# New era in dark matter searches the dawn of the nuclear clocks

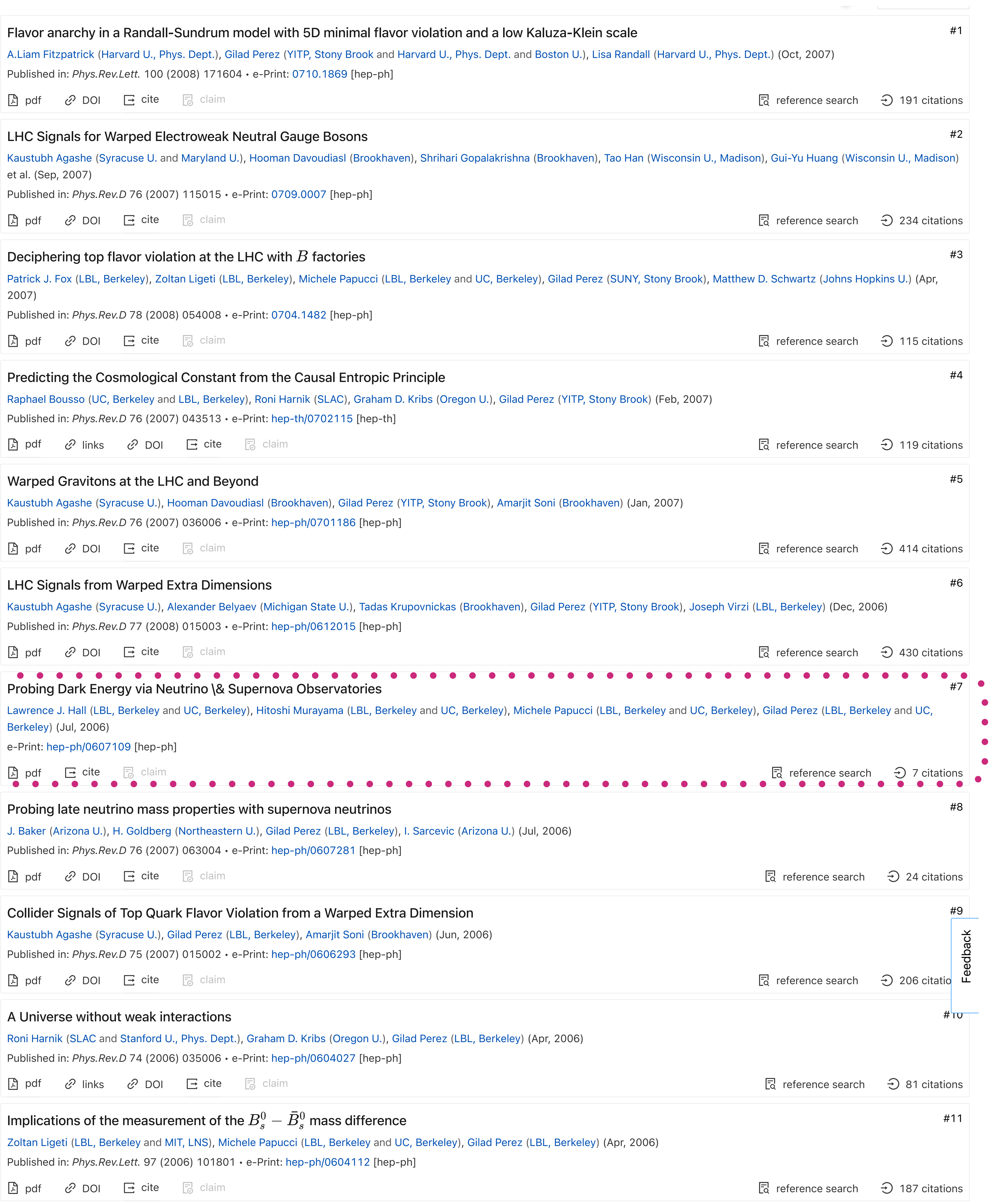
Gilad Perez

Weizmann Institute of Science

Unraveling the Particle World and the Cosmos at Berkeley

# Why my time at Berkeley was the best ever?
# How is it connected to Hitoshi & Lawrence ?

# Hitoshi & Lawrence: our miserable record together



Flavor anarchy in a Randall-Sundrum model with 5D minimal flavor violation and a low Kaluza-Klein scale #1
A.Liam Fitzpatrick (Harvard U., Phys. Dept.), Gilad Perez (YITP, Stony Brook and Harvard U., Phys. Dept. and Boston U.), Lisa Randall (Harvard U., Phys. Dept.) (Oct, 2007)
Published in: *Phys.Rev.Lett.* 100 (2008) 171604 • e-Print: 0710.1869 [hep-ph]

191 citations

LHC Signals for Warped Electroweak Neutral Gauge Bosons #2
Kaustubh Agashe (Syracuse U. and Maryland U.), Hooman Davoudiasl (Brookhaven), Shrihari Gopalakrishna (Brookhaven), Tao Han (Wisconsin U., Madison), Gui-Yu Huang (Wisconsin U., Madison) et al. (Sep, 2007)
Published in: *Phys.Rev.D* 76 (2007) 115015 • e-Print: 0709.0007 [hep-ph]

234 citations

Deciphering top flavor violation at the LHC with $B$ factories #3
Patrick J. Fox (LBL, Berkeley), Zoltan Ligeti (LBL, Berkeley), Michele Papucci (LBL, Berkeley and UC, Berkeley), Gilad Perez (SUNY, Stony Brook), Matthew D. Schwartz (Johns Hopkins U.) (Apr, 2007)
Published in: *Phys.Rev.D* 78 (2008) 054008 • e-Print: 0704.1482 [hep-ph]

115 citations

Predicting the Cosmological Constant from the Causal Entropic Principle #4
Raphael Bousso (UC, Berkeley and LBL, Berkeley), Roni Harnik (SLAC), Graham D. Kribs (Oregon U.), Gilad Perez (YITP, Stony Brook) (Feb, 2007)
Published in: *Phys.Rev.D* 76 (2007) 043513 • e-Print: hep-th/0702115 [hep-th]

119 citations

Warped Gravitons at the LHC and Beyond #5
Kaustubh Agashe (Syracuse U.), Hooman Davoudiasl (Brookhaven), Gilad Perez (YITP, Stony Brook), Amarjit Soni (Brookhaven) (Jan, 2007)
Published in: *Phys.Rev.D* 76 (2007) 036006 • e-Print: hep-ph/0701186 [hep-ph]

414 citations

LHC Signals from Warped Extra Dimensions #6
Kaustubh Agashe (Syracuse U.), Alexander Belyaev (Michigan State U.), Tadas Krupovnickas (Brookhaven), Gilad Perez (YITP, Stony Brook), Joseph Virzi (LBL, Berkeley) (Dec, 2006)
Published in: *Phys.Rev.D* 77 (2008) 015003 • e-Print: hep-ph/0612015 [hep-ph]

430 citations

Probing Dark Energy via Neutrino \& Supernova Observatories #7
Lawrence J. Hall (LBL, Berkeley and UC, Berkeley), Hitoshi Murayama (LBL, Berkeley and UC, Berkeley), Michele Papucci (LBL, Berkeley and UC, Berkeley), Gilad Perez (LBL, Berkeley and UC, Berkeley) (Jul, 2006)
e-Print: hep-ph/0607109 [hep-ph]

7 citations

Probing late neutrino mass properties with supernova neutrinos #8
J. Baker (Arizona U.), H. Goldberg (Northeastern U.), Gilad Perez (LBL, Berkeley), I. Sarcevic (Arizona U.) (Jul, 2006)
Published in: *Phys.Rev.D* 76 (2007) 063004 • e-Print: hep-ph/0607281 [hep-ph]

24 citations

Collider Signals of Top Quark Flavor Violation from a Warped Extra Dimension #9
Kaustubh Agashe (Syracuse U.), Gilad Perez (LBL, Berkeley), Amarjit Soni (Brookhaven) (Jun, 2006)
Published in: *Phys.Rev.D* 75 (2007) 015002 • e-Print: hep-ph/0606293 [hep-ph]

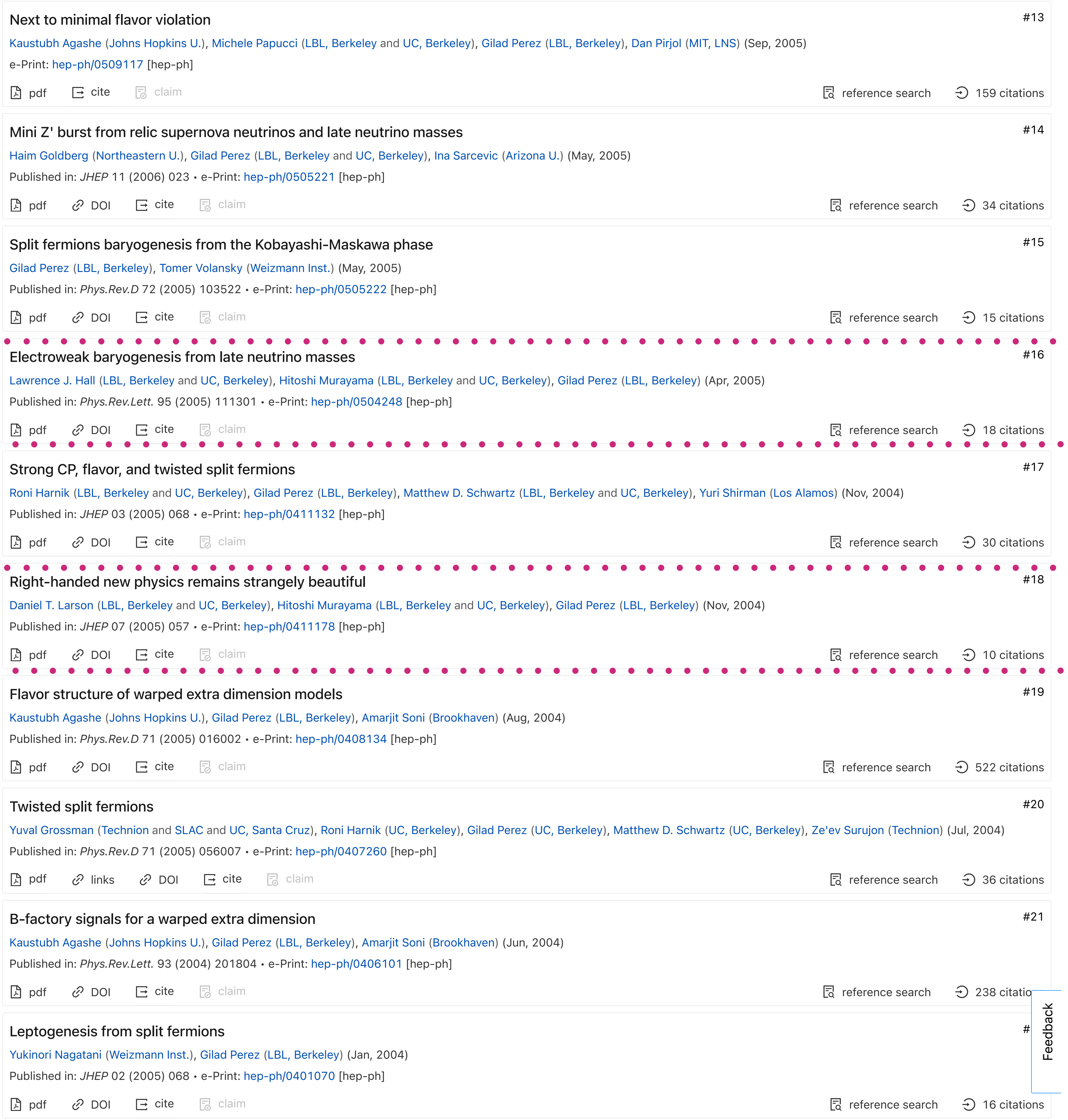
206 citatio

A Universe without weak interactions #10
Roni Harnik (SLAC and Stanford U., Phys. Dept.), Graham D. Kribs (Oregon U.), Gilad Perez (LBL, Berkeley) (Apr, 2006)
Published in: *Phys.Rev.D* 74 (2006) 035006 • e-Print: hep-ph/0604027 [hep-ph]

81 citations

Implications of the measurement of the $B_s^0 - \bar{B}_s^0$ mass difference #11
Zoltan Ligeti (LBL, Berkeley and MIT, LNS), Michele Papucci (LBL, Berkeley and UC, Berkeley), Gilad Perez (LBL, Berkeley) (Apr, 2006)
Published in: *Phys.Rev.Lett.* 97 (2006) 101801 • e-Print: hep-ph/0604112 [hep-ph]

187 citations



Next to minimal flavor violation #13
Kaustubh Agashe (Johns Hopkins U.), Michele Papucci (LBL, Berkeley and UC, Berkeley), Gilad Perez (LBL, Berkeley), Dan Pirjol (MIT, LNS) (Sep, 2005)
e-Print: hep-ph/0509117 [hep-ph]

159 citations

Mini Z' burst from relic supernova neutrinos and late neutrino masses #14
Haim Goldberg (Northeastern U.), Gilad Perez (LBL, Berkeley and UC, Berkeley), Ina Sarcevic (Arizona U.) (May, 2005)
Published in: *JHEP* 11 (2006) 023 • e-Print: hep-ph/0505221 [hep-ph]

34 citations

Split fermions baryogenesis from the Kobayashi-Maskawa phase #15
Gilad Perez (LBL, Berkeley), Tomer Volansky (Weizmann Inst.) (May, 2005)
Published in: *Phys.Rev.D* 72 (2005) 103522 • e-Print: hep-ph/0505222 [hep-ph]

15 citations

Electroweak baryogenesis from late neutrino masses #16
Lawrence J. Hall (LBL, Berkeley and UC, Berkeley), Hitoshi Murayama (LBL, Berkeley and UC, Berkeley), Gilad Perez (LBL, Berkeley) (Apr, 2005)
Published in: *Phys.Rev.Lett.* 95 (2005) 111301 • e-Print: hep-ph/0504248 [hep-ph]

18 citations

Strong CP, flavor, and twisted split fermions #17
Roni Harnik (LBL, Berkeley and UC, Berkeley), Gilad Perez (LBL, Berkeley), Matthew D. Schwartz (LBL, Berkeley and UC, Berkeley), Yuri Shirman (Los Alamos) (Nov, 2004)
Published in: *JHEP* 03 (2005) 068 • e-Print: hep-ph/0411132 [hep-ph]

30 citations

Right-handed new physics remains strangely beautiful #18
Daniel T. Larson (LBL, Berkeley and UC, Berkeley), Hitoshi Murayama (LBL, Berkeley and UC, Berkeley), Gilad Perez (LBL, Berkeley) (Nov, 2004)
Published in: *JHEP* 07 (2005) 057 • e-Print: hep-ph/0411178 [hep-ph]

10 citations

Flavor structure of warped extra dimension models #19
Kaustubh Agashe (Johns Hopkins U.), Gilad Perez (LBL, Berkeley), Amarjit Soni (Brookhaven) (Aug, 2004)
Published in: *Phys.Rev.D* 71 (2005) 016002 • e-Print: hep-ph/0408134 [hep-ph]

522 citations

Twisted split fermions #20
Yuval Grossman (Technion and SLAC and UC, Santa Cruz), Roni Harnik (UC, Berkeley), Gilad Perez (UC, Berkeley), Matthew D. Schwartz (UC, Berkeley), Ze'ev Surujon (Technion) (Jul, 2004)
Published in: *Phys.Rev.D* 71 (2005) 056007 • e-Print: hep-ph/0407260 [hep-ph]

36 citations

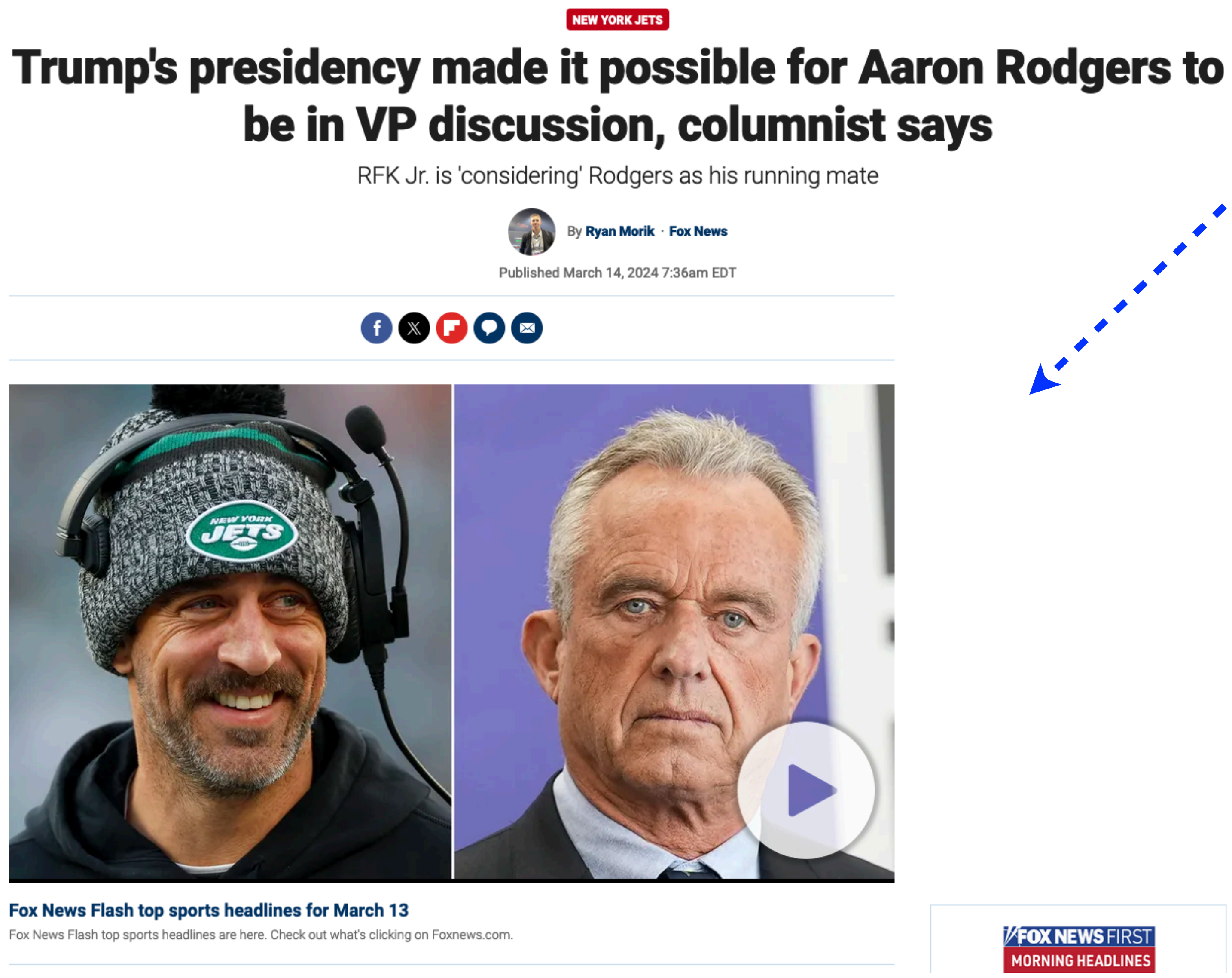
B-factory signals for a warped extra dimension #21
Kaustubh Agashe (Johns Hopkins U.), Gilad Perez (LBL, Berkeley), Amarjit Soni (Brookhaven) (Jun, 2004)
Published in: *Phys.Rev.Lett.* 93 (2004) 201804 • e-Print: hep-ph/0406101 [hep-ph]

238 citatio

Leptogenesis from split fermions #
Yukinori Nagatani (Weizmann Inst.), Gilad Perez (LBL, Berkeley) (Jan, 2004)
Published in: *JHEP* 02 (2005) 068 • e-Print: hep-ph/0401070 [hep-ph]

16 citations

# Combination of intensity & freedom



NEW YORK JETS

**Trump's presidency made it possible for Aaron Rodgers to be in VP discussion, columnist says**

RFK Jr. is 'considering' Rodgers as his running mate

By **Ryan Morik** · **Fox News**

Published March 14, 2024 7:36am EDT

**Fox News Flash top sports headlines for March 13**

Fox News Flash top sports headlines are here. Check out what's clicking on Foxnews.com.

