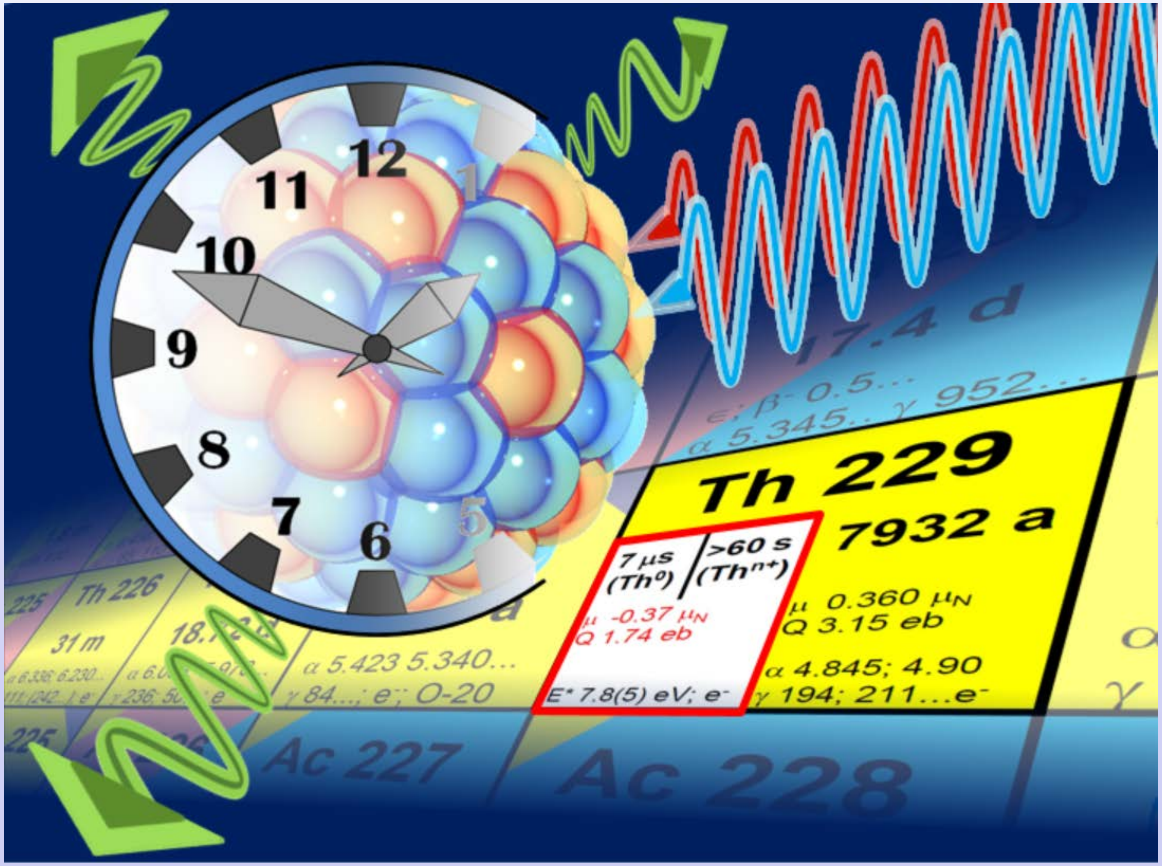
Development of a Nuclear Clock: Status and Perspectives

Peter G. Thirolf, LMU München



Outline

- **Thorium nuclear clock & applications**
- **Status:**
  "Search & Characterization Phase"
  (nuclear physics driven)

  - ^{229m}Th: experimental approach
  - direct decay identification
  - halflife
  - hyperfine structure
  - excitation energy

