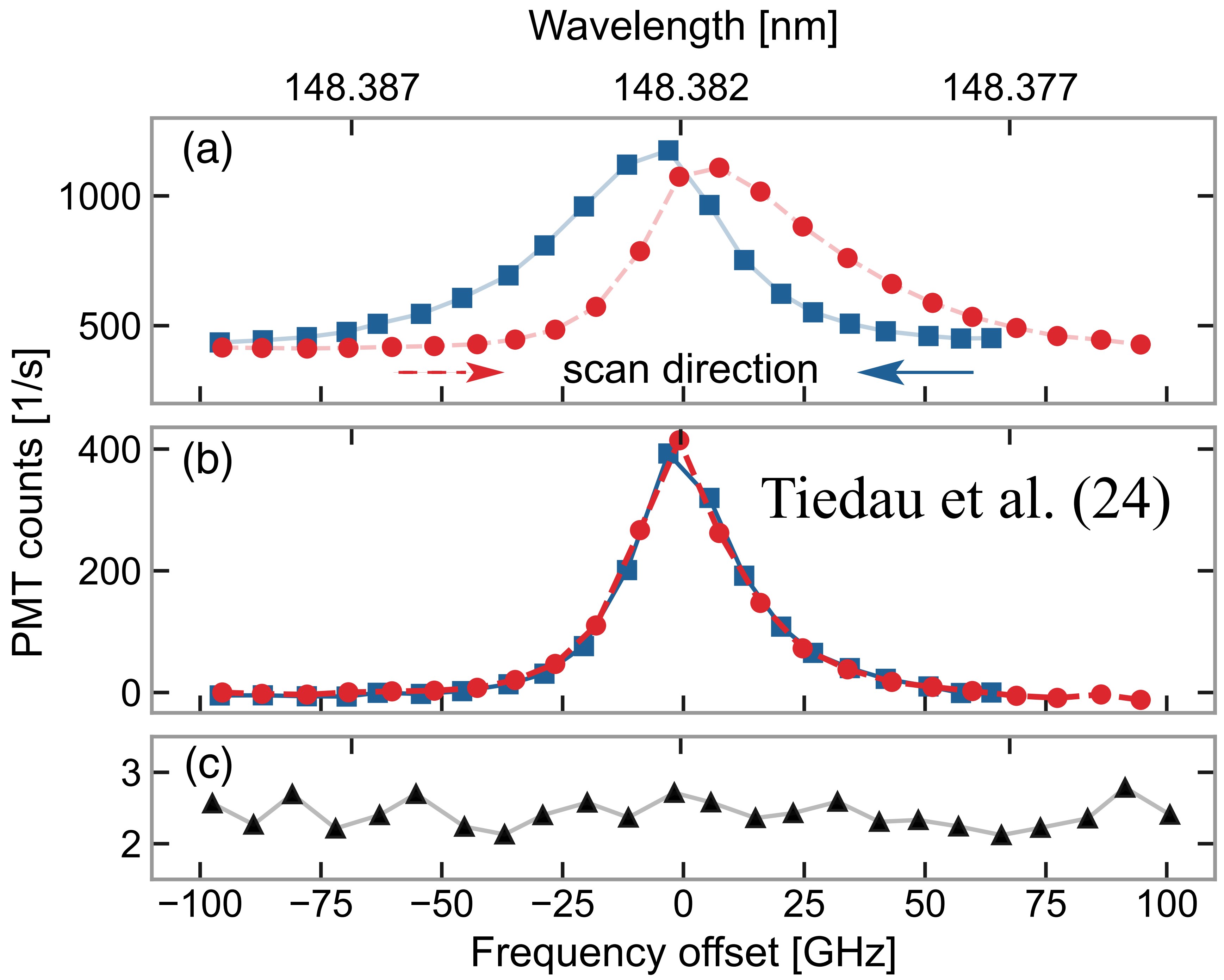
0.1 (2020) => 0.001 (2022) => 1:10^6 (Mar/Apr/24) => 1:10^{11} (Jun/24)

Mathematica's fit to double exponent:
IP = LogPlot[10^(1.7^(t - 20)), {t, 20, 24.5}];
Show[{LP, IP}]



What was measured ? (ex. from Tiedau et al.)

- Used super broad super powerful laser ~ few GHz to shine on Th-229-doped CaF_2 crystal
- 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



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

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:

$$f_{\mathrm{Th-229}} = \Delta E_{\mathrm{nu-clock}} \sim \Delta E_{\mathrm{nuc}} - \Delta E_{\mathrm{EM}} \sim 8\,\mathrm{eV} \ll \Delta E_{\mathrm{nuc}} \sim \Delta E_{\mathrm{EM}}$$

Therefore the lore says: $K_{\mathrm{canc}} = \Delta E_{\mathrm{nuc}}/f_{\mathrm{Th-229}} \sim 10^5 \gg 1$

- Now let's assume that we have a UDM couples only to the QCD sector ($\alpha_s(t)$):

$$\frac{\partial \log f_{\mathrm{Th-229}}}{\partial \log \alpha_s} = \frac{\alpha_s}{f_{\mathrm{Th-229}}}\frac{\partial \Delta E_{\mathrm{nuc}}}{\partial \alpha_s} = \frac{E_{\mathrm{nuc}}}{f_{\mathrm{Th-229}}}\frac{\partial \log E_{\mathrm{nuc}}}{\partial \log \alpha_s} \equiv K_{\mathrm{canc}} \times \frac{\partial \log E_{\mathrm{nuc}}}{\partial \log \alpha_s}$$