# Lawrence Hall joy of physics

# Lawrence Hall joy of physics

# Combination of intensity & freedom

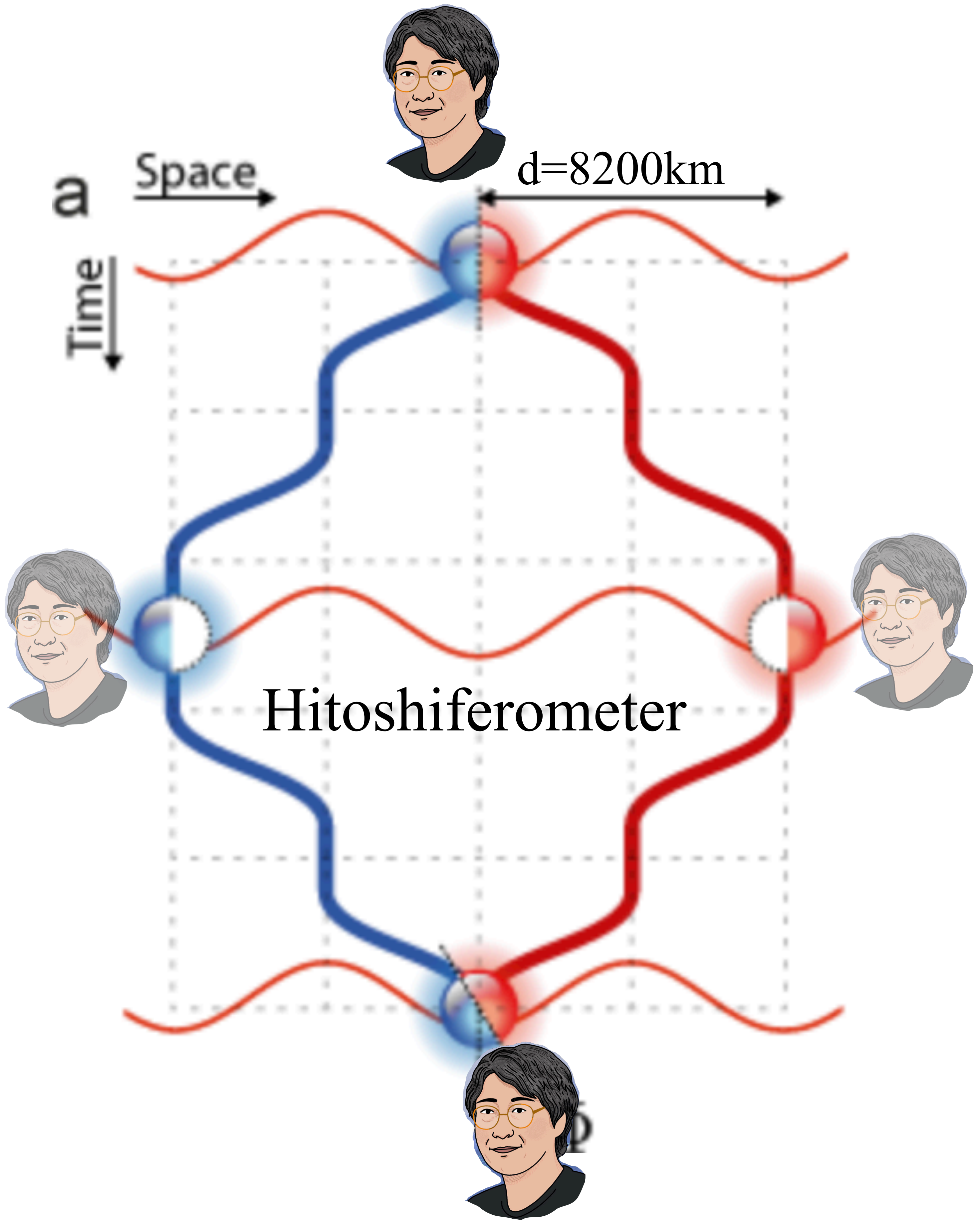
Enabling atmosphere to freely speculate:

Landscape Prediction for the Higgs Boson and Top Quark Masses
Feldstein, Hall & Watari (06)

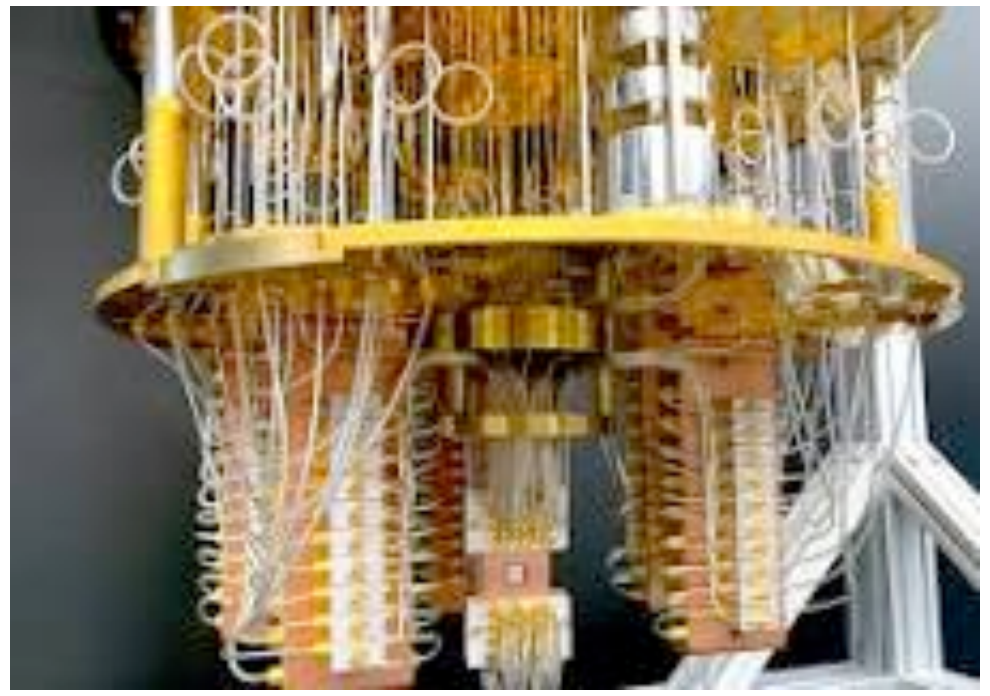
The weakness universe
Harnik, Kribs & GP (06)

# Quantum Hitoshi

Several people swore they saw you at
different location same time



Encyclopedic expertise
Quantum brain



***Supporting the postdocs***
***Positive reinforcement***
***Spreading the knowledge***

# Prologue

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

1:10 (2020) => 1:$10^3$ (2022) => 1:$10^6$ (Mar/Apr/24) => 1:$10^{11}$ (Jun/24)

We're on a verge of a new era

sensitivity to models may be improved soon by $10^{10}$

How ?

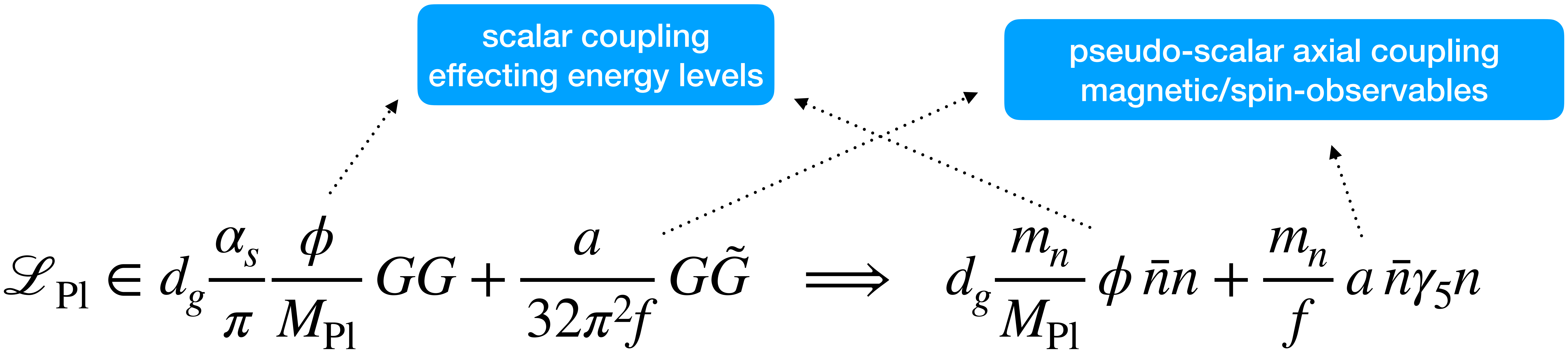
Caveats ?

# Outline

- Intro: current status, UDM searches
- Laser excitation of Th-229 (news, sensitivity & robustness)
- Probes of non-dark-matter physics, nuclear clock as “QCDometer”
- Summary

# 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

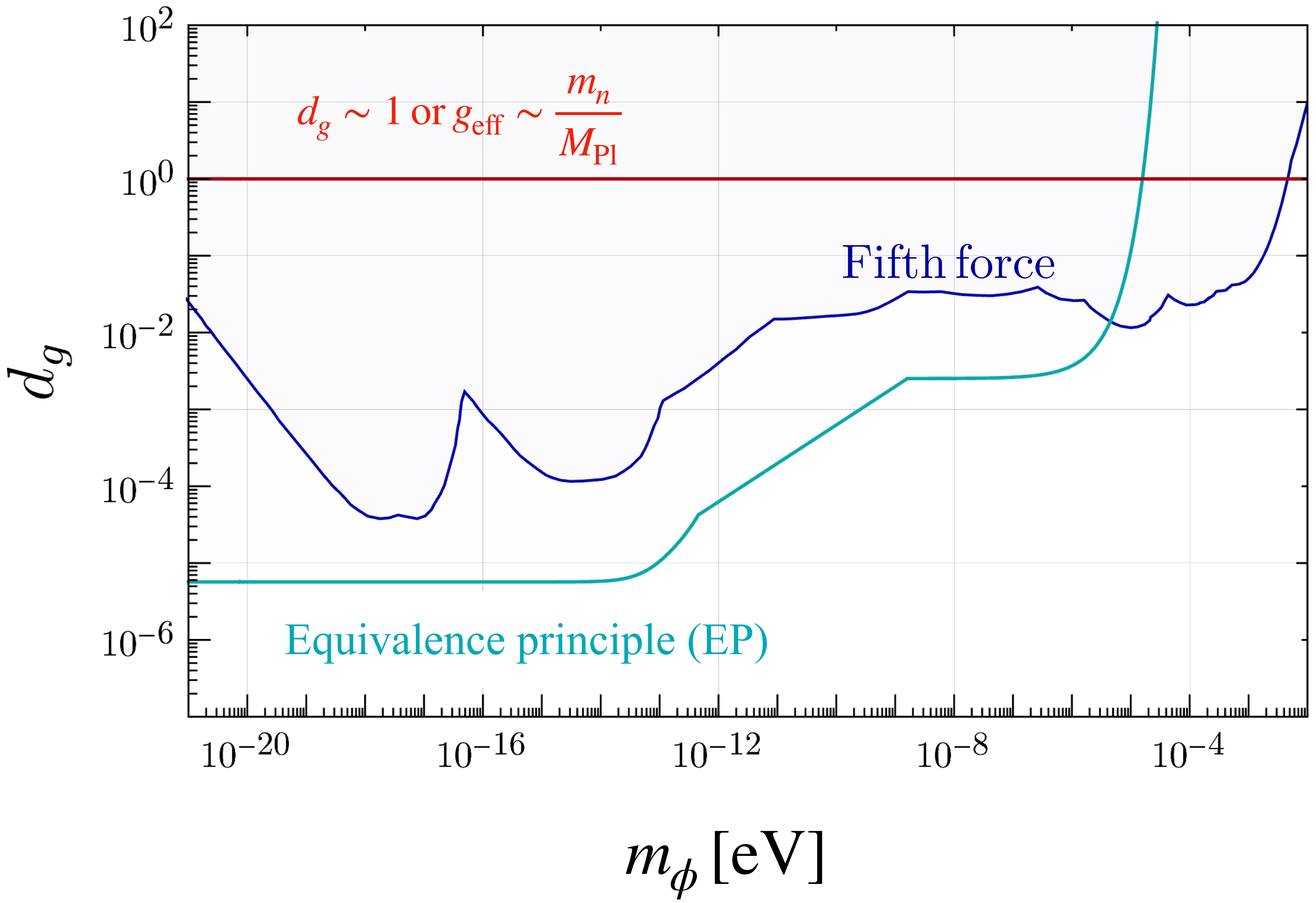
pseudo-scalar axial coupling magnetic/spin-observables

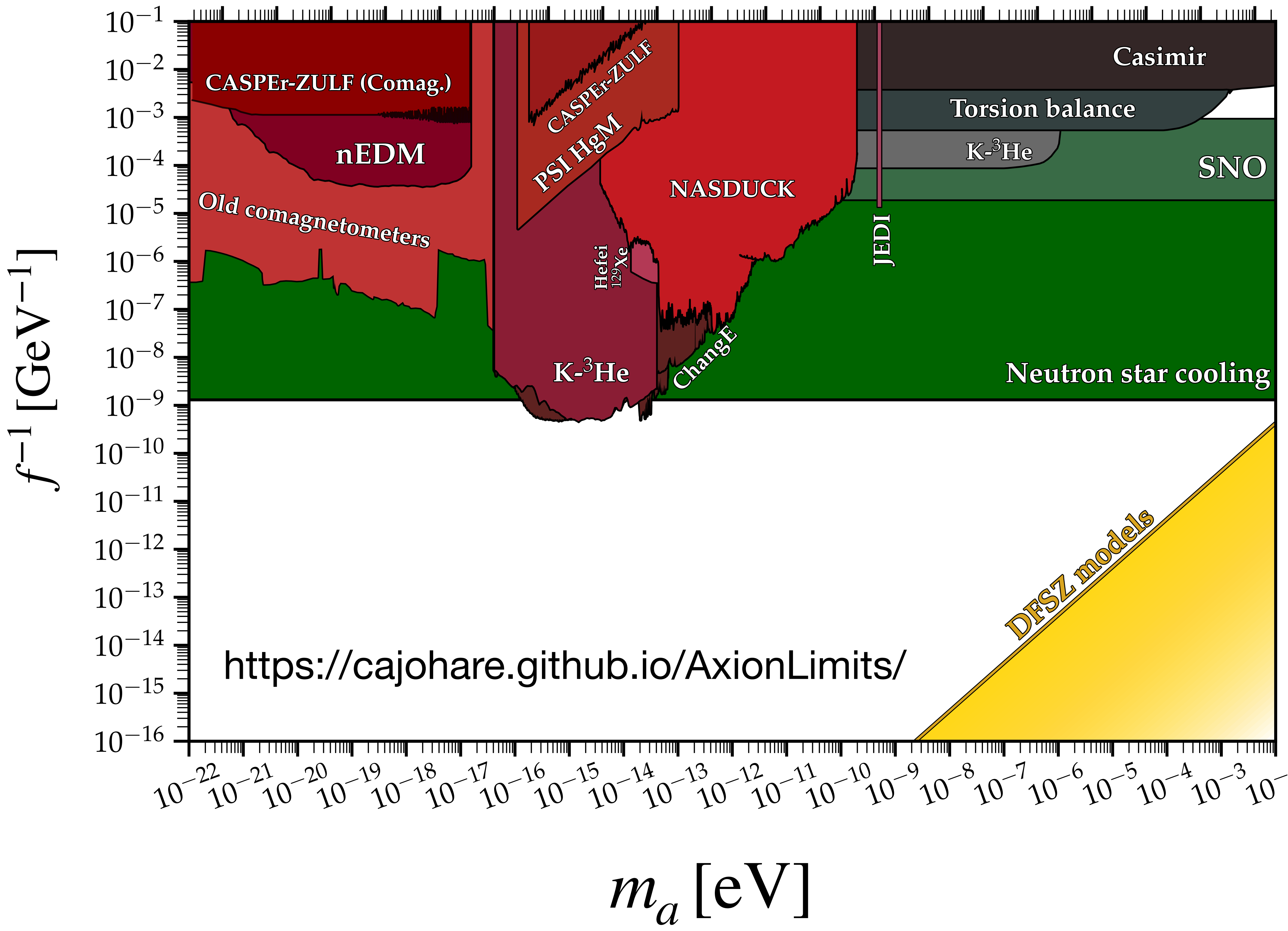
$$\mathscr{L}_{\mathrm{Pl}} \in d_g \frac{\alpha_s}{\pi}\frac{\phi}{M_{\mathrm{Pl}}} GG + \frac{a}{32\pi^2 f} G\tilde{G} \quad \Longrightarrow \quad d_g \frac{m_n}{M_{\mathrm{Pl}}}\phi\,\bar{n}n + \frac{m_n}{f}\,a\,\bar{n}\gamma_5 n$$