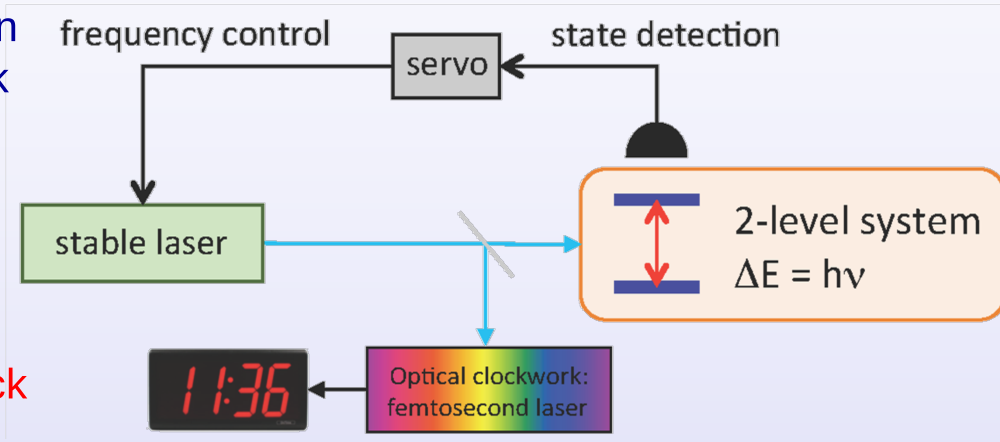
- **Perspectives:**
  "Consolidation & Realization Phase"
  (laser driven)

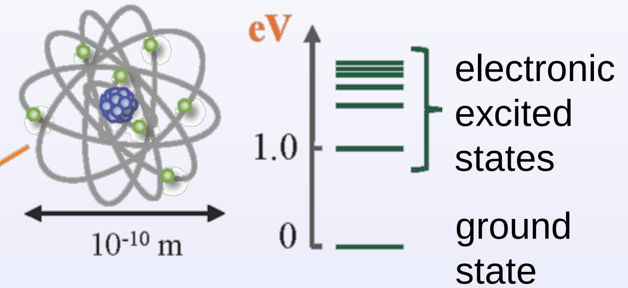
  - ongoing efforts and upcoming next steps

- **Summary/Conclusion**

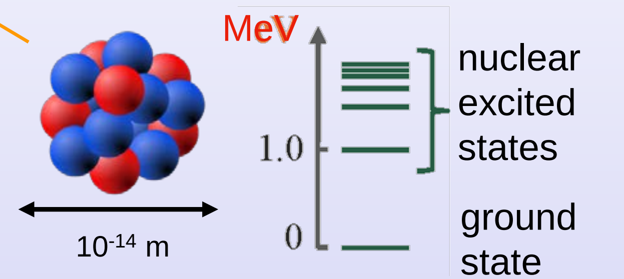
Thorium Nuclear Clock

scheme of an **atomic** clock

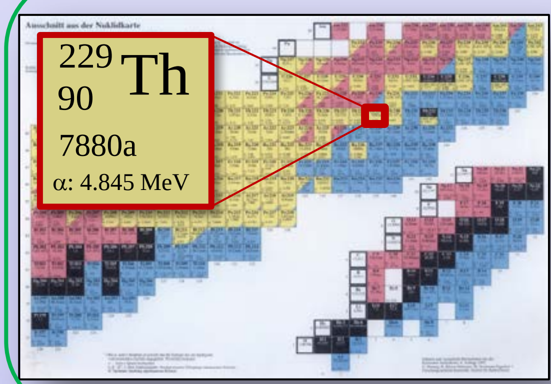




scheme of a **nuclear** clock



Nuclear clock proposal: E. Peik and Chr. Tamm, Europhys. Lett. 61, 181-186 (2003)
10^{-19} perfomance estimate of ^{229}Th ion clock: C. J. Campbell, et al., PRL 108, 120802 (2012)

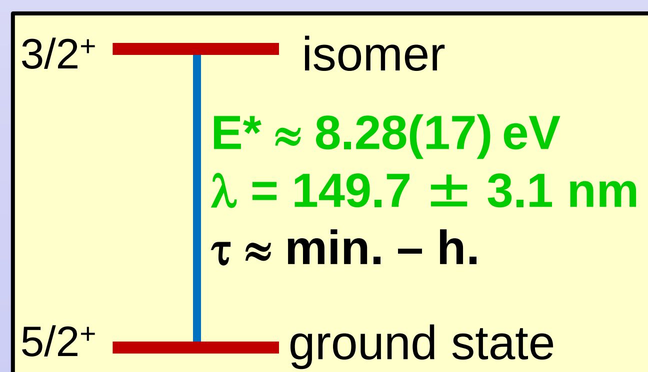


^{229m}Th properties:

lowest E* of all ~184000 presently known nuclear excited states

ΔE/E ~ 10^{-20}

~ 0.1 mHz nat. linewidth



Applications of Nuclear Clocks

- **Fundamentally different operation principle compared to atomic clocks:**

- **Coulomb + weak + strong interaction** contribute to clock frequency
- **small nuclear moments:** less sensitivity to perturbations by external fields
- **sensitvity** to new physics searches: **enhanced by 10^4-10^6** compared to present clocks