⬇

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

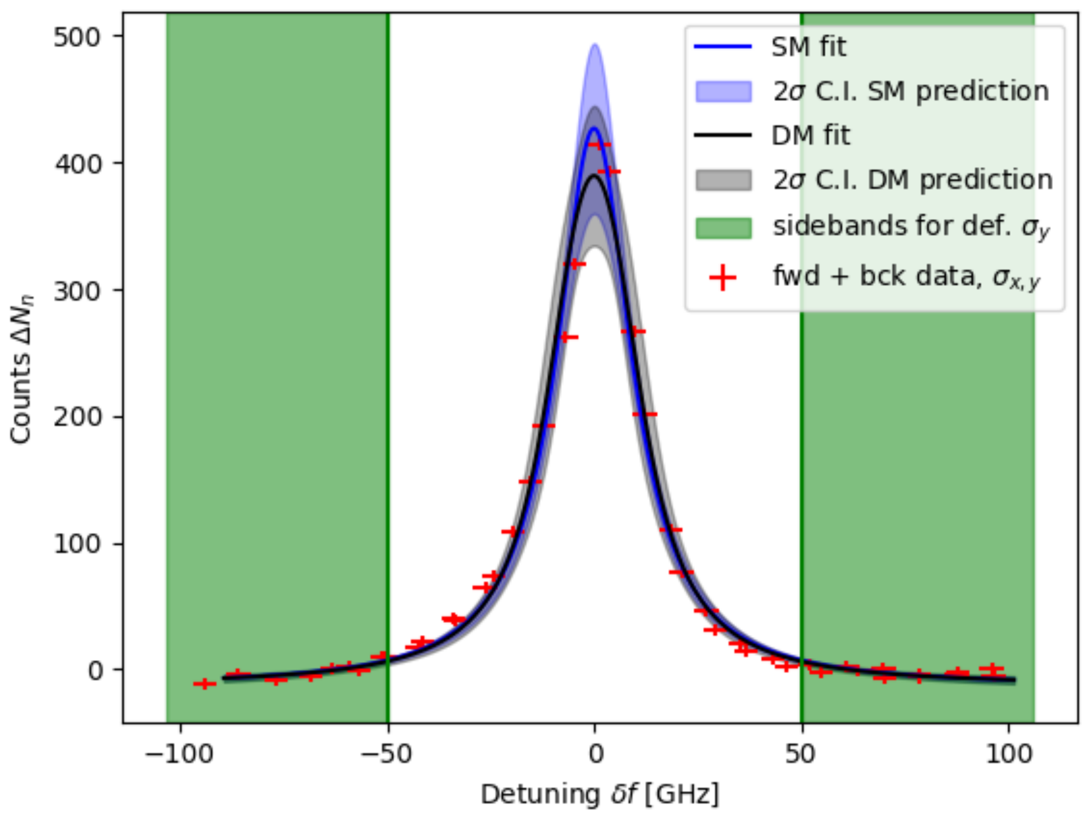
Present and near future implications

- We have now $\frac{\delta f}{f} \sim 10^{-6-11}$, this should be translated to effective sensitivity

$$\frac{\delta f}{f} \times R_{\text{atom}} \times K_{\text{canc}} \sim \ 10^{-14-19} - 10^{-16-21}$$ of atomic clocks, possibly beyond the frontier!

- However, how can we use the existing info where nuclear clocks are unavailable ?

- Line shape analysis:



can already be used to search for DM

& other phenomena

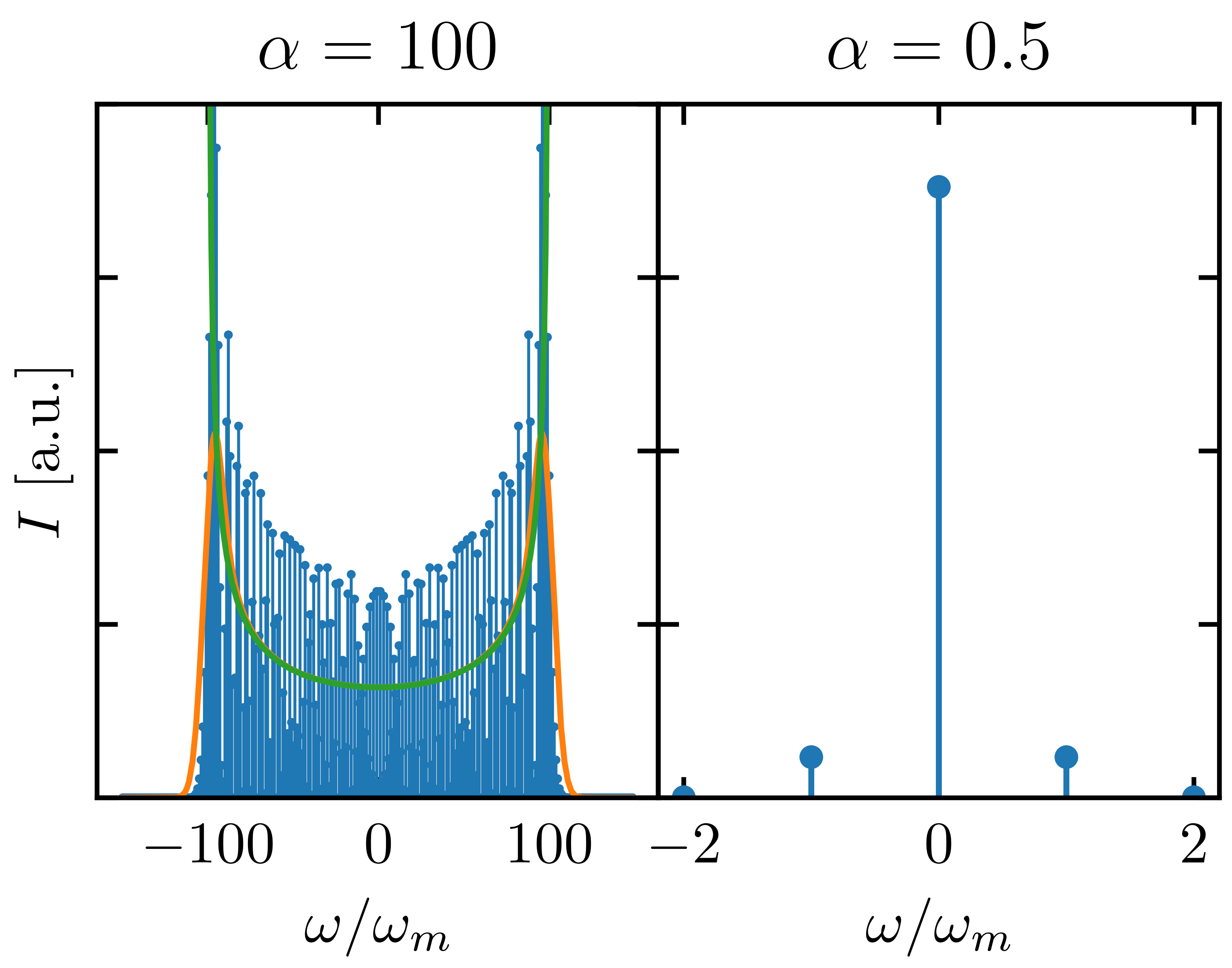
with: Elina Fuchs, Fiona Kirk, Eric Madge, Chaitanya Paranjape, Ekkehard Peik, Wolfram Ratzinger & Johannes Tiedau