# Scalar coupling vs/ pseudo-scalar axial coupling

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

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



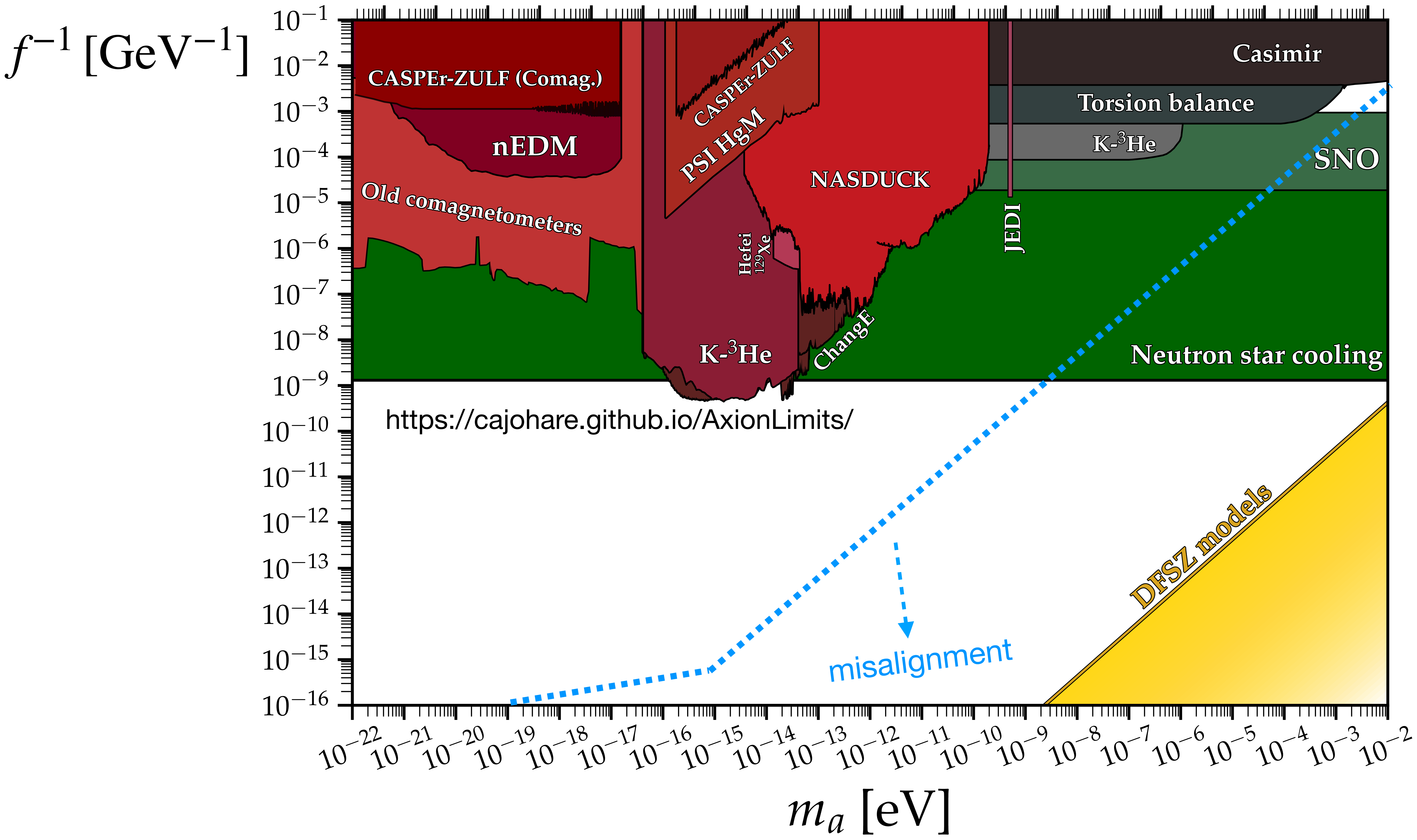


EP: Planck suppressed operators excluded for $m_\phi \lesssim 10^{-5}$ eV
5th force: operators are excluded for $m_\phi \lesssim 10^{-3}$ eV

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

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

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



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

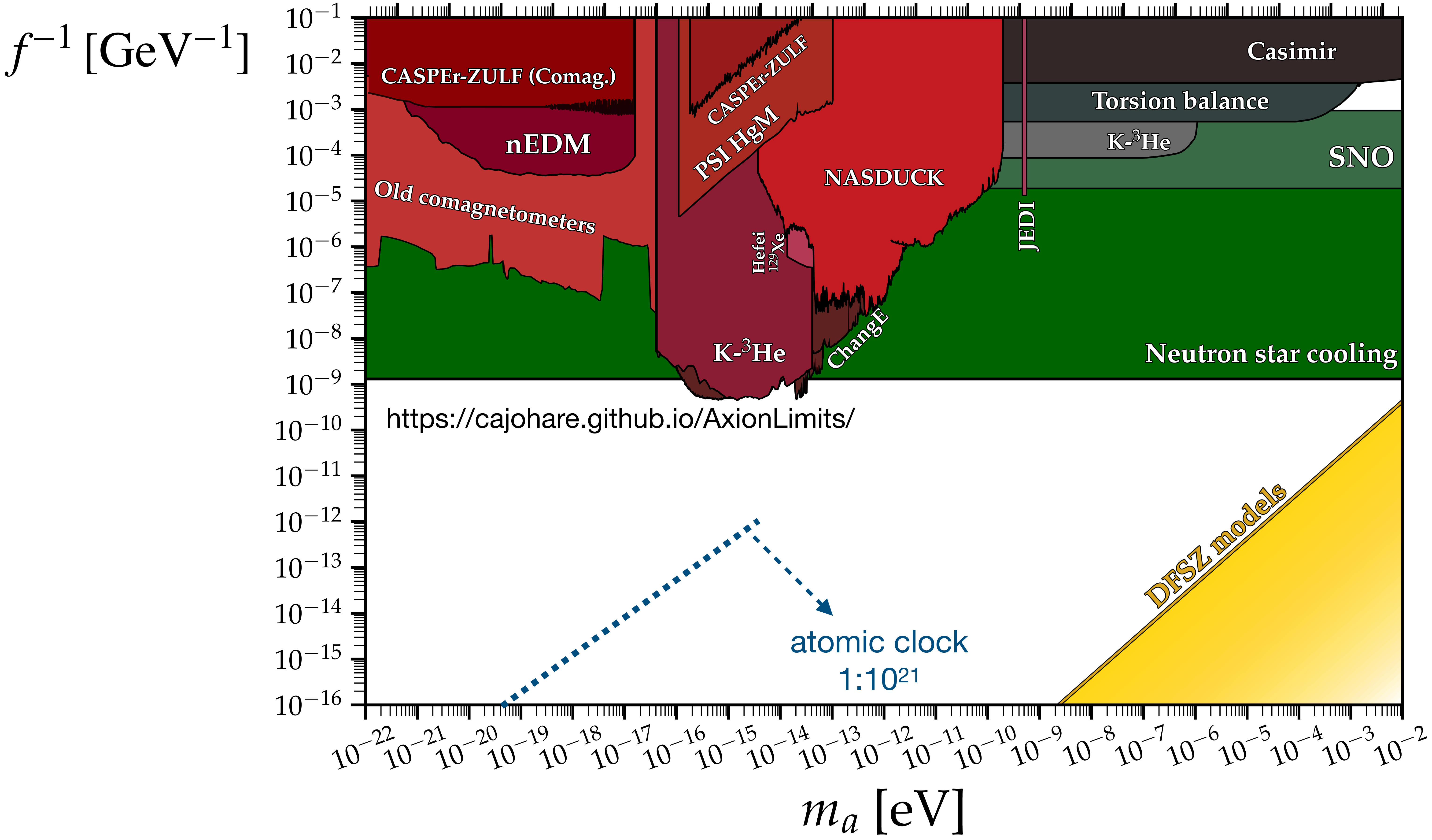
Banerjee, GP, Safronova, Savoray & Shalit (22)

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

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

# 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)

$\vdots$

# Why probing the strong sector \w clocks is challenging ?

To understand let’s talk about how clocks probe DM

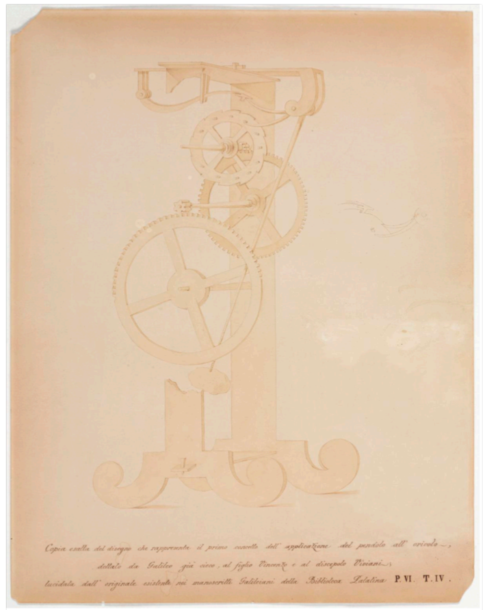
(theorist’s perspective - simplified model …)

# Atomic clock in 1-slide

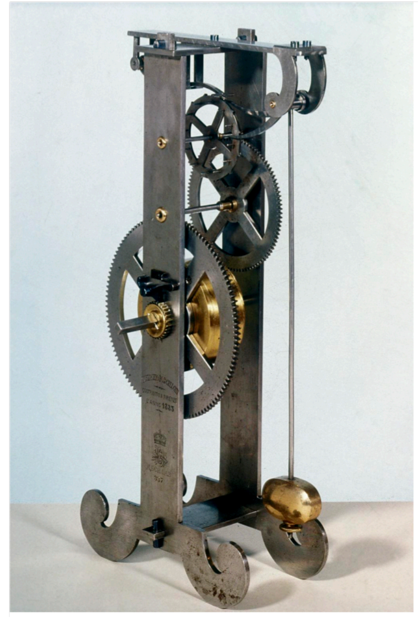
- A clock requires an apparatus that repeat itself in a very precise manner
- Atomic clocks are based on cases where there are electronic transitions between stable 2-level system, $H \approx \Delta E \times \sigma_Z$
- In the experiment, via laser, one prepare a linear combination of these levels

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

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

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

- 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 $\sqrt{\frac{m_e}{A m_p}} \sim 10^{-3}$ (could be ameliorated)

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

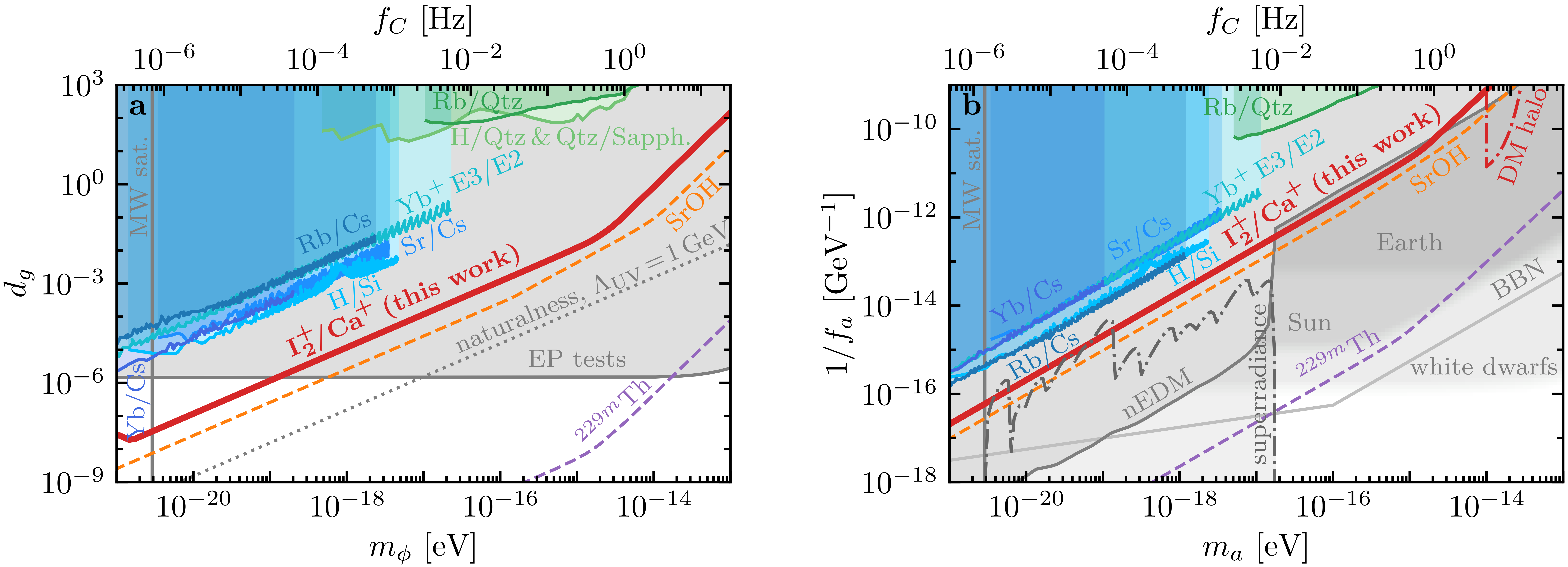
- Or charge radius effect, scales like $A^{8/3}\alpha\left(\frac{m_{\text{Bohr}}}{m_p}\right)^3$

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

Result \w 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: Andrea Caputo, Doron Gazit, Hans-Werner Hammer, Joachim Kopp , Gil Paz & Konstantin Springmann (24)

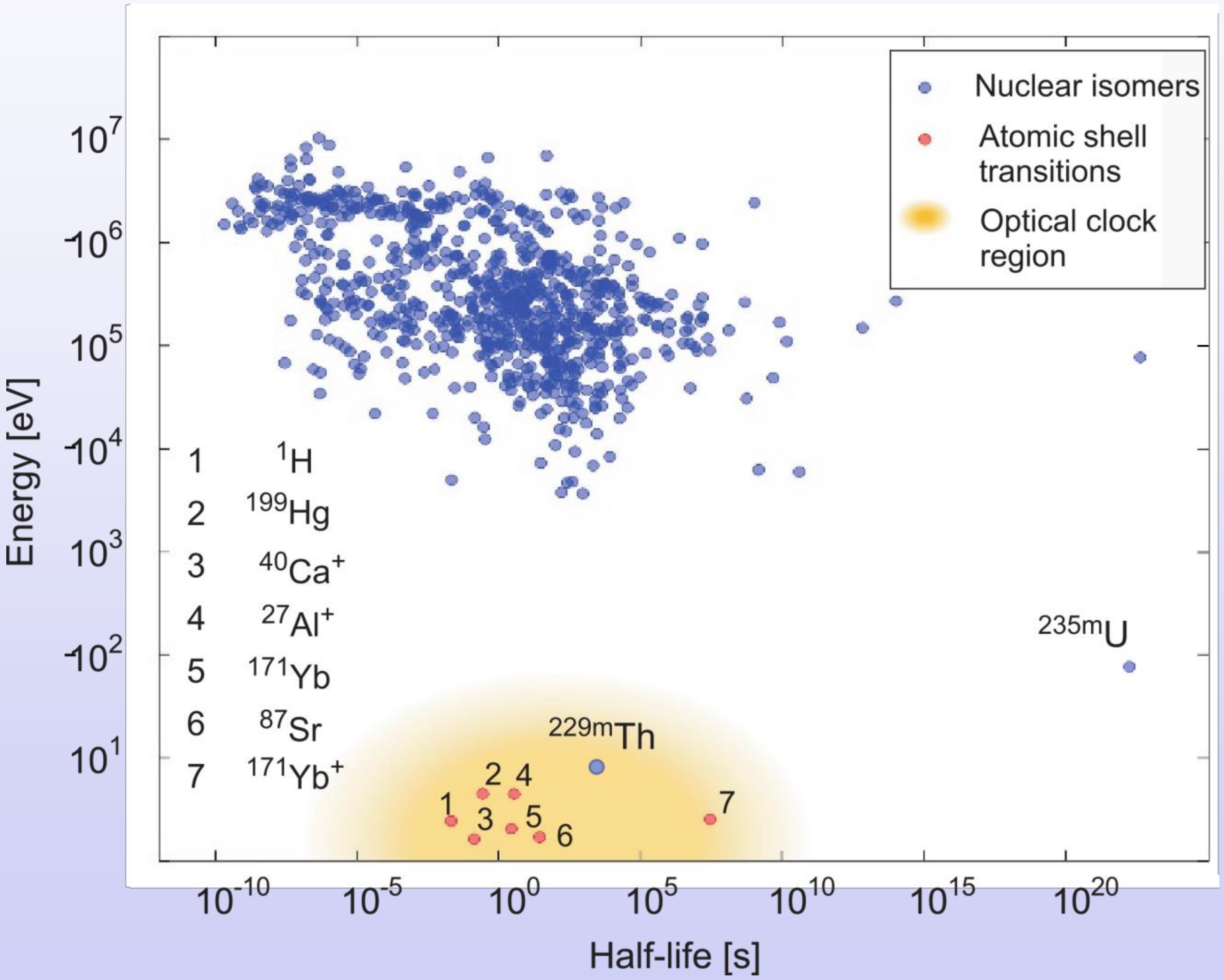
(*ii*) BSM implications (line-shape)