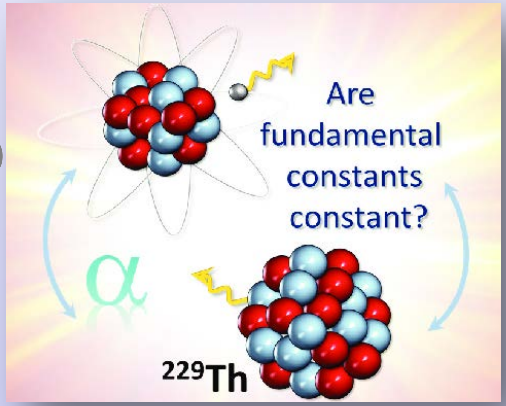
M.S. Safronova et al., Rev. Mod. Phys 90, 025008 (2018)

→ unique opportunity for new physics discoveries which cannot be accomplished with any other technology: Tests of fundamental physics and dark matter searches

- **Temporal variation of fundamental constants**
  - theoretical suggestion: temporal (spatial) variations of fundamental "constants" J.P. Uzan, Living Rev. Relativ. 14, 2 (2011)

$$\dot{\alpha}/\alpha = (-0.7 \pm 2.1) \cdot 10^{-17}\ \mathrm{yr}^{-1}$$

R. Godun et al., PRL 113, 201801 (2014)



- enhanced sensitivity by (10^5 – 10^6) of ^{229m}Th expected

V.V. Flambaum, PRL 97, 092502 (2006)

- measurements involve monitoring the ratio of nuclear/atomic clock over time

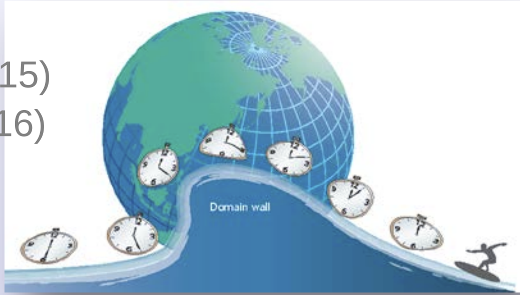
PT et al., Annalen d. Physik 531, 1800391 (2019)

Applications of Nuclear Clocks

- **Test coupling of fundamental constants on changing gravitational potential**
  tests the local position invariance hypothesis and thus Einstein's Equivalence Principle
  V. V. Flambaum, PRL 117, 072501 (2016)

- **Search for Dark Matter**
  - *ultralight scalar fields:* searches for oscillatory variation of fundamental constants   Arvanitaki et al., PRD 91, 015015 (2015)
  Van Tilburg et al., PRL 115, 011802 (2015), Hees et al., PRL 117, 061301 (2016)
  - *topological dark matter*: monopoles, 1D strings, 2D 'domain walls'   Derevianko & Pospelov, Nat. Phys. 10, 933 (2014)

  use networks of ultra-precise synchronized clocks



- **Improved precision of satellite-based navigation**
  (GPS, Galileo..): m → cm (mm ?)
  - autonomous driving
  - freight-/ component tracking …

- **3D gravity sensor:** 'relativistic geodesy'
  - clock precision of 10^{-18}: detect gravitational shifts of ± 1 cm
  - precise, fast measurements of nuclear clock network: monitor volcanic magma chambers, tectonic plate movements