Searching for DM via the line shape

- Line shape analysis, we can understand via considering 2 interesting limits:

(*i*) slow oscillation - (DM-mass)$^{-1}$ >> typical time scale of measurement => drift of line

(*ii*) fast oscillation - (DM-mass)$^{-1}$ << typical time scale => sidebands, and if the amplitude of oscillation >> DM-mass => "Barad-Dur" modification of line  => new constrain

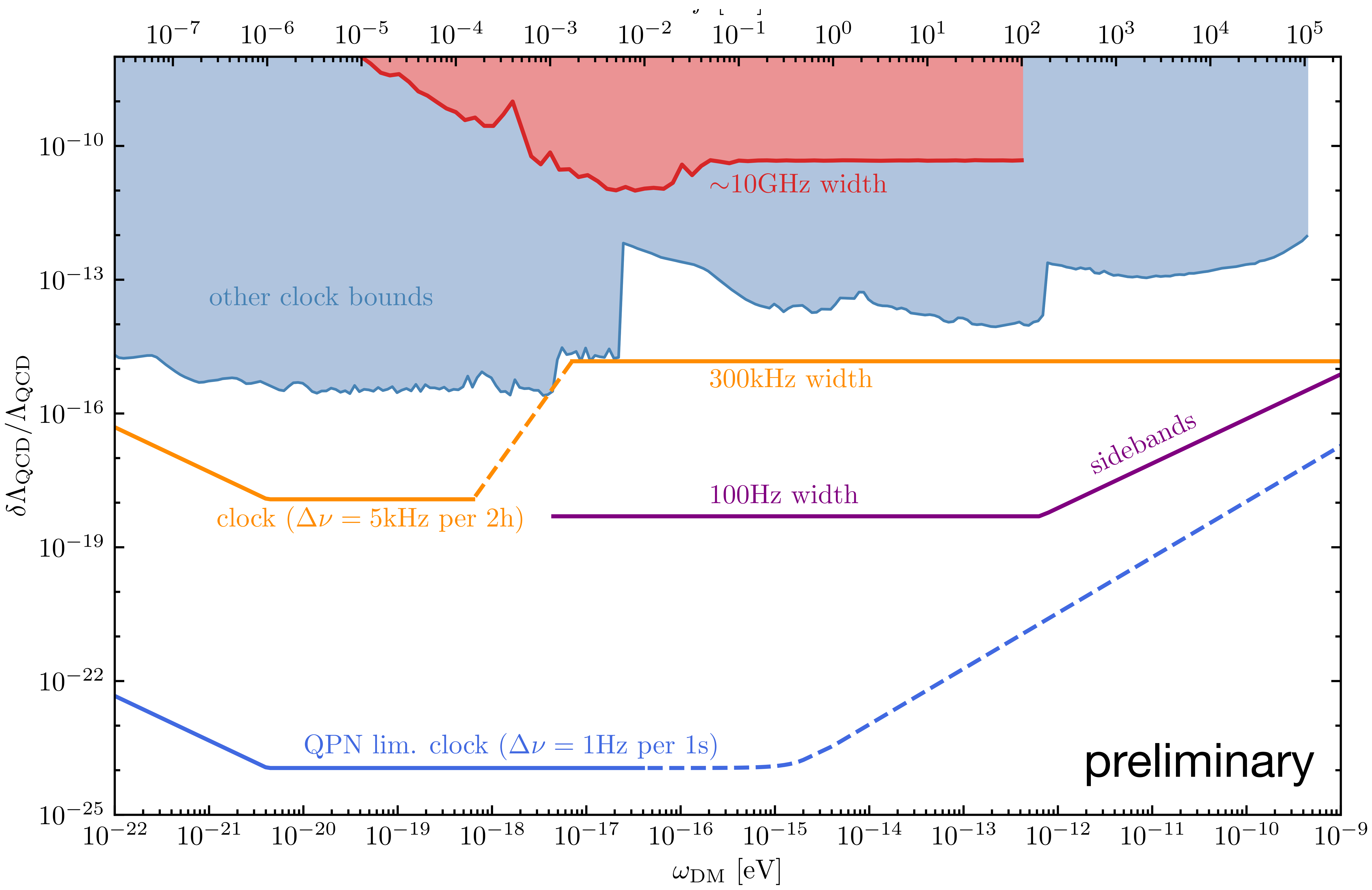


$$\nu(t) \simeq \nu_0 + \delta\nu_{\rm DM}\cos(\omega_{\rm DM}t + \varphi_{\rm DM})$$