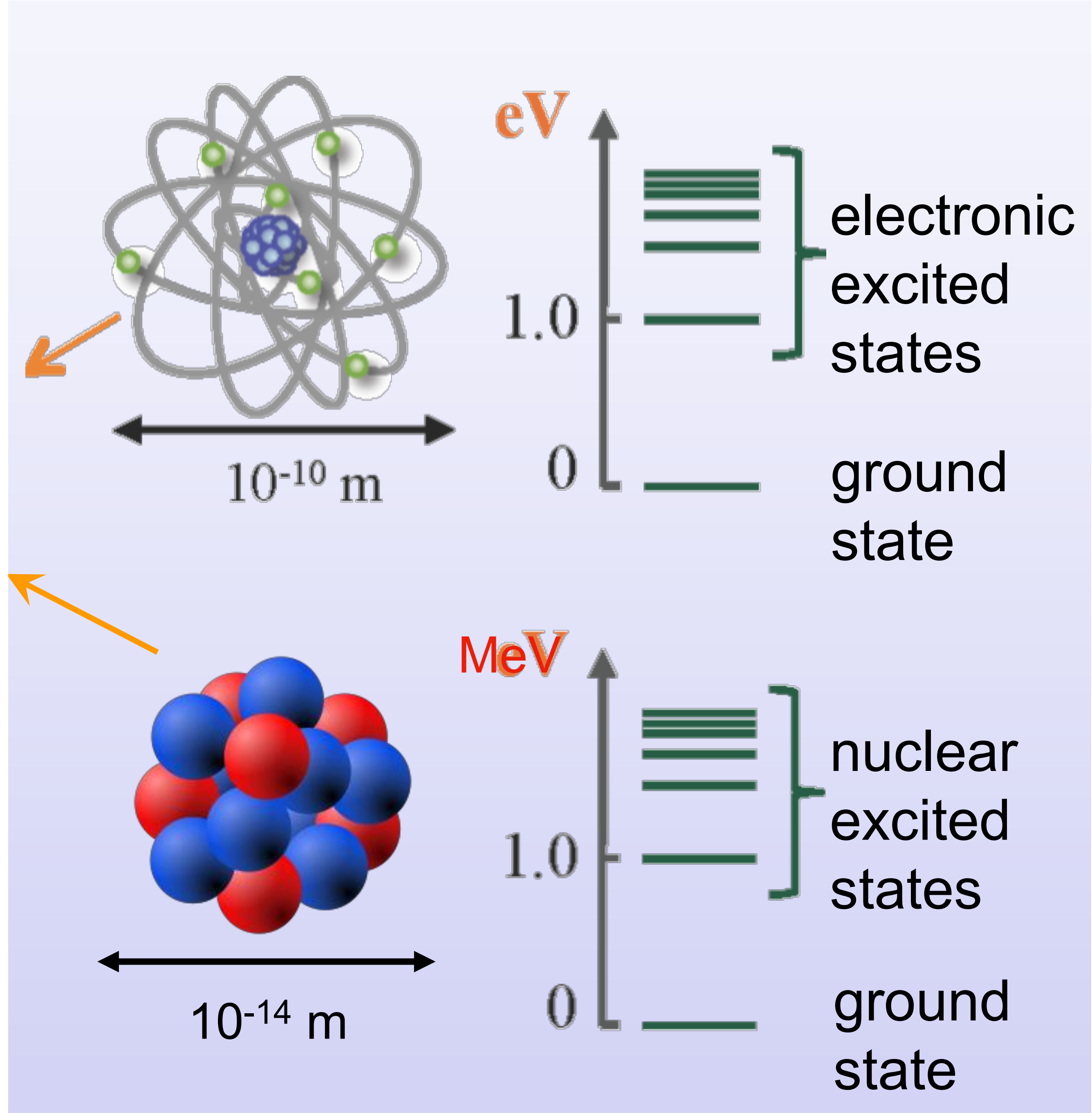
with: Elina Fuchs, Fiona Kirk, Eric Madge, Chaitanya Paranjape, Ekkehard Peik, Wolfram Ratzinger & Johannes Tiedau (24)

(*iii*) Beyond dark matter: nuclear clock as a QCDometer

# Natural fine tuning, Th-229 isomeric excitation

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

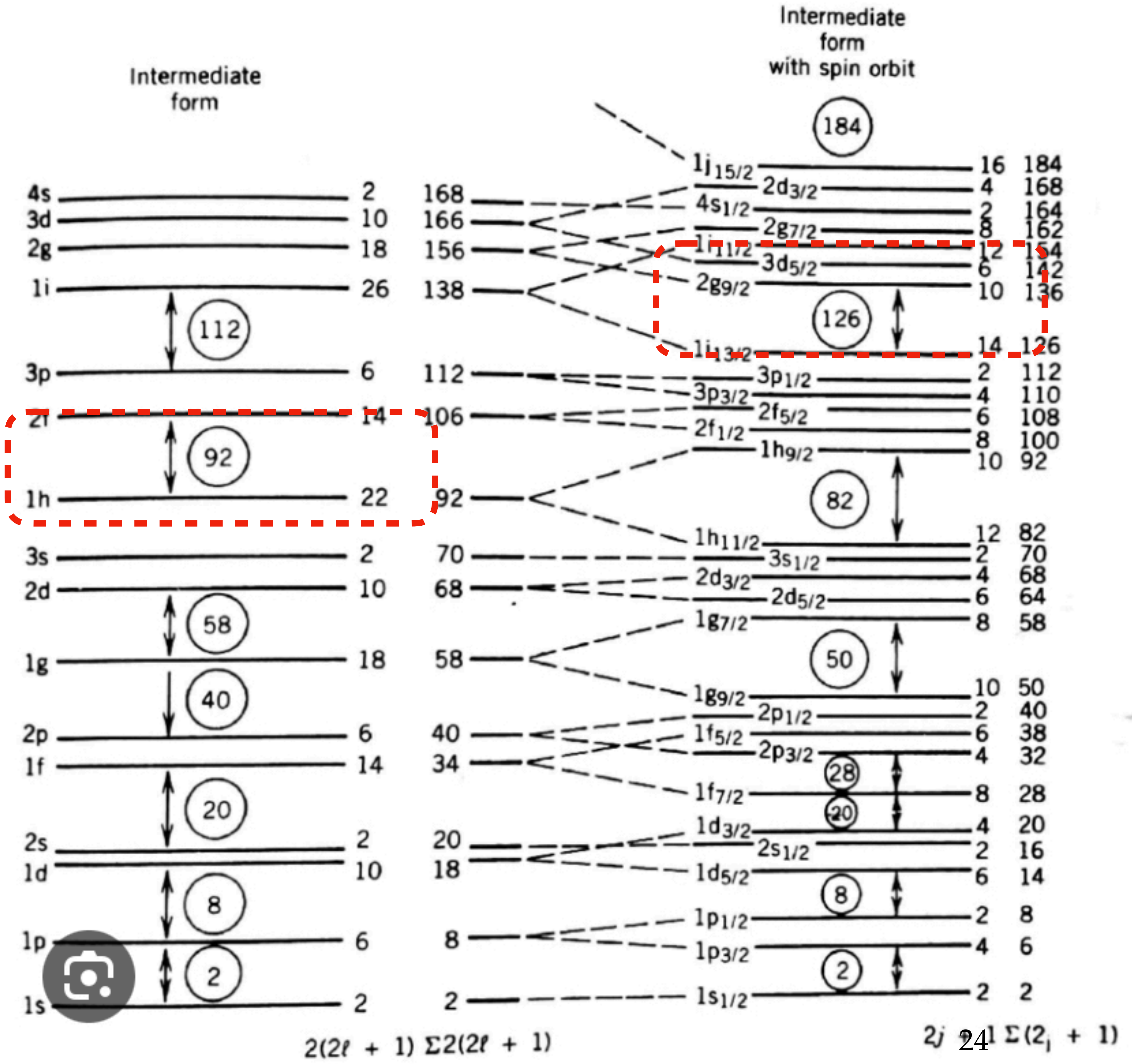


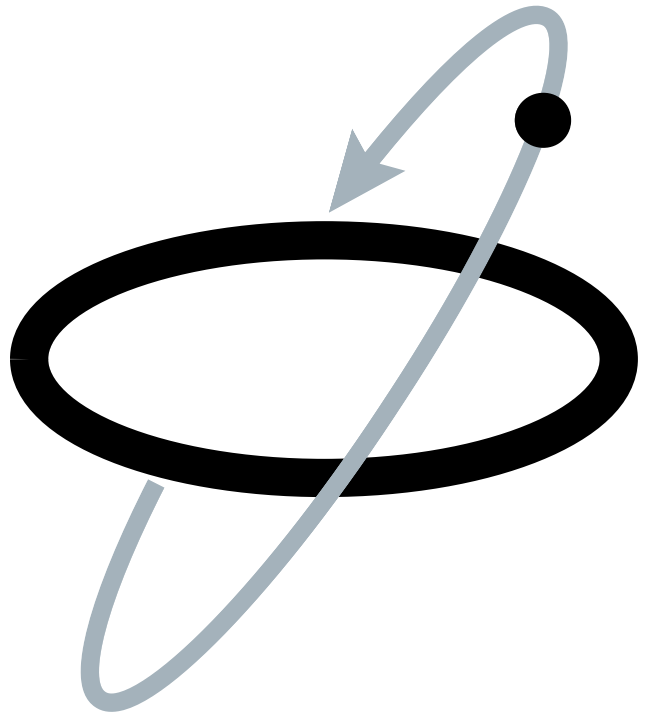


**lowest E* of all ca. 186000 presently known nuclear excited states**

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

$90$ *protons*, $139$ *neutrons*

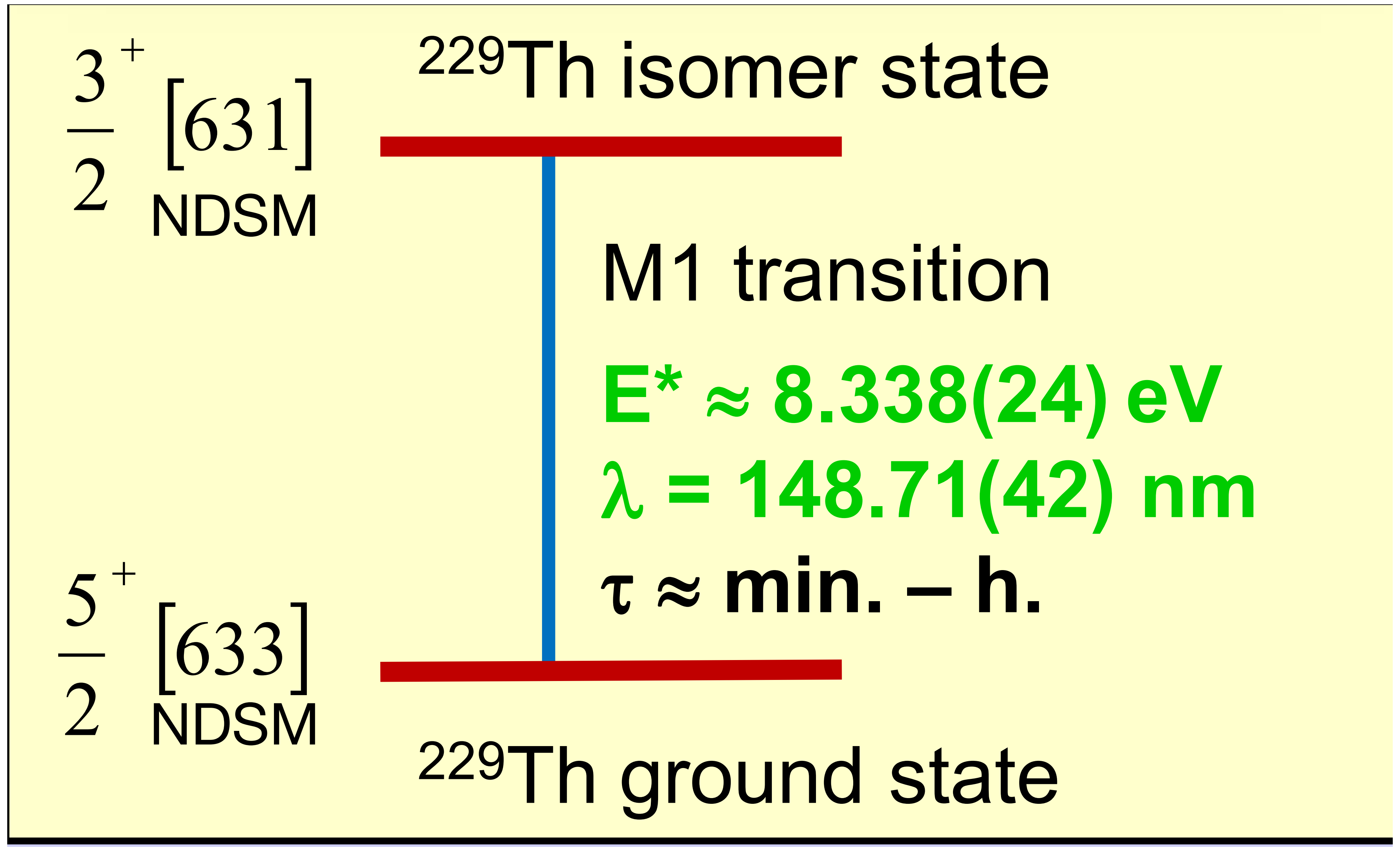




The nuclear level structure “can be described”

in terms of an elliptic core and an unpaired neutron

Beeks et al: Nat. Rev. (21)



$\frac{3}{2}^{+}[631]$ NDSM

$^{229}$Th isomer state

M1 transition

**E* ≈ 8.338(24) eV**

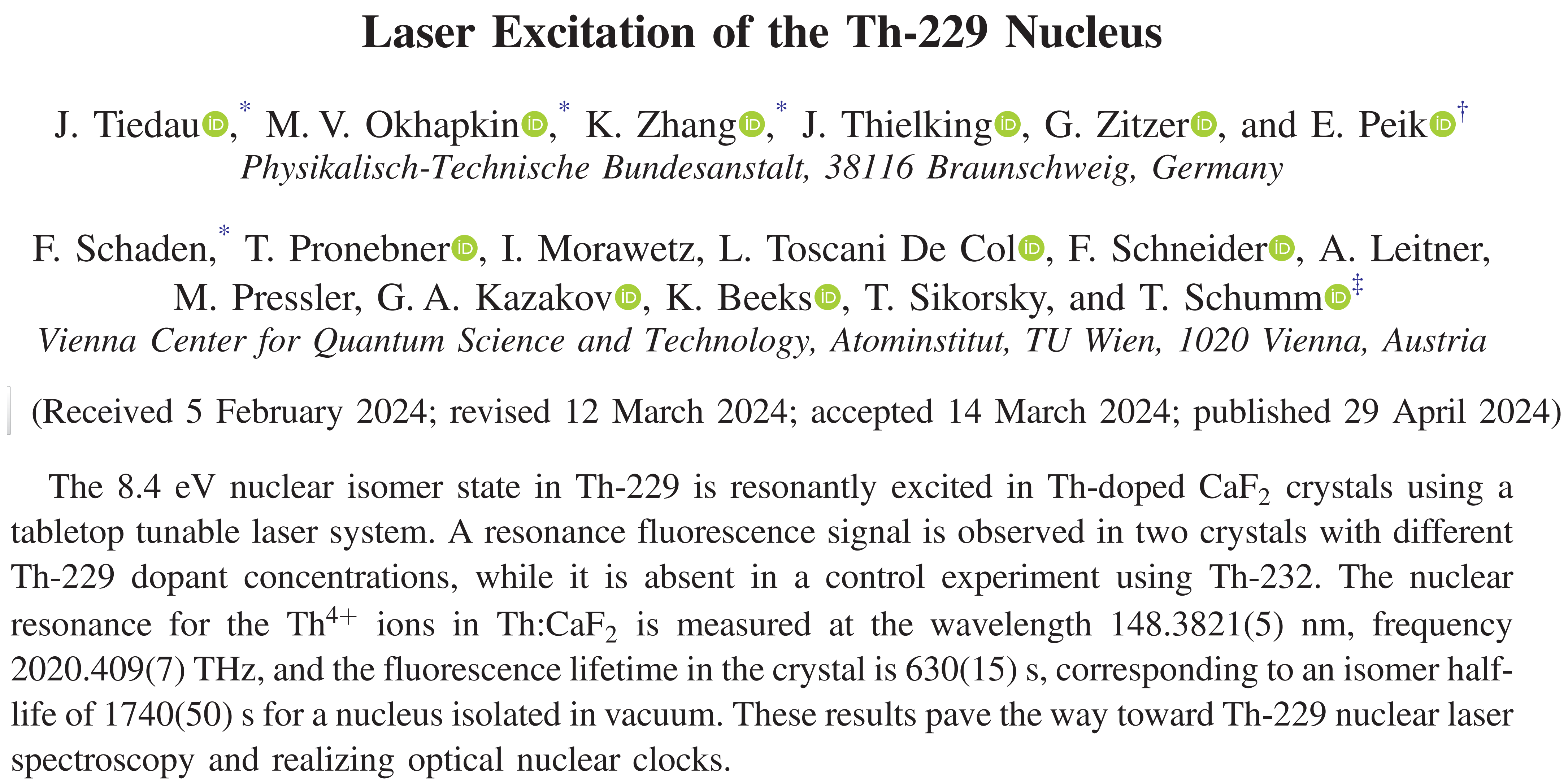
**λ = 148.71(42) nm**

**τ ≈ min. – h.**

$\frac{5}{2}^{+}[633]$ NDSM

$^{229}$Th ground state

# The (other) April revolution?



## Laser Excitation of the Th-229 Nucleus

J. Tiedau,* M. V. Okhapkin,* K. Zhang,* J. Thielking, G. Zitzer, and E. Peik†
*Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany*