$$\Delta f / f = -\Delta U / c^2$$

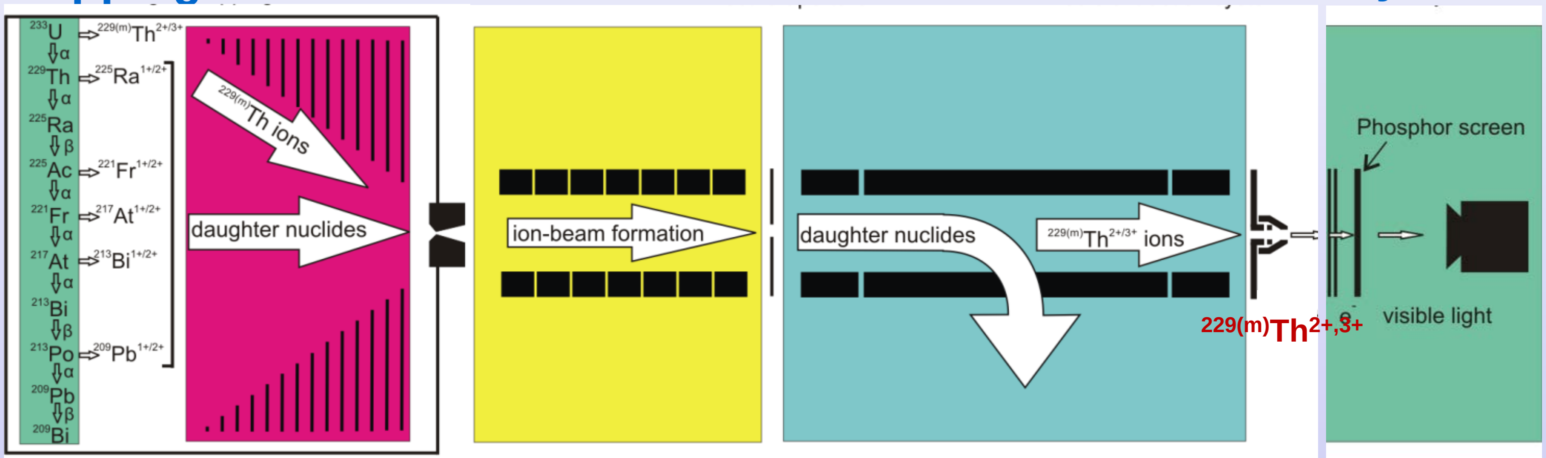
f: clock frequency
U: gravitat. potential

PT et al., Annalen d. Physik 531, 1800391 (2019)

Experimental Approach @ LMU

concept:
- populate the isomeric state via 2% decay branch in the α decay of ^{233}U
- spatially decouple $^{229(m)}Th$ recoils from the ^{233}U source
- detect the subsequently occurring isomeric decay

Buffer gas stopping cell | Laval nozzle | aperture electrode | triodic extraction electrode | detection system



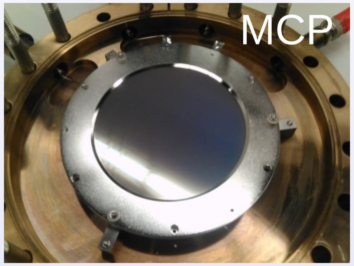
^{233}U source | RF + DC funnel | RF quadrupole ion guide | Quadrupole mass separator | MCP | CCD

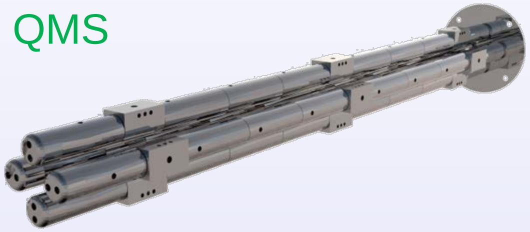
~30 mbar (He) | 10^{-2} mbar | 10^{-6} mbar

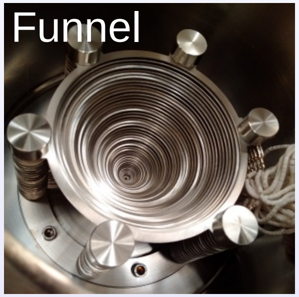
→ accumulate $^{229(m)}Th$ ions directly onto MCP surface