$$\alpha = 2\pi\delta\nu_{\rm DM}/\omega_{\rm DM}$$

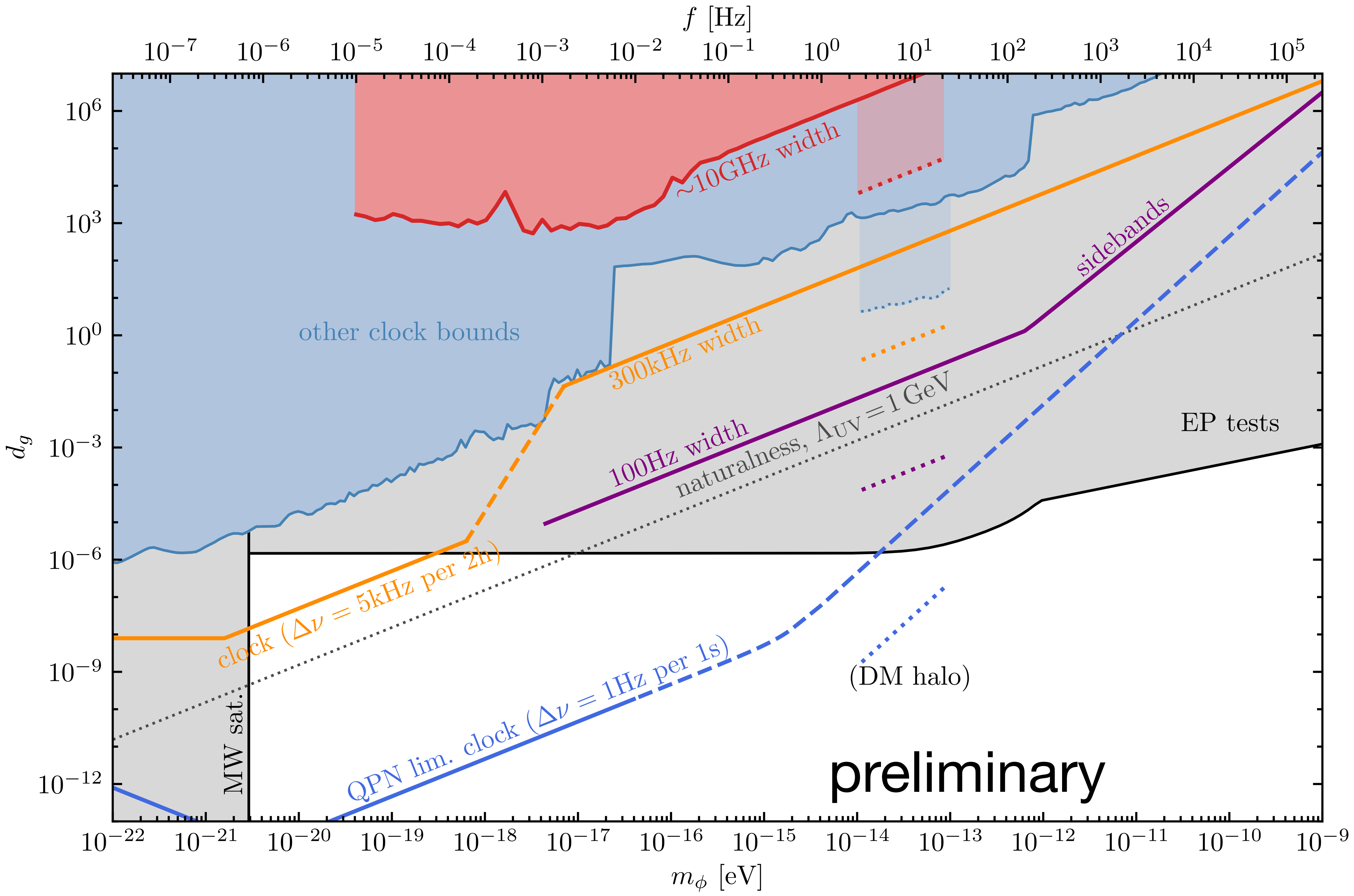
Using Th-229 to search for oscillating signal

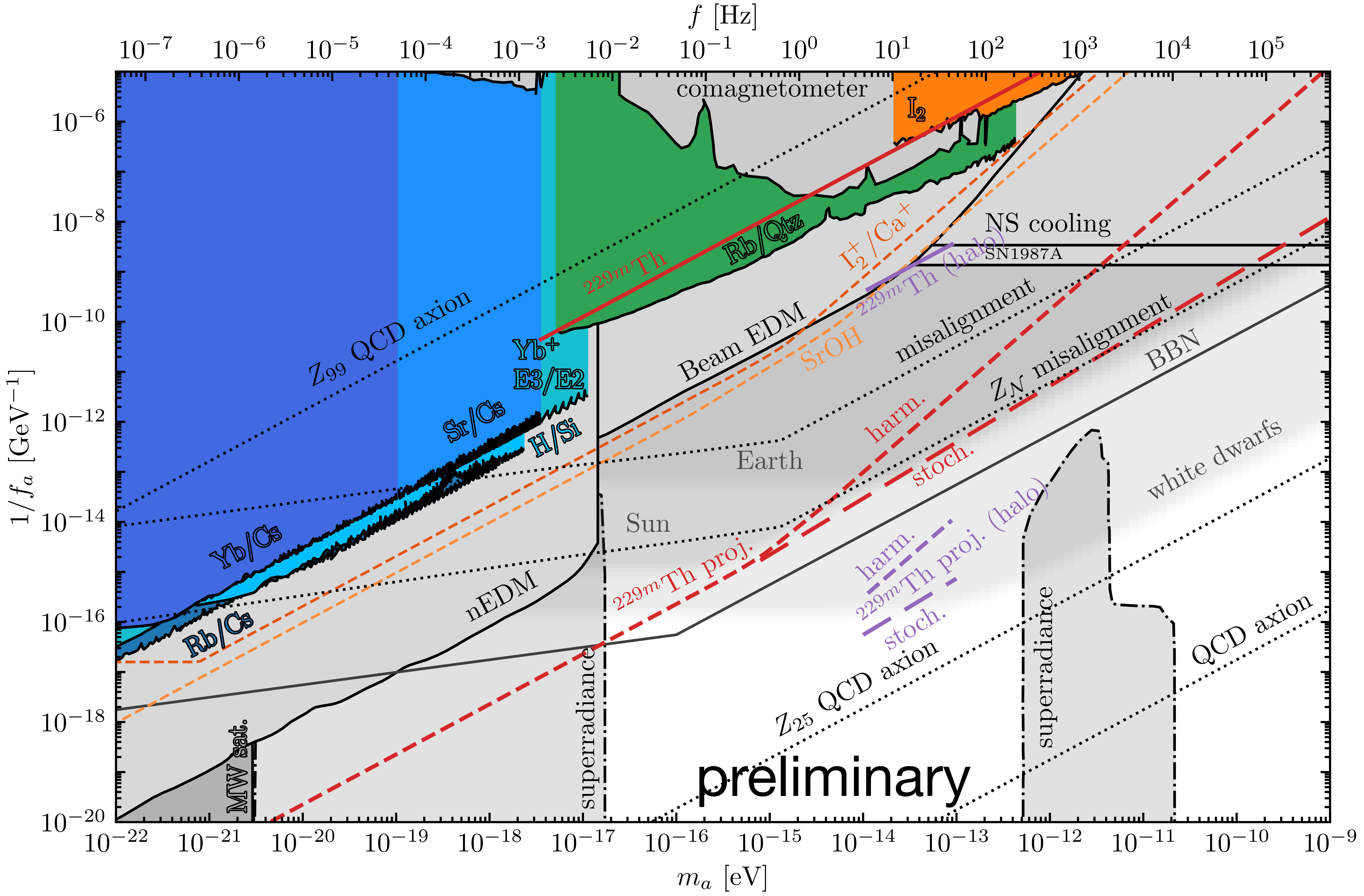
Th-229 as a QCDometer, nuclear supremacy?