F. Schaden,* T. Pronebner, I. Morawetz, L. Toscani De Col, F. Schneider, A. Leitner,
M. Pressler, G. A. Kazakov, K. Beeks, T. Sikorsky, and T. Schumm‡
*Vienna Center for Quantum Science and Technology, Atominstitut, TU Wien, 1020 Vienna, Austria*

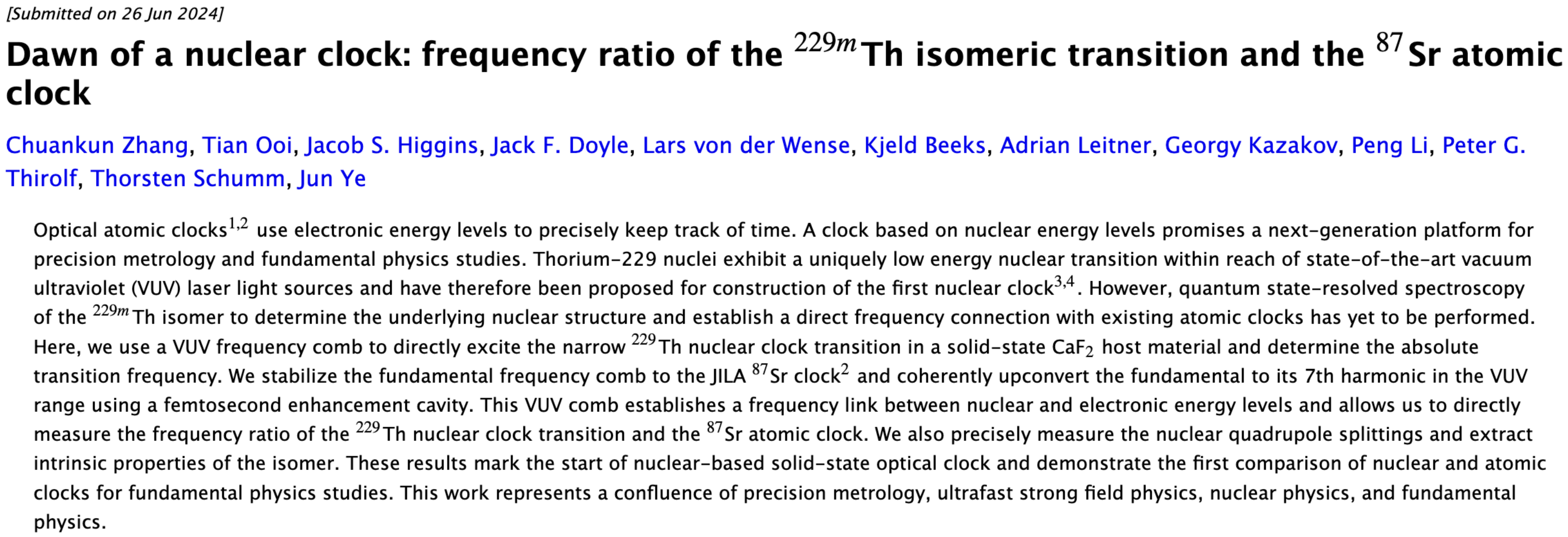
(Received 5 February 2024; revised 12 March 2024; accepted 14 March 2024; published 29 April 2024)

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<br>• Electoral fraud |

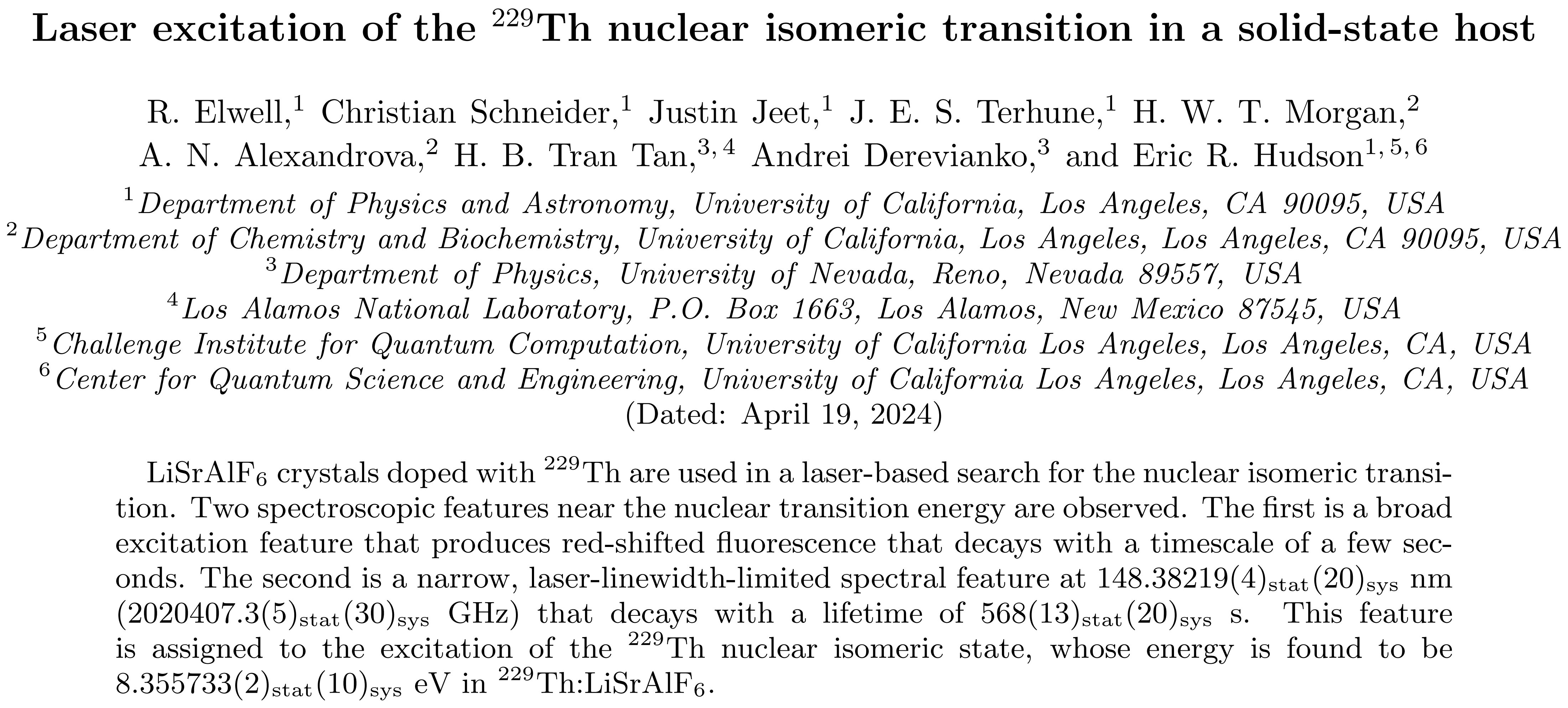


*[Submitted on 26 Jun 2024]*

## 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

R. Elwell,[1] Christian Schneider,[1] Justin Jeet,[1] J. E. S. Terhune,[1] H. W. T. Morgan,[2]
A. N. Alexandrova,[2] H. B. Tran Tan,[3,4] Andrei Derevianko,[3] and Eric R. Hudson[1,5,6]
[1] *Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA*
[2] *Department of Chemistry and Biochemistry, University of California, Los Angeles, Los Angeles, CA 90095, USA*
[3] *Department of Physics, University of Nevada, Reno, Nevada 89557, USA*
[4] *Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, New Mexico 87545, USA*
[5] *Challenge Institute for Quantum Computation, University of California Los Angeles, Los Angeles, CA, USA*
[6] *Center for Quantum Science and Engineering, University of California Los Angeles, Los Angeles, CA, USA*

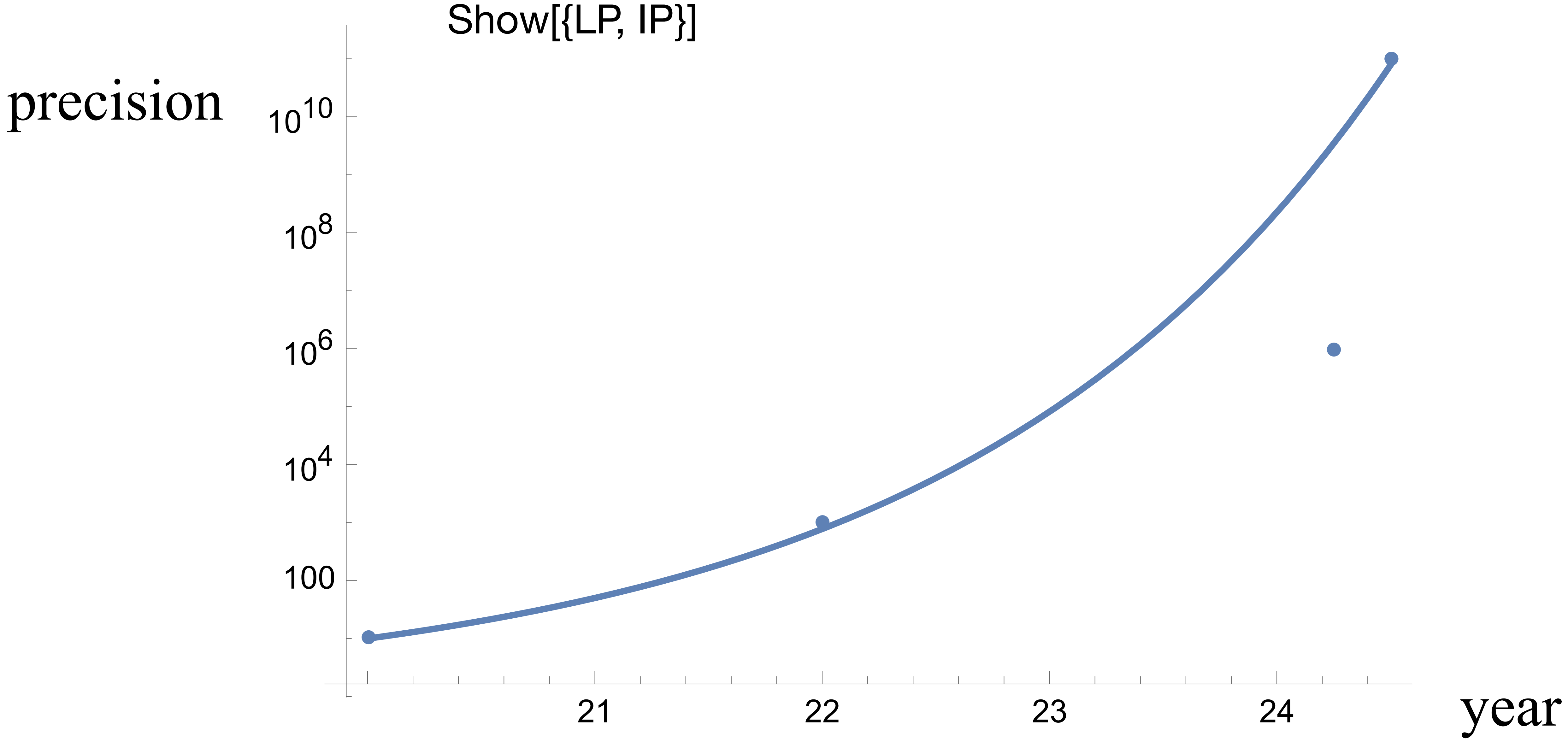
(Dated: April 19, 2024)

$LiSrAlF_6$ 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 $148.38219(4)_{\mathrm{stat}}(20)_{\mathrm{sys}}$ nm ($2020407.3(5)_{\mathrm{stat}}(30)_{\mathrm{sys}}$ GHz) that decays with a lifetime of $568(13)_{\mathrm{stat}}(20)_{\mathrm{sys}}$ s. This feature is assigned to the excitation of the $^{229}$Th nuclear isomeric state, whose energy is found to be $8.355733(2)_{\mathrm{stat}}(10)_{\mathrm{sys}}$ 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)