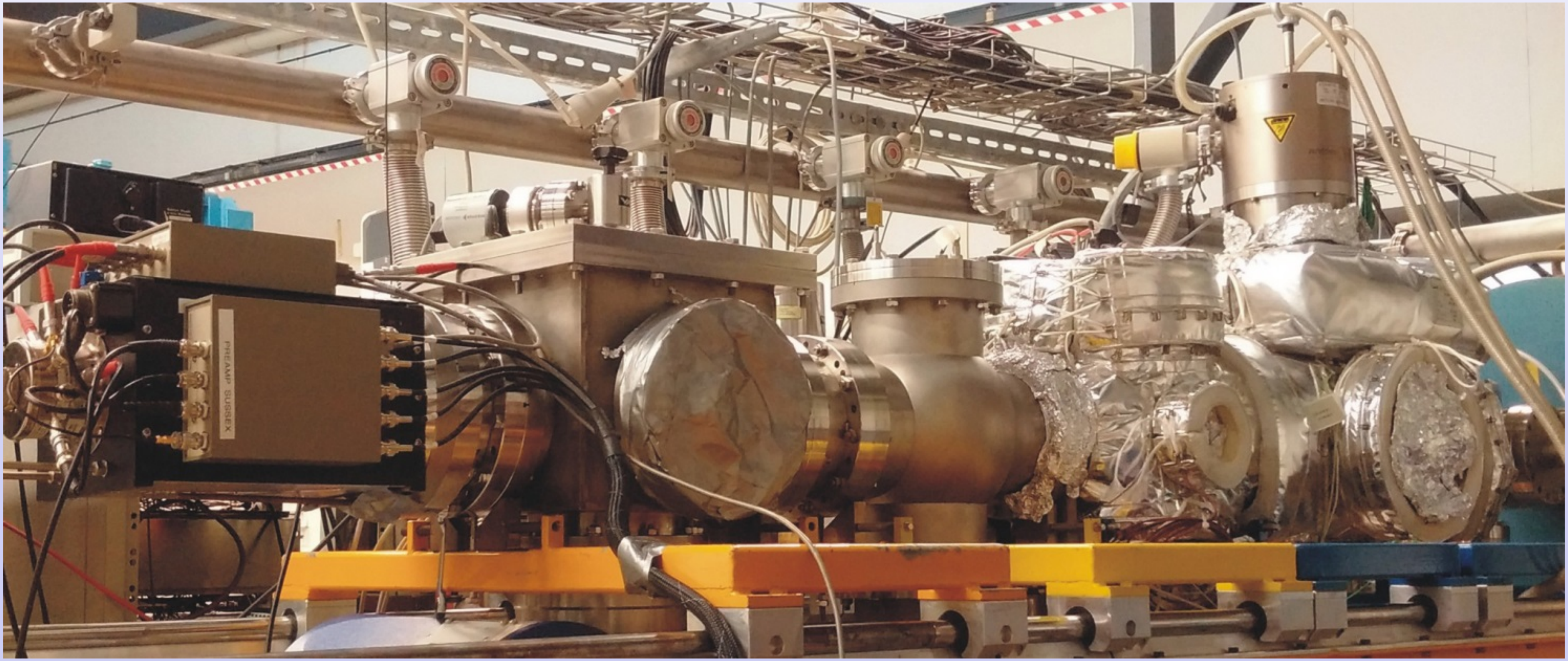
Experimental Setup

located at Maier-Leibnitz Laboratory, Garching:





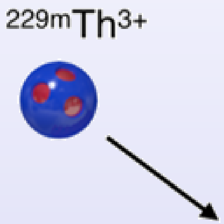


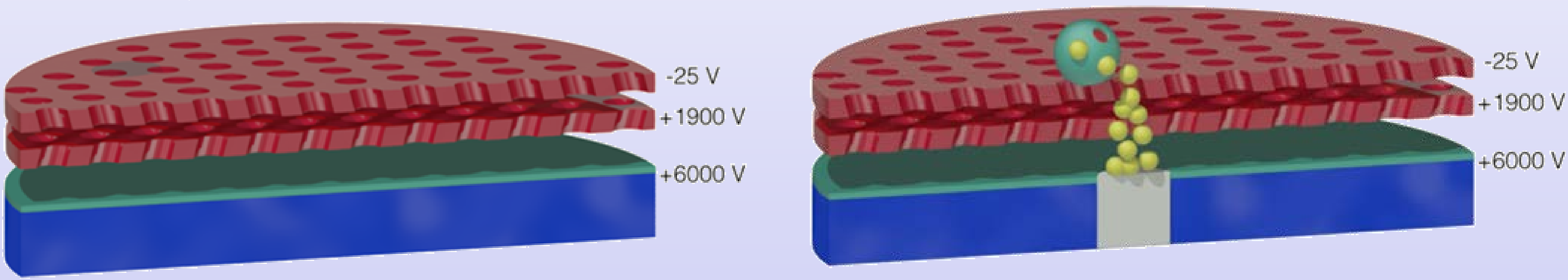


Isomer Detection Process

extracted $^{229(m)}Th^{3+}$ ions:

- **impinging directly onto MCP surface (behind QMS)**
- **'soft landing' on MCP surface: avoid ionic impact signal**
- **neutralization of Th ions**
- **isomer decay by Internal Conversion: electron emission**
- **electron cascade generated, accelerated towards phosphor screen**
- **visible light imaged by CCD camera**