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

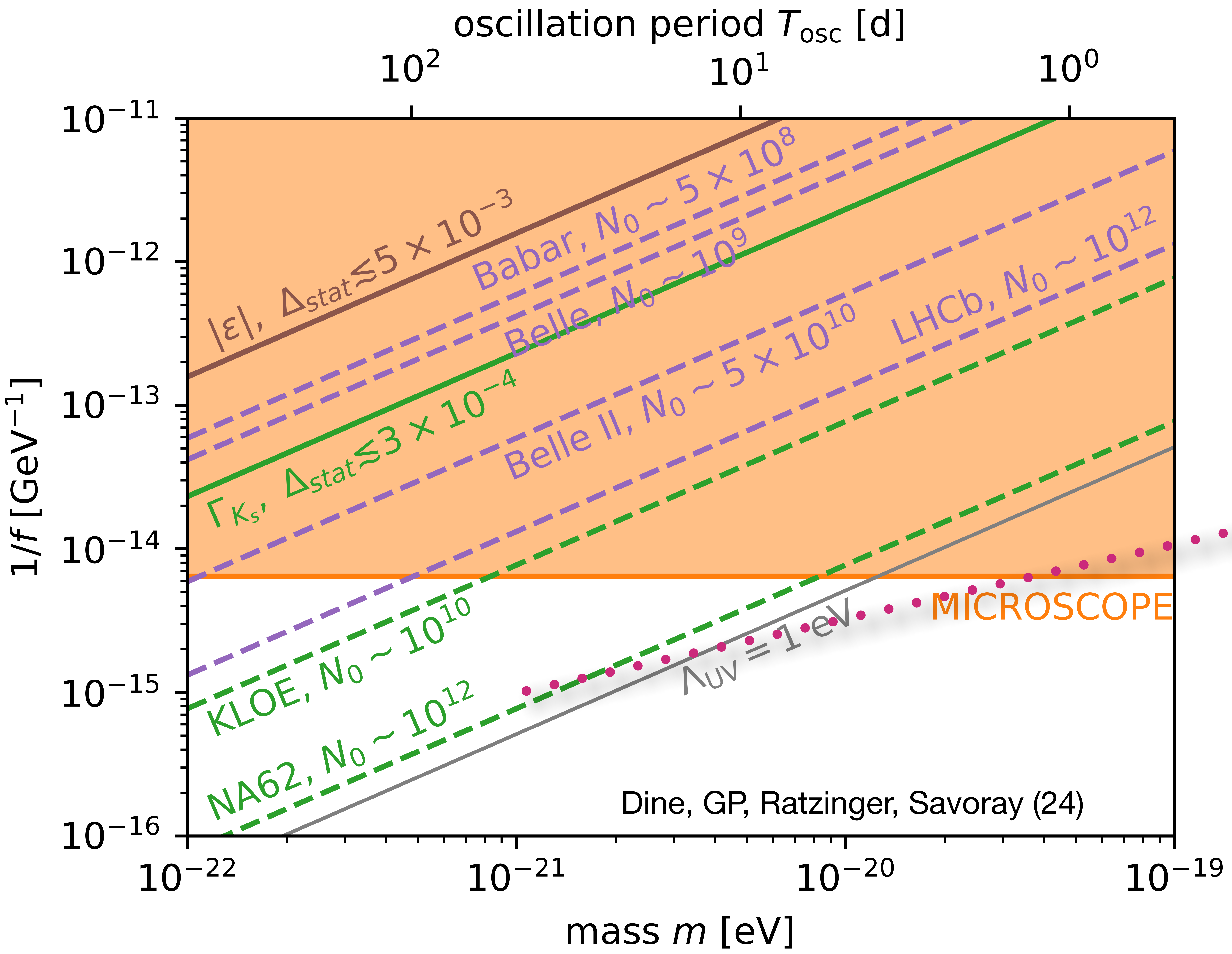
Using Th-229 to search for UDM signal

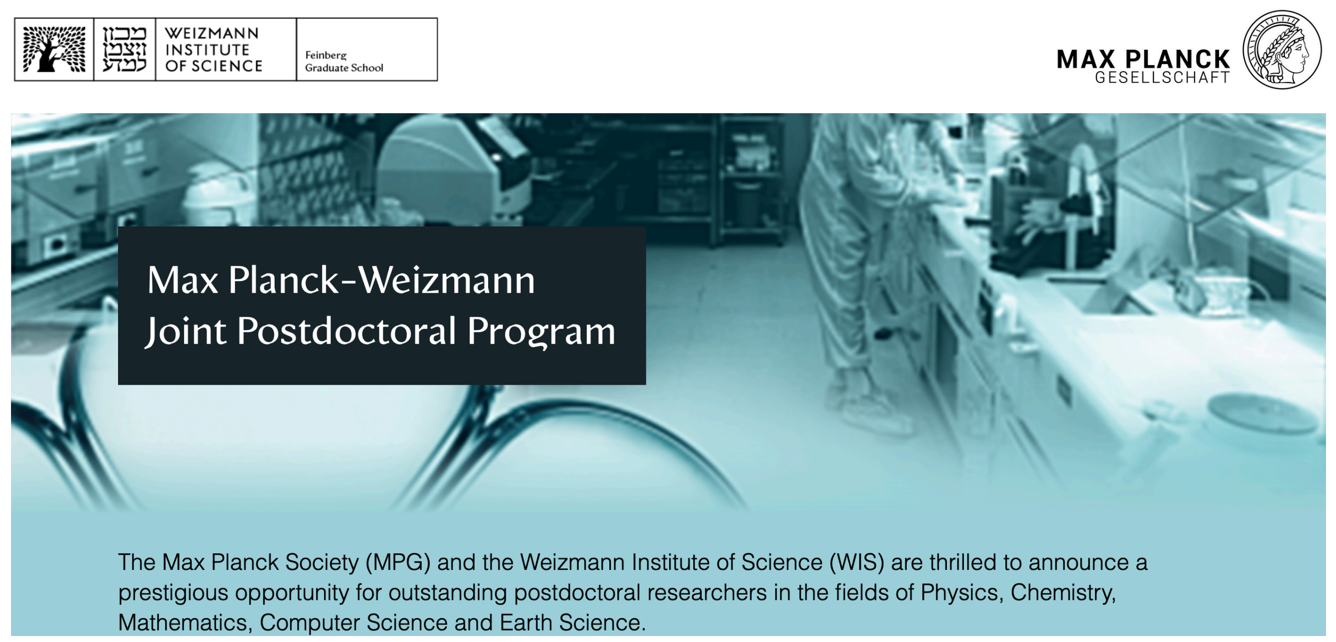




with: Elina Fuchs, Fiona Kirk, Eric Madge, Chaitanya Paranjape, Ekkehard Peik, Wolfram Ratzinger & Johannes Tiedau