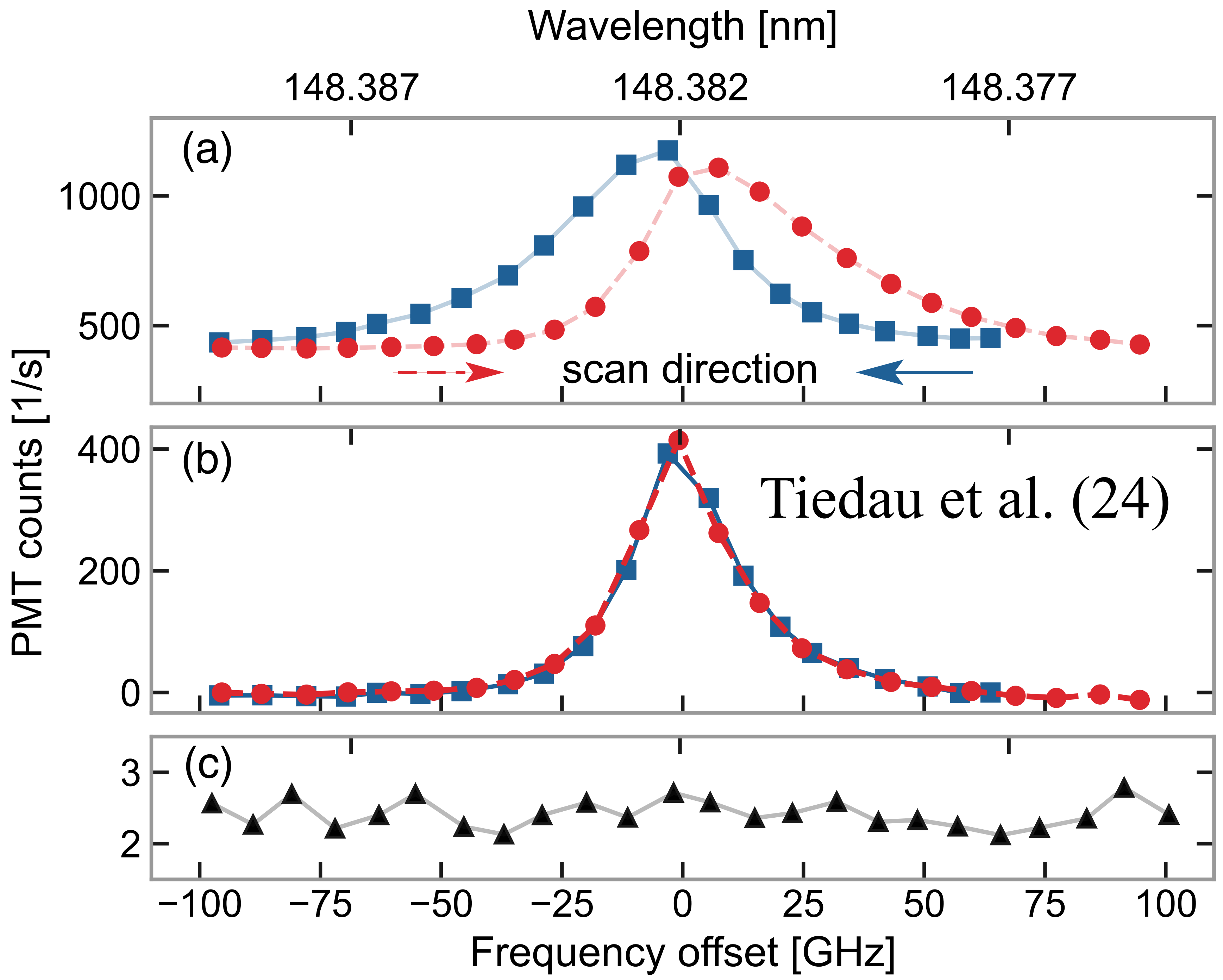


Mathematica's fit to double exponent:

```
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: $K_{\mathrm{canc}} \sim \Delta E_{\mathrm{nuc}}/f_{\mathrm{Th-229}} \sim \Delta E_{\mathrm{EM}}/f_{\mathrm{Th-229}} \sim 10^5 \gg 1$

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

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

$$\Downarrow$$

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

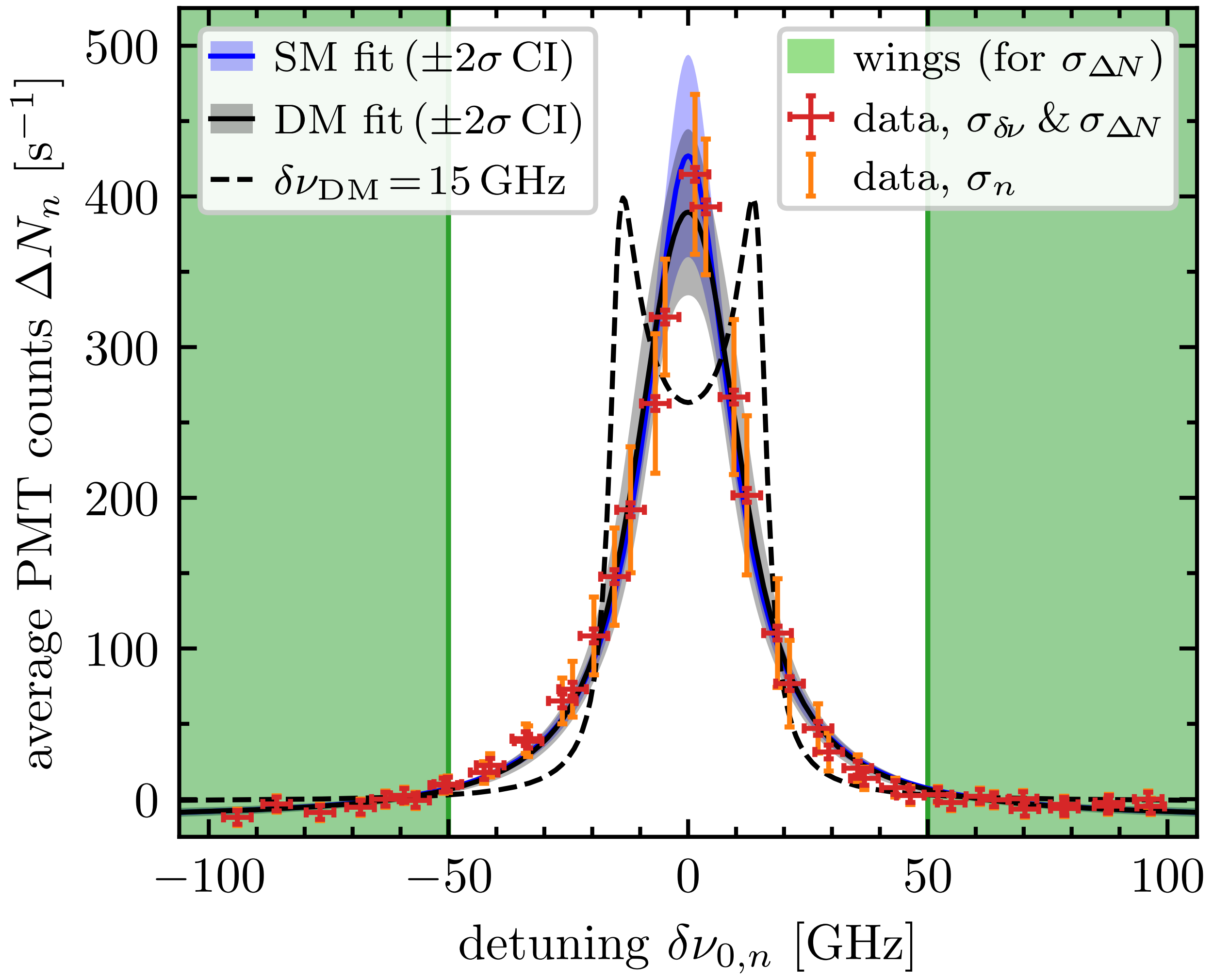
# Present and near future implications

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

$\frac{\delta f}{f} / (R_{\mathrm{atom}} \times K_{\mathrm{canc}}) \sim \; 10^{-14-19} - 10^{-16-21}$ of atomic clocks, going beyond the frontier!

- However, can we use current data to search for UDM before nuclear clocks are available ?

- Line shape analysis: can already be used to search for DM



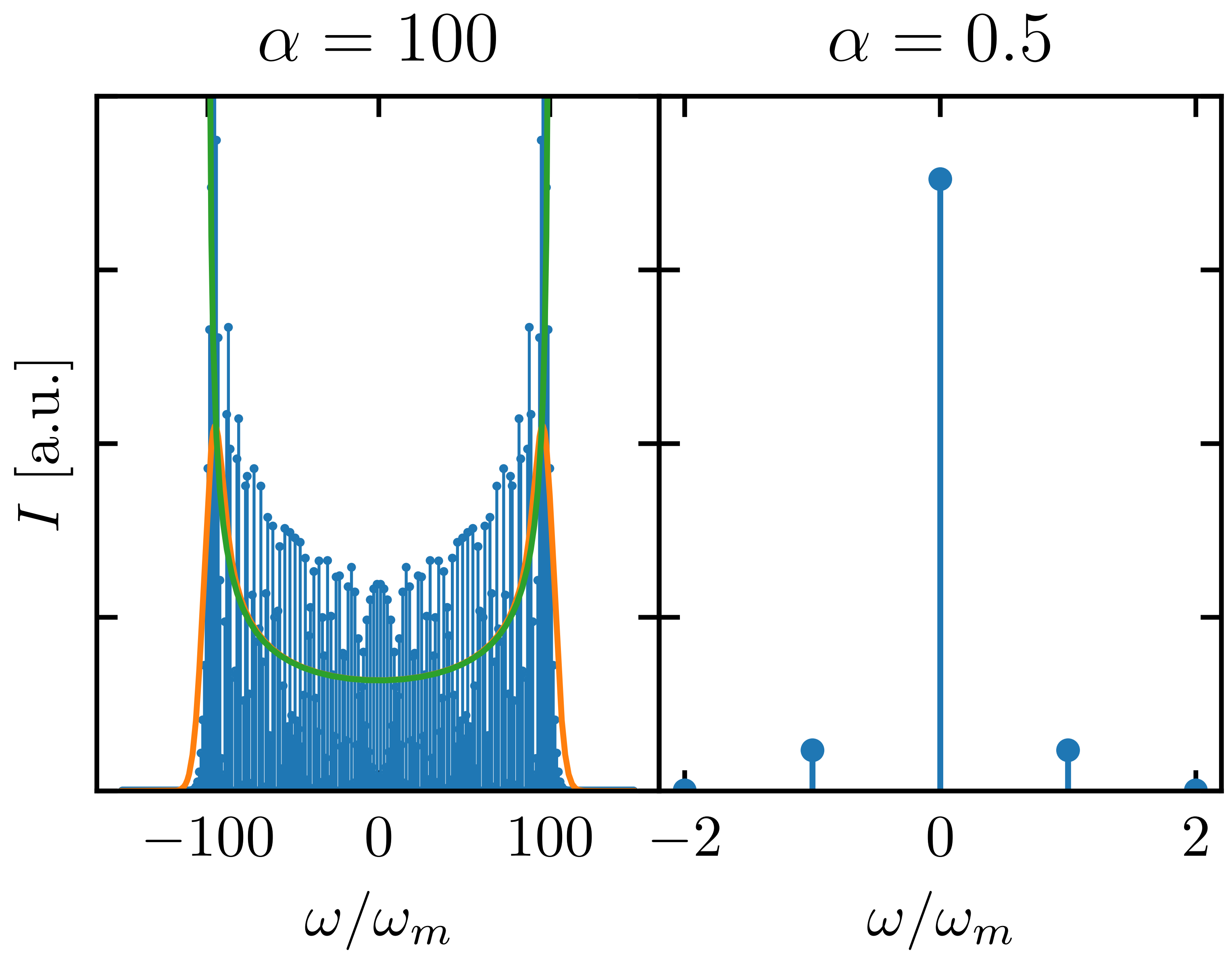
Fuchs, et al. (24)

# 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

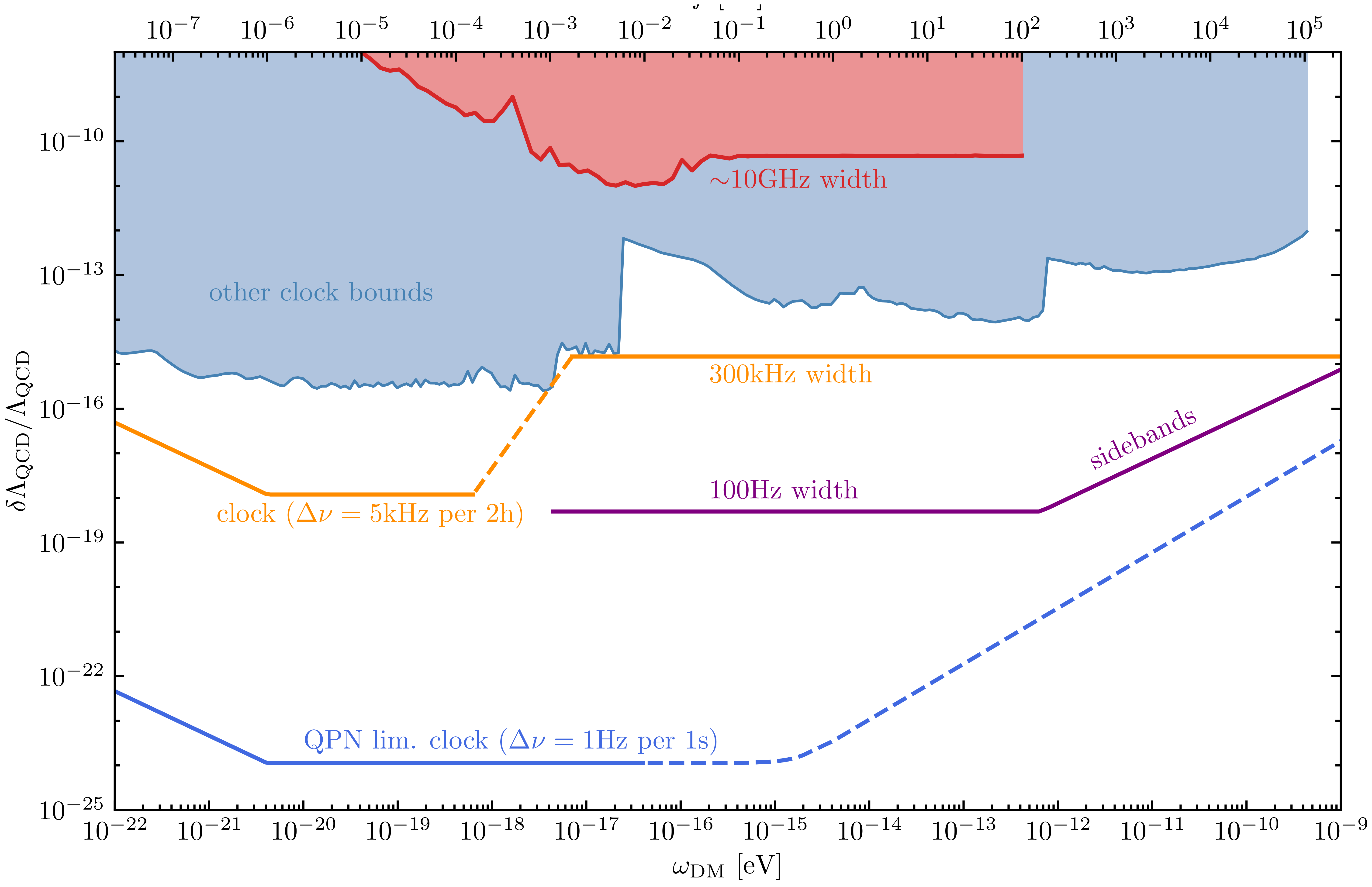


$$\nu(t) \simeq \nu_0 + \delta\nu_{\rm DM}\cos(\omega_{\rm DM}t + \varphi_{\rm DM})$$

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

# 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

# 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

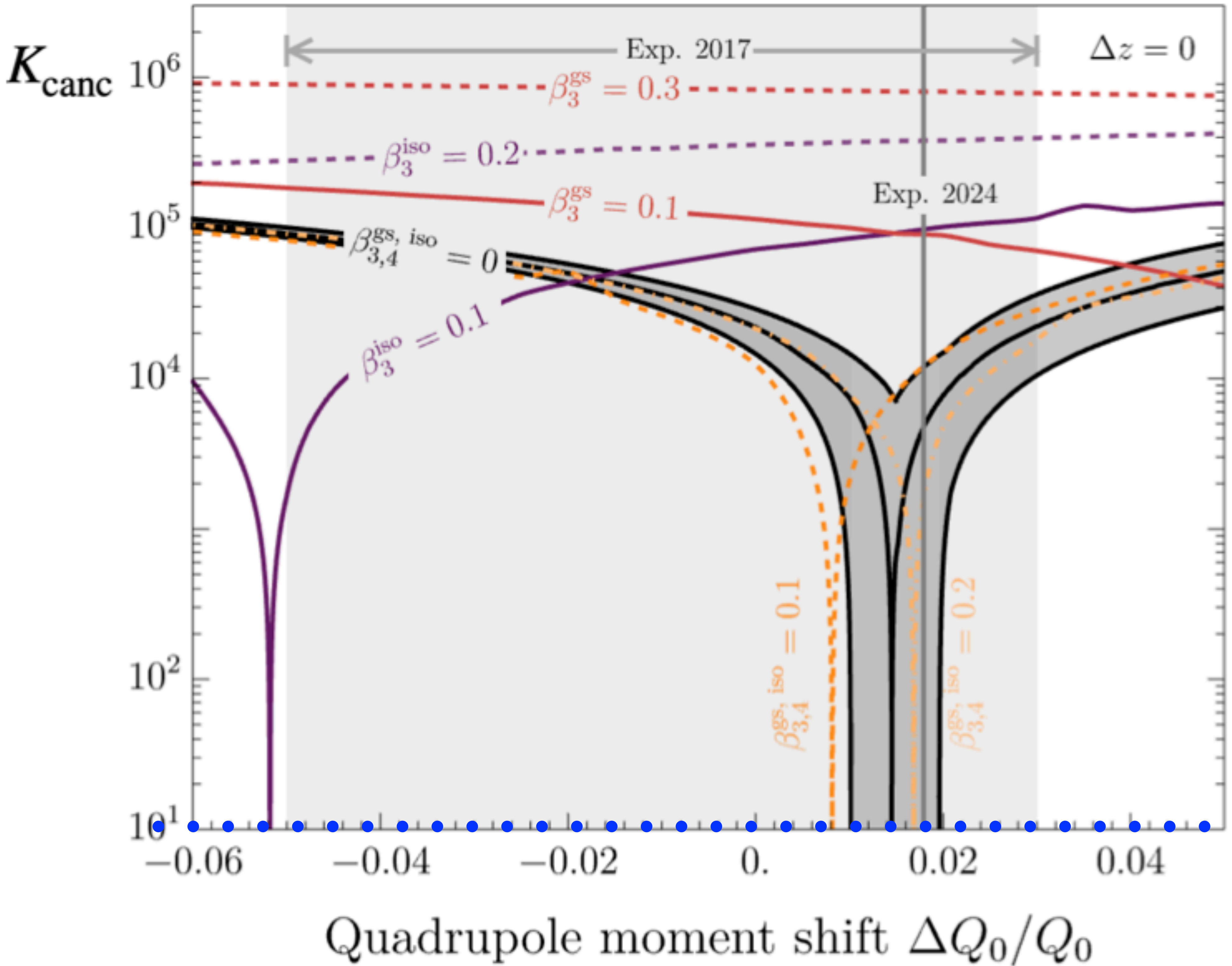
Hammer, König, & van Kolck (19)

# Geometrical/classical model

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

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

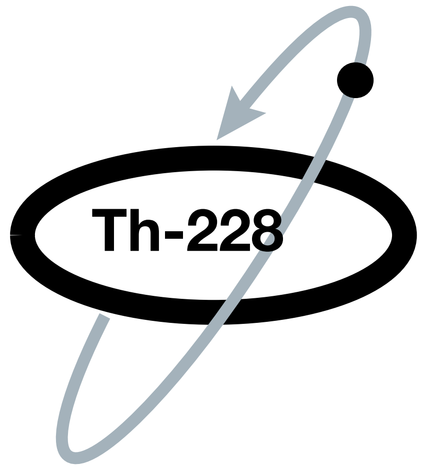
Caputo, Gazit, Hammer, Kopp , Paz, GP & Springmann; See also: Beeks et al. (24)



Caputo, Gazit, Hammer, Kopp , Paz, GP & Springmann (24)

nightmare scenario

# Halo-inspired model



Caputo, Gazit, Hammer, Kopp , Paz, GP & Springmann (24)

- 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 leading contributions arise due to the splitting of EM-energy from spin-orbit coupling of the halo-neutron resulting with reasonable agreement for the value of the quadrupole and charge radius different
- The sensitivity parameter is estimated to be: $K_{\text{canc}} = \mathcal{O}\left(10^4\right)$

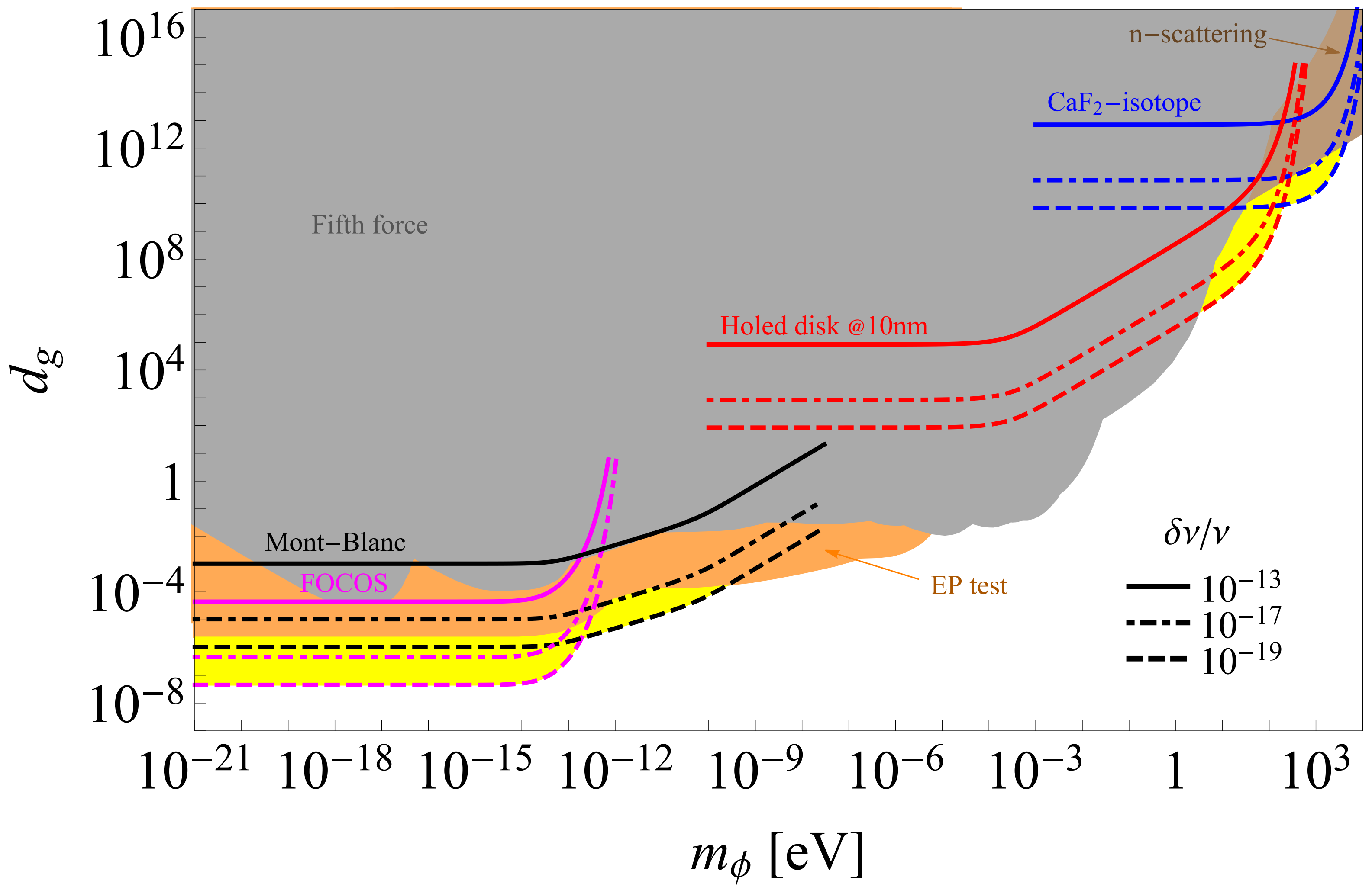
# Nuclear clock as a QCDometer

- We saw that nuclear clock is extremely sensitive to variation in the strong coupling; can replace time-varying DM with scalar space-dependence value, $\delta\phi$, to search for -

(*i*) light scalar “5th-force” mediator

associate with a moving source:

\w: Delaunay, Lee, Ozeri, Ratzinger & Yu



(*ii*) topological defects/scalar vacuum-expec.-value - /w weak (super-Planckian) coupling to us

Thin-wall energy density’s: $\Omega^R_\phi = (\nabla\phi)^2 \sim (\delta\phi)^2/R^2$, $R$ = typical length of defect.

\w: Dvali, Lo Chiatto & Springmann

the ratio to cosmological constant:

$$\frac{\Omega^R_\phi}{\Lambda_{\rm CC}} = 10^{-12}\left(\frac{\delta\phi}{10^3\,{\rm eV}}\right)^2 \times \left(\frac{\Delta_{\rm Th-229}}{10^{-24}}\right)^2 \left(\frac{10^5\,{\rm km}}{R}\right)^2$$

# Summary & overview

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

  ($i$) direct coupling to nuclear sector ($ii$) enhanced sensitivity due to fine cancellation
- New measurement => game changer moving to precision phase, maybe already entered the era of thorium-supremacy
- The sensitivity parameter is uncertain however
- New directions, nuclear clock as a QCDometer

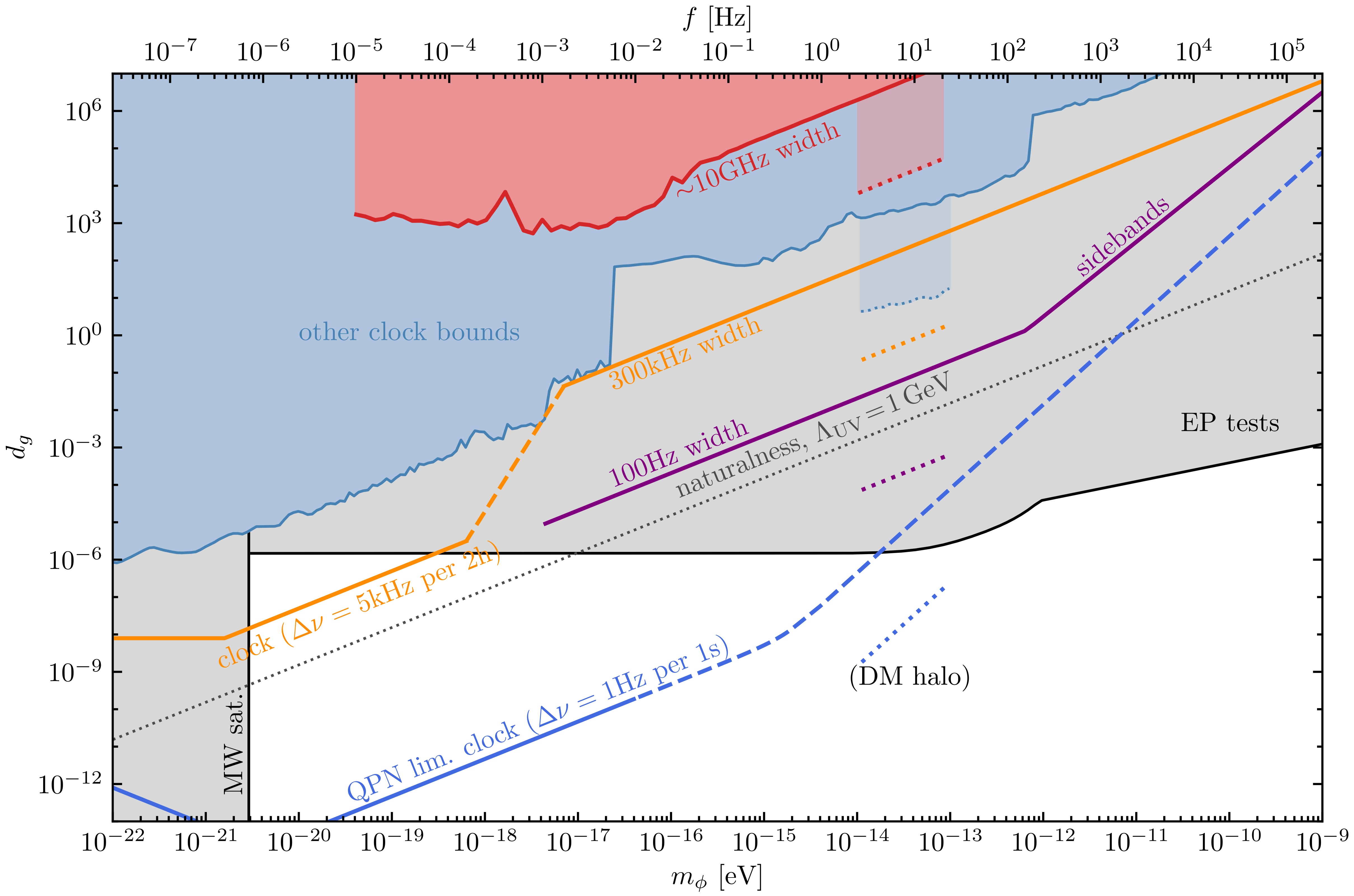
Thank you for your inspiration

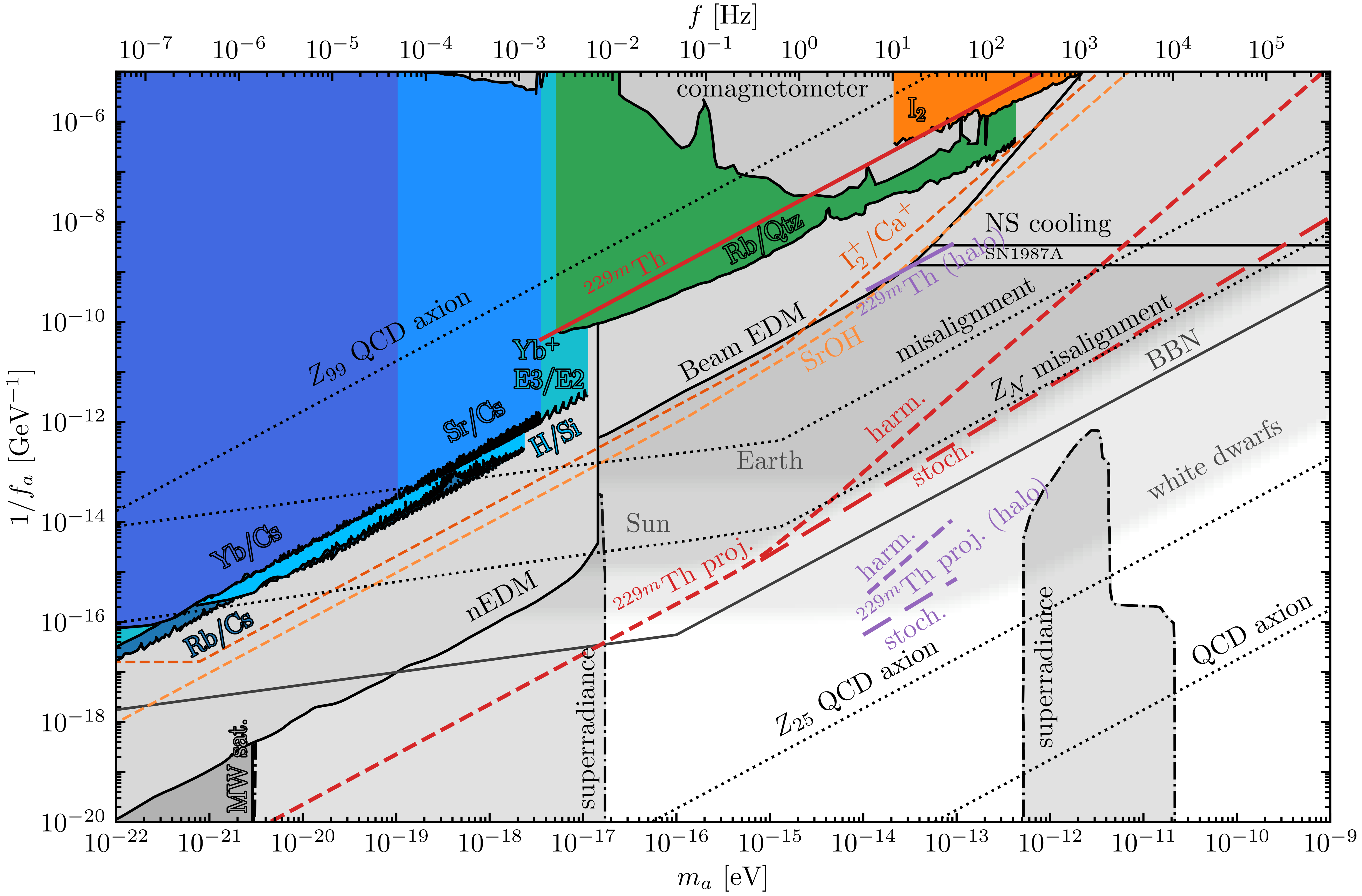
For the support

Most important: for the Berkeley spirit!

# *Backups*

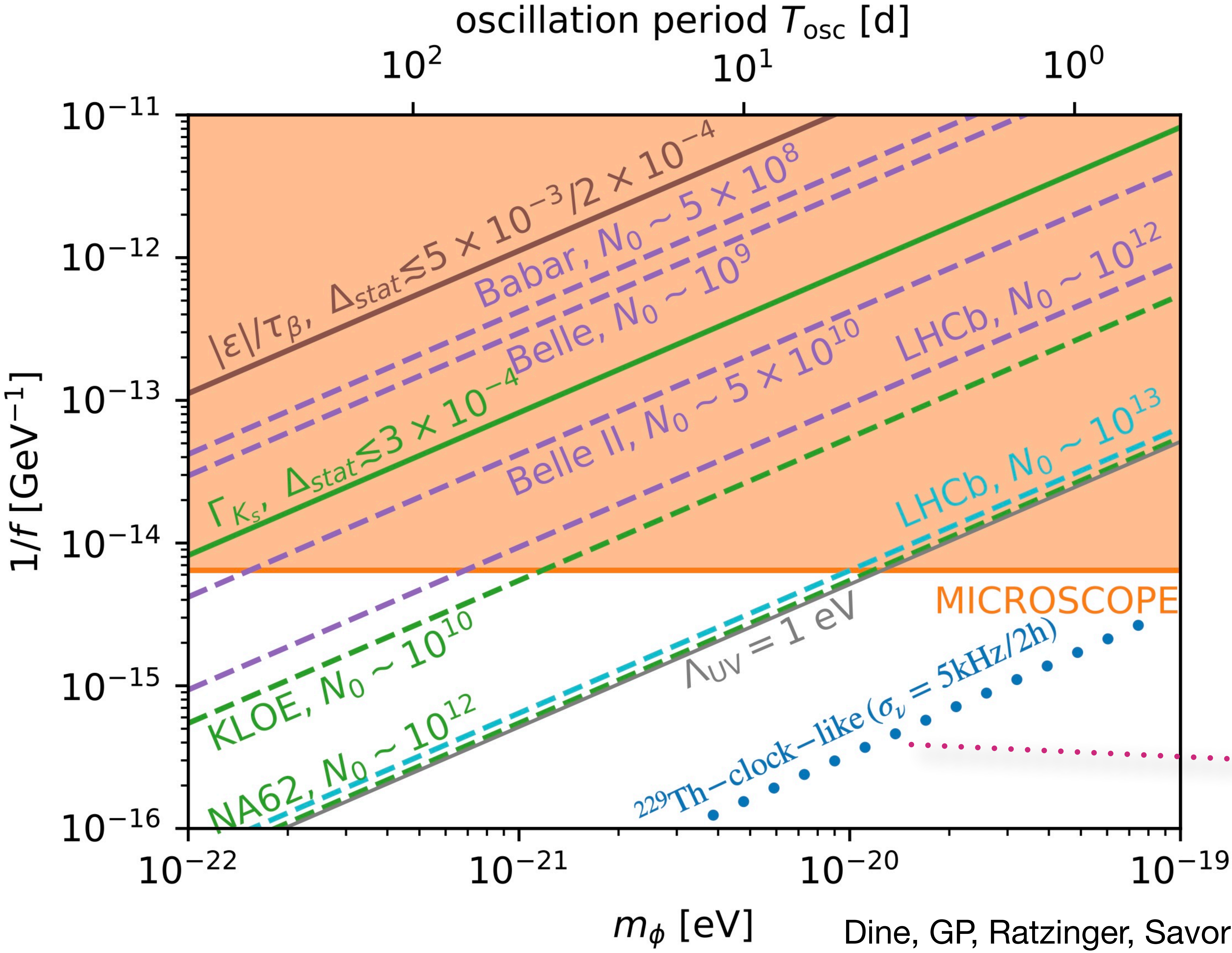
# Using Th-229 to search for UDM signal





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

# Nelson-Barr-UDM parameter space, luminosity exp.



Dine, GP, Ratzinger, Savoray (24)

Line-shape