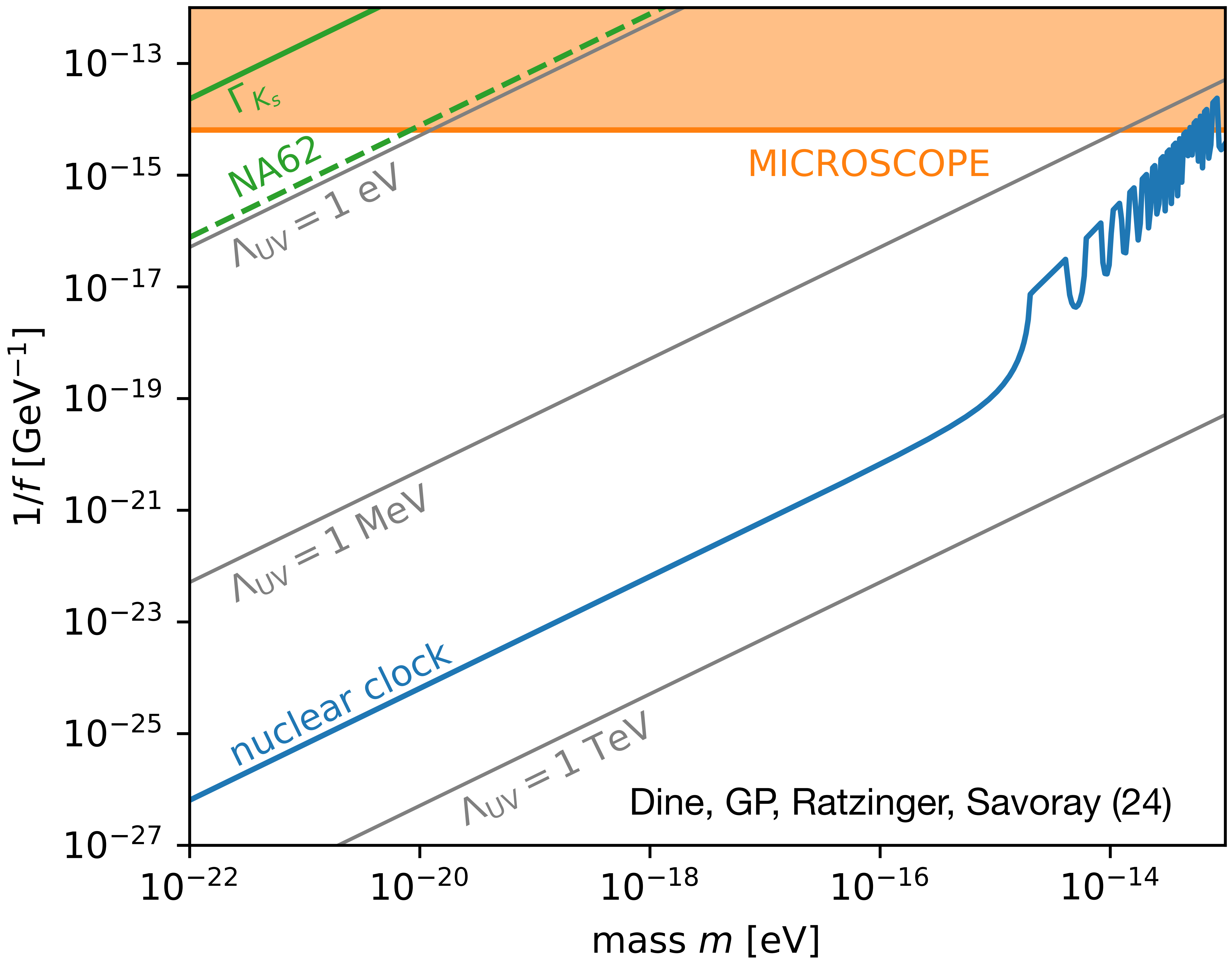
Nelson-Barr-UDM parameter space, luminosity exp.





Joint postdoc: P. Chiatto \w Babette Dobrich

Nelson-Barr-UDM & nuclear clock



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, $K_{\rm canc} = \Delta E_{\rm nu}/\Delta E_{\rm nu-clock} \sim 10^5 \gg 1$?

- Calculation of the nuclear binding energy difference is very challenging …

- Can instead consider at the electrostatic binding energy of the two states

- We provide two ways to do it:

  (i) classical approach to the nuclei (charge density is a simple function)

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

  (ii) QFT-EFT inspired way, using QM model of the neutron-core system

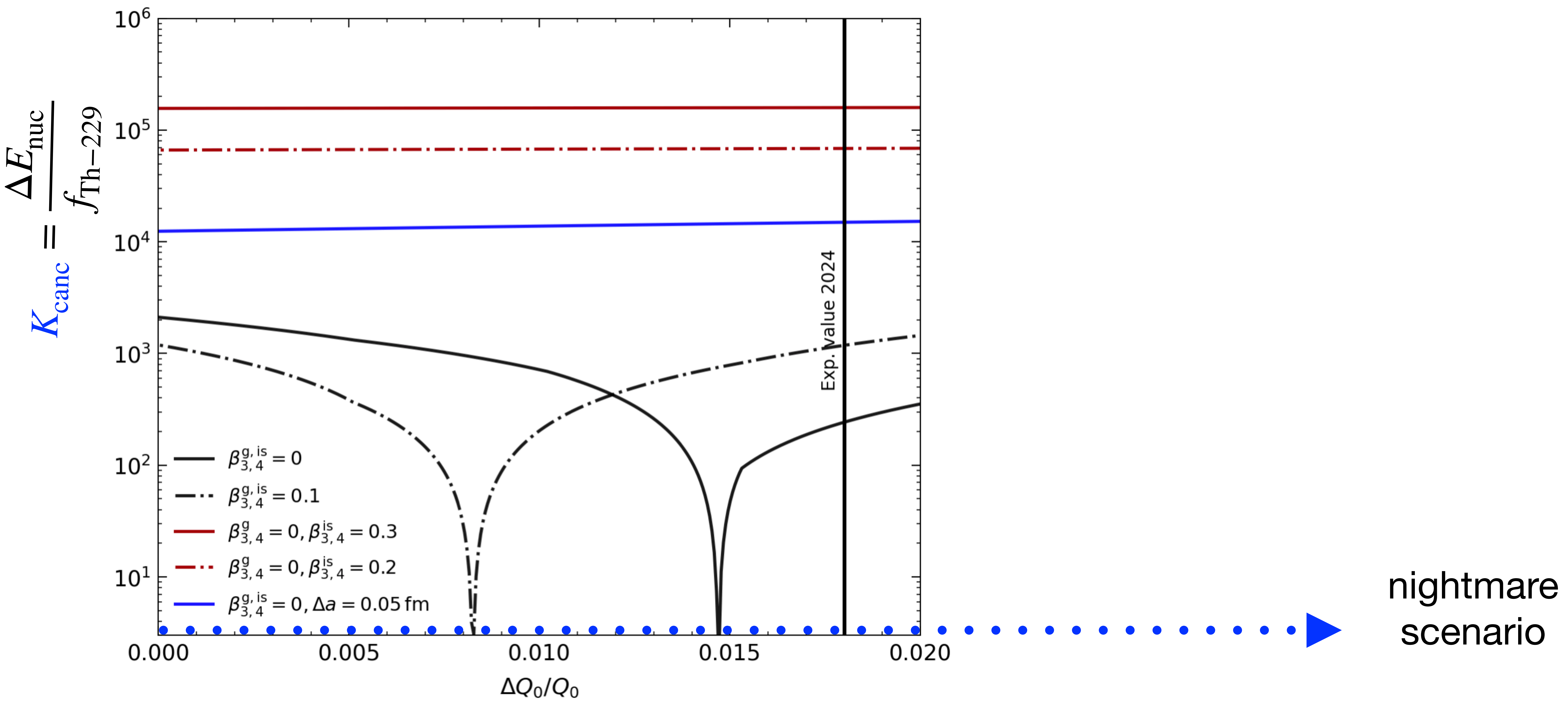
  Hammer, König, & van Kolck (19)

Geometrical/classical model

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

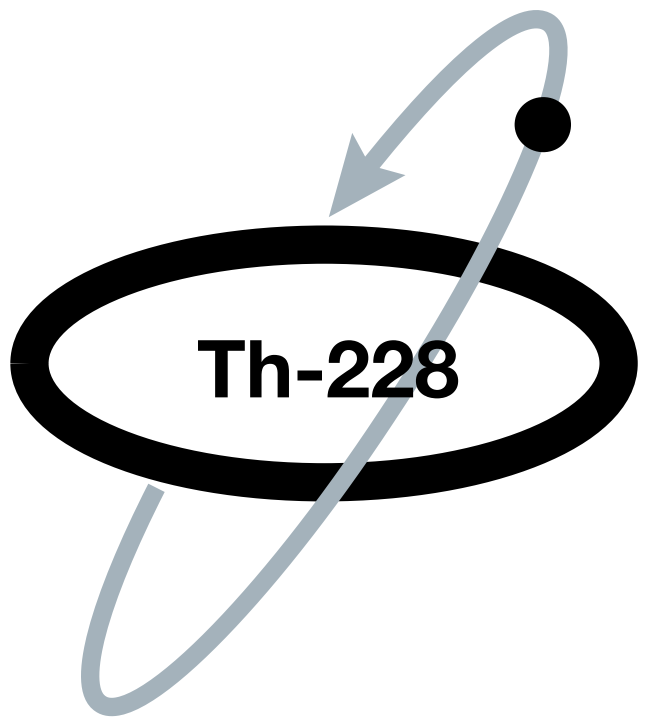
- Given a shape and charge density of both states we can evaluate $\Delta E_{\rm EM}$
- Result depends on number of variables (some are measured some are not)

with Q_0 being the quadrupole moment, Δ stands for isomer-ground-state difference, $\beta_{3,4}$ corresponds to higher moments (charge radius is set to mean) Δa corresponds to thickness using WS (Fermi) distribution



Halo-inspired model

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



- Consider QM model of single neutron at d=2 state, weakly boundedfar from a Th-228 core
- Th-228 is a scalar thus one can match all the effects to a simple leading set of operators and calculate observables, up to possible short distance effects
- The results are rather interesting (exciting?), but you'd have to wait for the paper to see how these fare with data, and the prediction of $K_{\rm canc}$ …

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 sector

  (ii) enhanced sensitivity due to the fine cancellation
- New measurement => game changer moving to precision nuclear phase
- Existing measurement already give impressive bounds - nuclear supremacy?
- Discussed robustness

Backups

NB-UDM signature & parameter space

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

- How to search such signal?

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

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

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

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

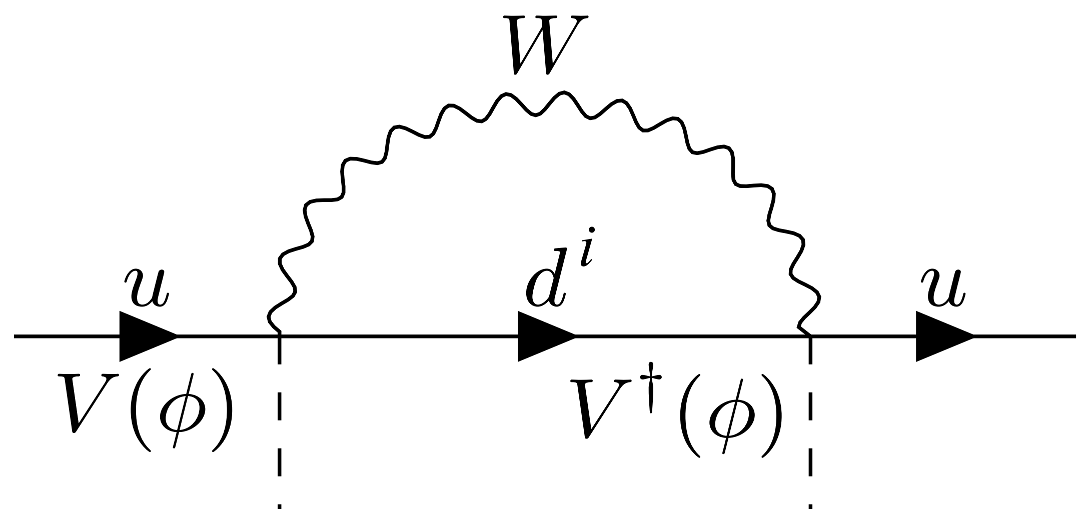
NB-UDM signature & parameter space

- 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}) $\Rightarrow f \gtrsim 10^{19}\,\mathrm{GeV} \times \frac{\mathrm{m_{NB}}}{10^{-15}\,\mathrm{eV}}$