# 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:

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

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

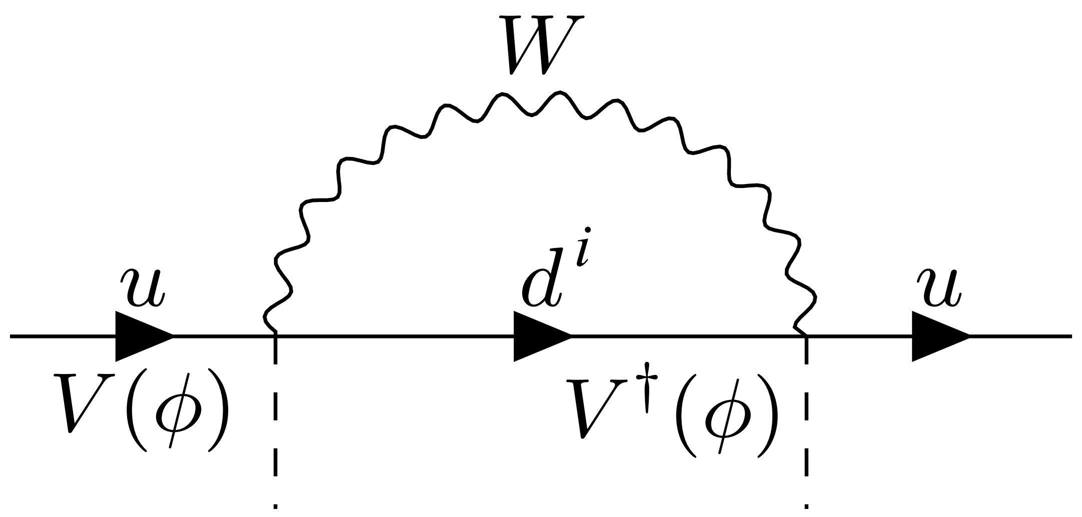
$\frac{\delta V_{ub}}{V_{ub}} \sim \delta a \Rightarrow$ oscillating semi inclusive *b*->*u* decay

# 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:

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

$Q^{U(1)}(\eta, \Phi, \psi, \psi^c, \bar{u}_1) = +1, +1/2, -1/2, -1/2, +1$ ($\eta$ 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 |
| $\frac{\left\lvert d_{m_e}^{(1)}\right\rvert}{M_{\rm Pl}}\phi\, m_e\psi_e\psi_e^c$ | $\left\lvert d_{m_e}^{(1)}\right\rvert \lesssim 2\times 10^{-3}$ [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:

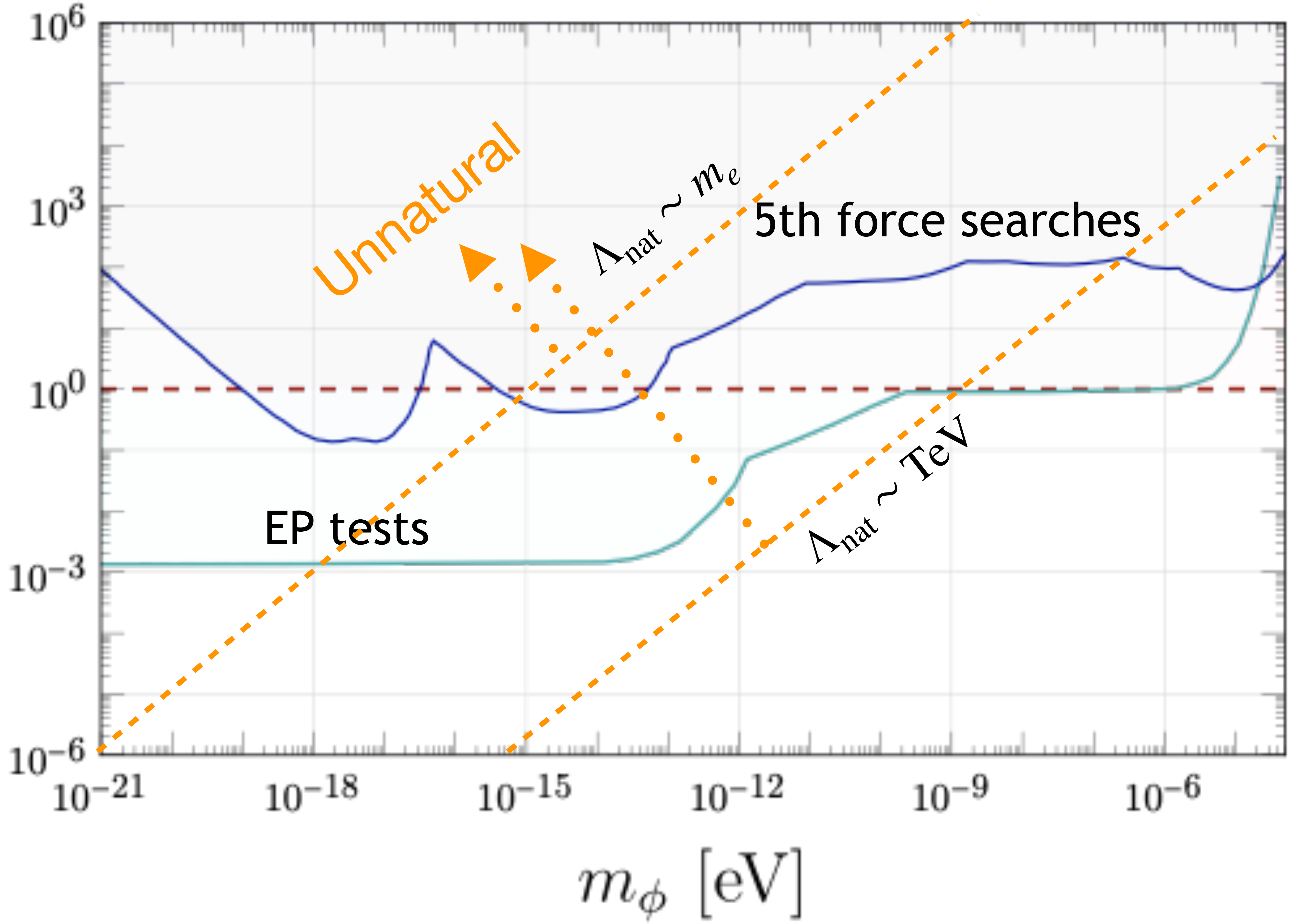
  If coupling is quadratic or more than situation is better -

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

# 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 $\alpha$:

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

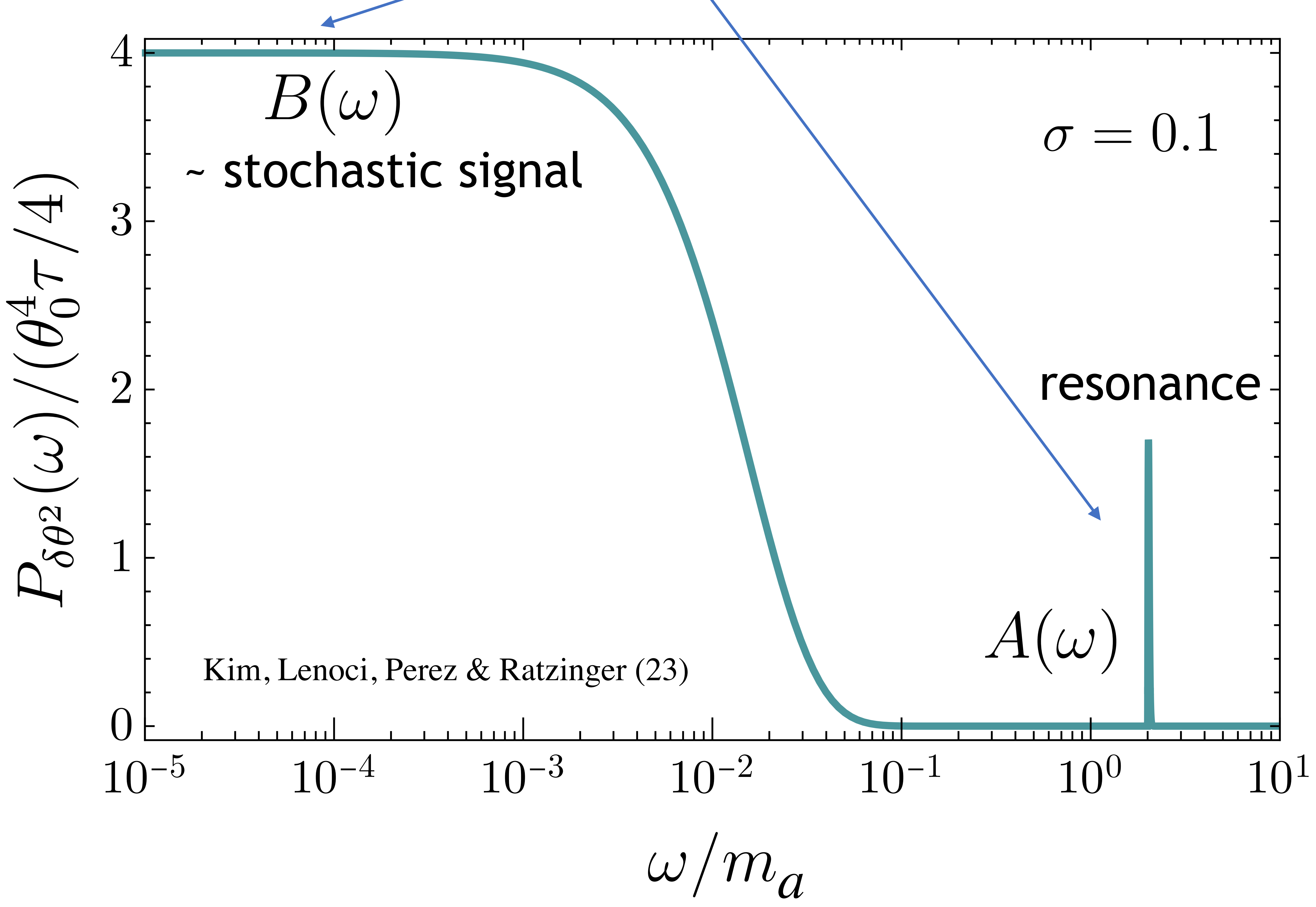
- Frequency transformed: it would result in a sharp signal at $\omega \sim m_a$ with width of $O\left(10^{-6}\right)$

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

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

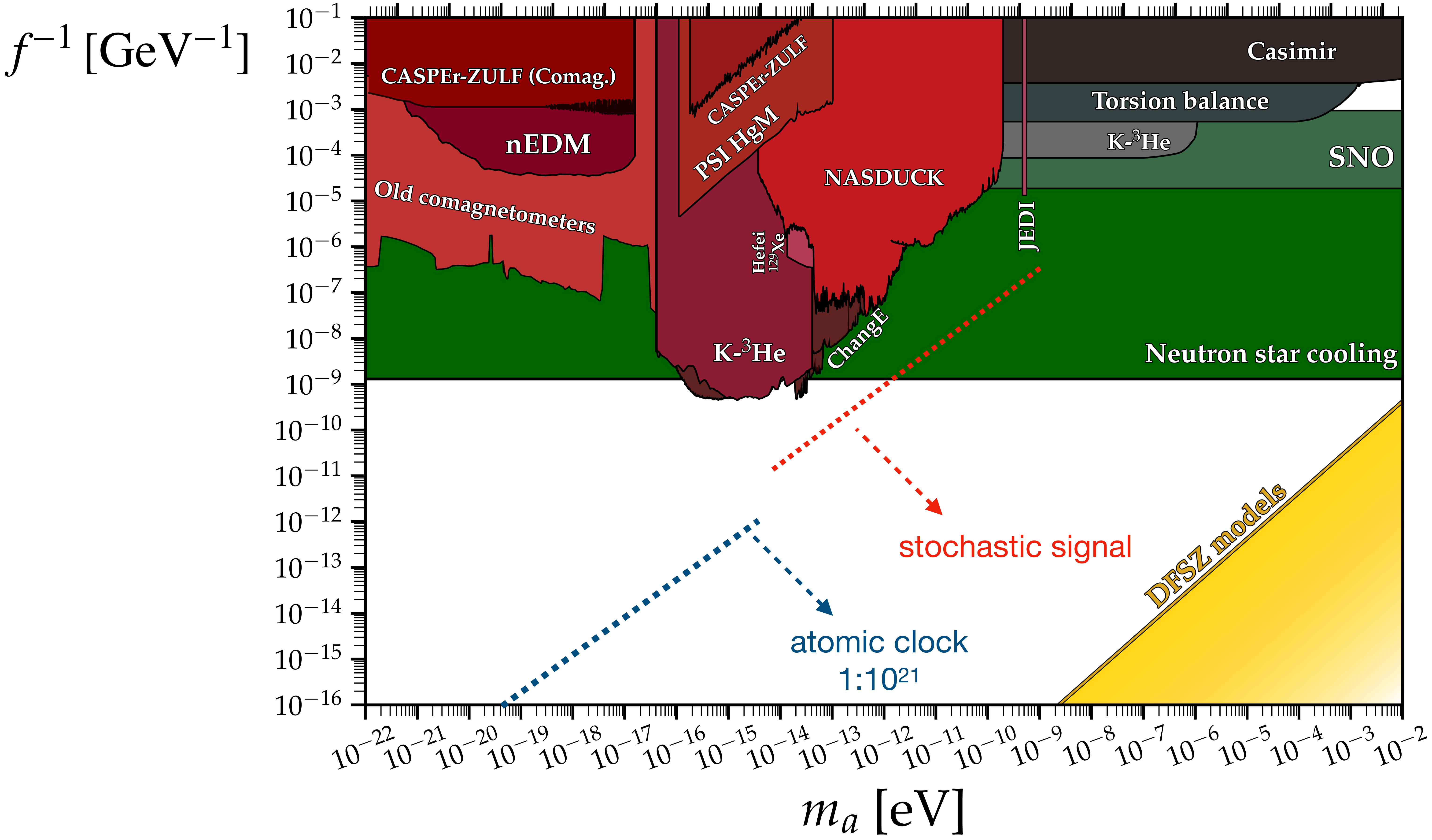
# Power spectrum of quadratic (axion) UDM

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



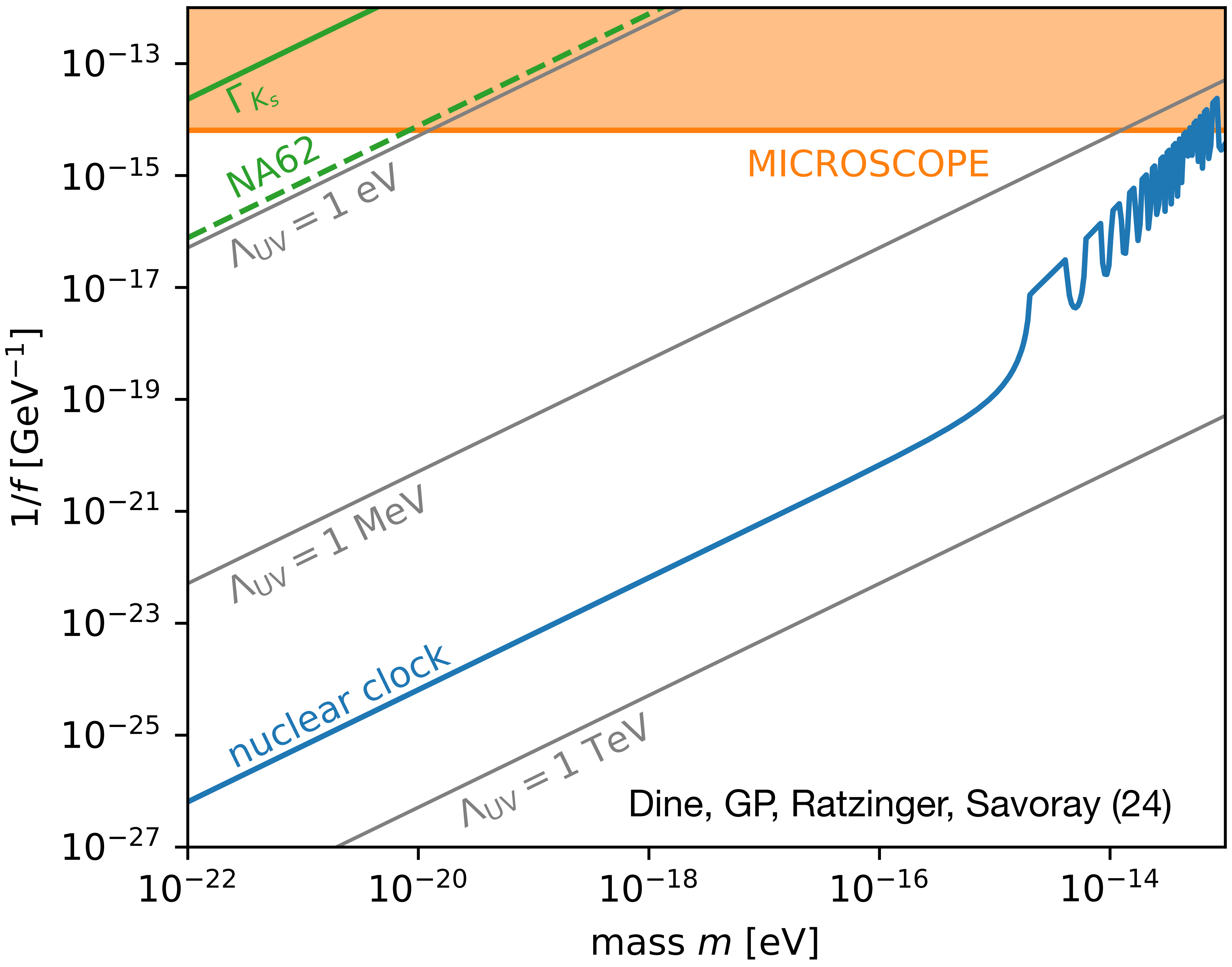
# Power spectrum of quadratic (axion) UDM, the stochastic signal

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



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

# Nelson-Barr-UDM & nuclear clock

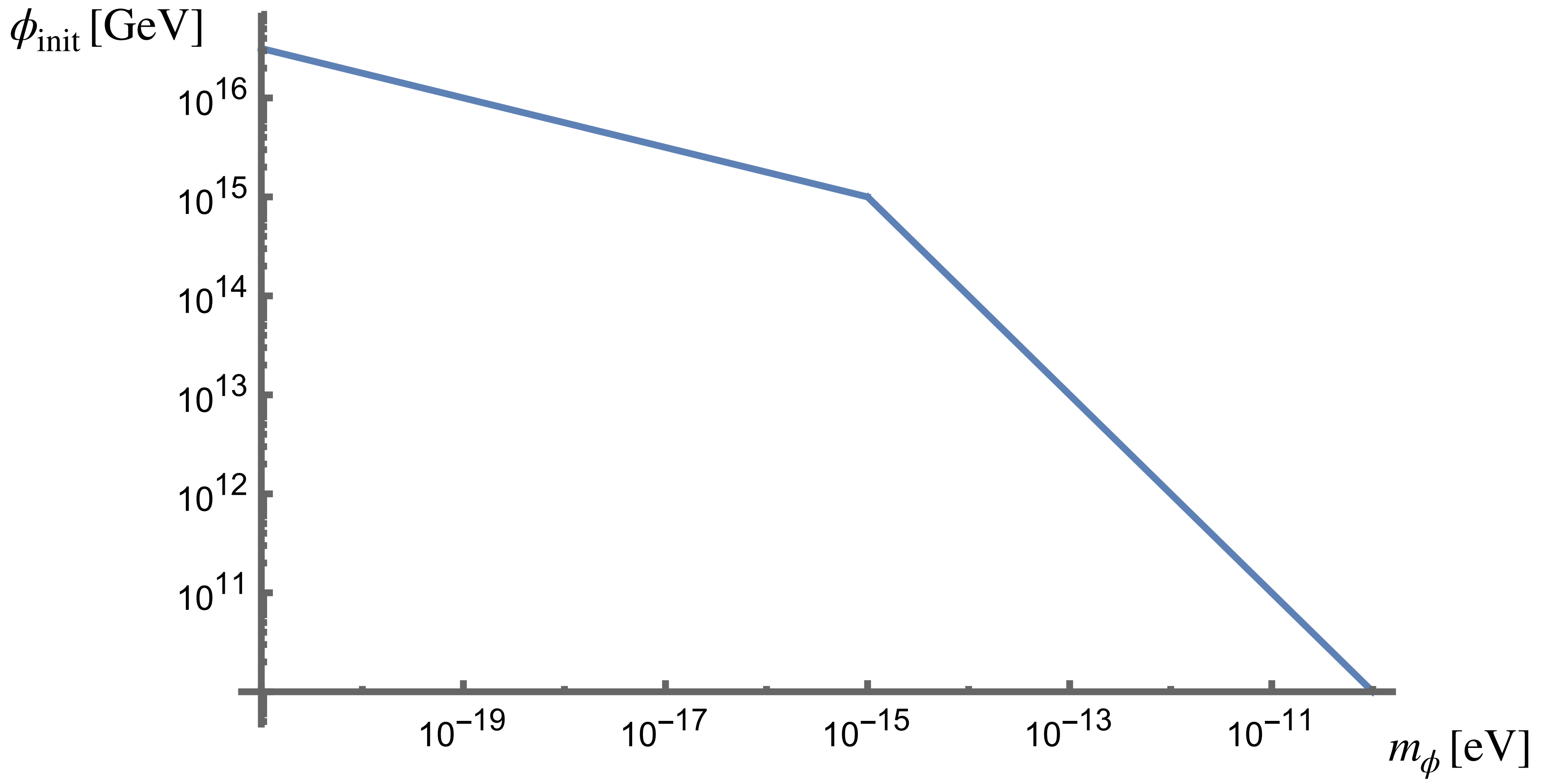


# Implication for ultralight dark matter (UDM) cosmology

- 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, $\phi_0$ :



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

[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