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)

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

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
$\frac{\left\lvert d_{m_e}^{(1)}\right\rvert}{M_{\rm Pl}}\phi\, m_e\psi_e\psi_e^c$	$\left\lvert d_{m_e}^{(1)}\right\rvert \lesssim 2\times 10^{-3}$ [58]	DDM Oscillations
$i\frac{\left\lvert \tilde{d}_{m_e}^{(1)}\right\rvert}{M_{\rm Pl}}\phi\, m_e\psi_e\psi_e^c$	$\left\lvert \tilde{d}_{m_e}^{(1)}\right\rvert \lesssim 7\times 10^{8}$ [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
$\frac{\left\lvert d_{m_N}^{(1)}\right\rvert}{M_{\rm Pl}}\phi\, m_N\psi_N\psi_N^c$	$\left\lvert d_{m_N}^{(1)}\right\rvert \lesssim 2\times 10^{-6}$ [67]	EP test: MICROSCOPE
$i\frac{\left\lvert \tilde{d}_{m_N}^{(1)}\right\rvert}{M_{\rm Pl}}\phi\, m_N\psi_N\psi_N^c$	$\left\lvert \tilde{d}_{m_N}^{(1)}\right\rvert \lesssim 4$ [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

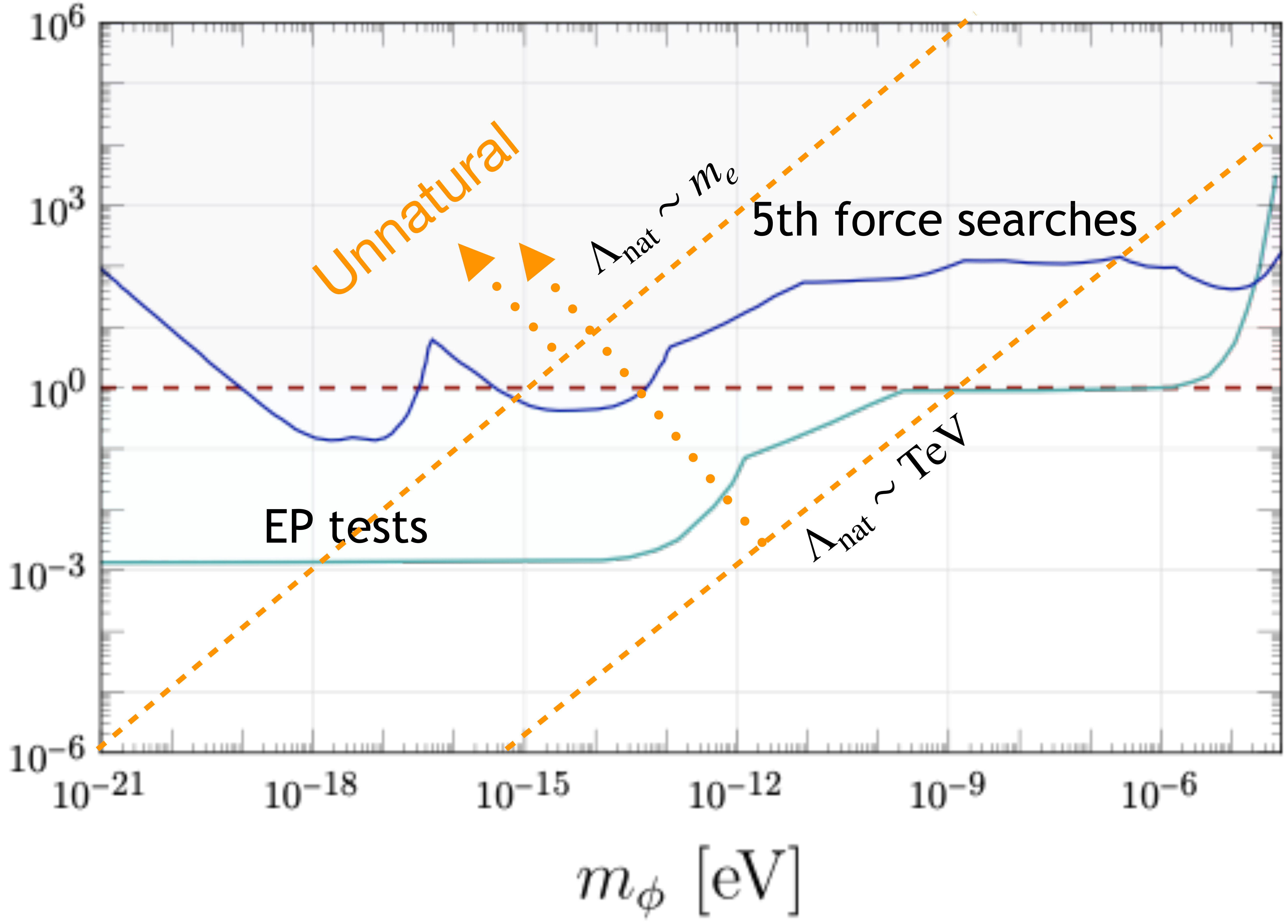
- It seems that genially linearly-coupled models are in troubles, however: If coupling is quadratic or more than situation is better -

$\frac{d_e^{(2)}}{8M_{\rm Pl}^2}\phi^2 F^{\mu\nu}F_{\mu\nu}$	$d_e^{(2)} \lesssim 10^{11}$ [67]	EP test: MICROSCOPE
$\frac{\left\vert d_{m_e}^{(2)}\right\vert}{2M_{\rm Pl}^2}\phi^2 m_e\psi_e\psi_e^c$	$\left\vert d_{m_e}^{(2)}\right\vert \lesssim 10^{12}$ [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.
$\frac{\left\vert d_{m_N}^{(2)}\right\vert}{2M_{\rm Pl}^2}\phi^2 m_N\psi_N\psi_N^c$	$\left\vert d_{m_N}^{(2)}\right\vert \lesssim 10^{11}$ [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 $\left(\alpha_s/8\right)\left(a/f\right)\ G\tilde{G}$ 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 $1{:}10^{18}$!