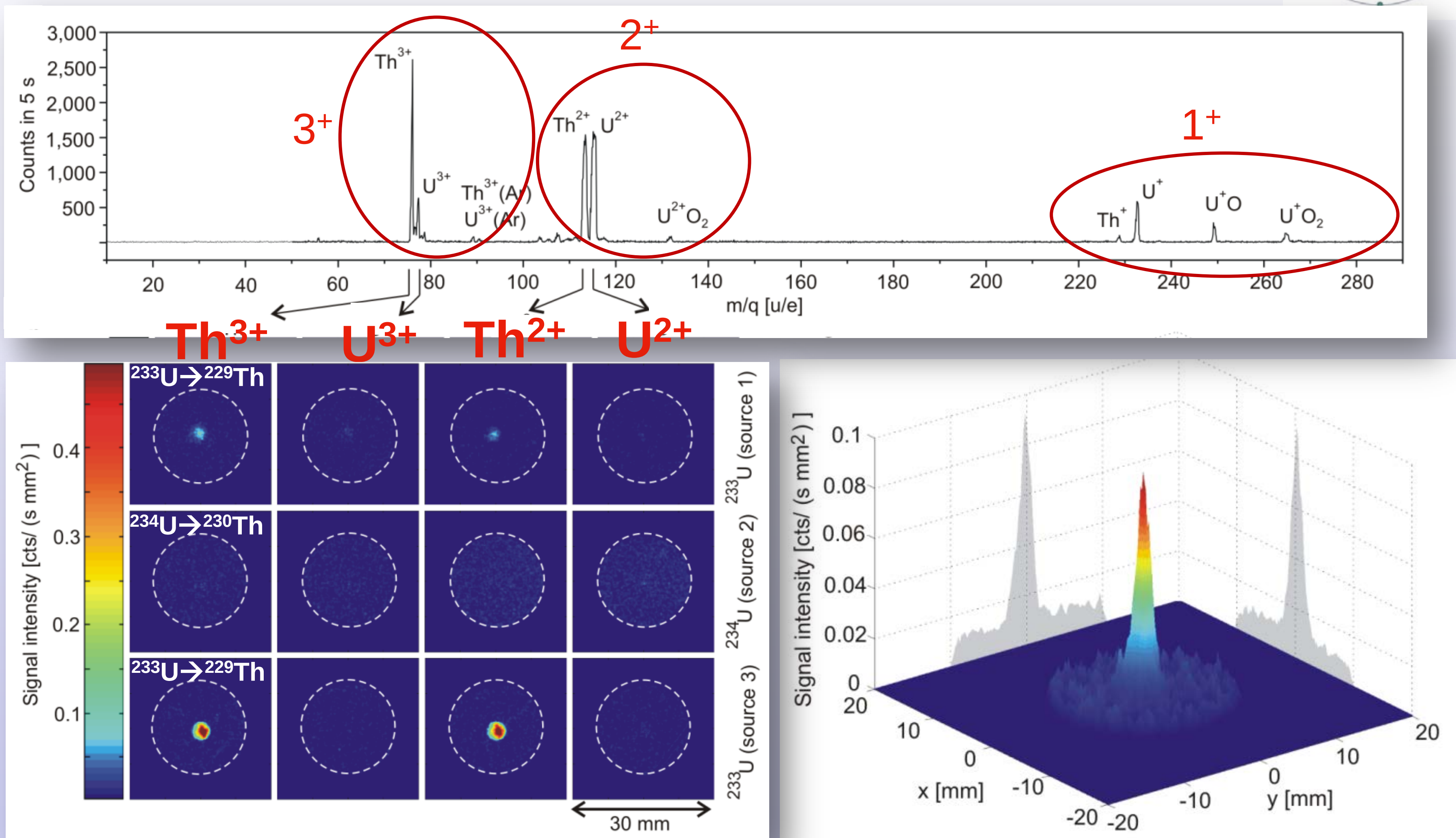


- internal conversion (IC) energetically allowed for neutral thorium:

  $I(Th^{+}, 6.31\ eV) < E^{*}(^{229m}Th, \sim 8.3\ eV)$

- isomer lifetime expected to be reduced by ca. 10^{-9} (from $\sim 10^{4}$ s → ~ 10 μs)
- Th^{q+} ions: IC is energetically forbidden, radiative decay branch may dominate

Direct Signal of IC Decay from ^{229m}Th

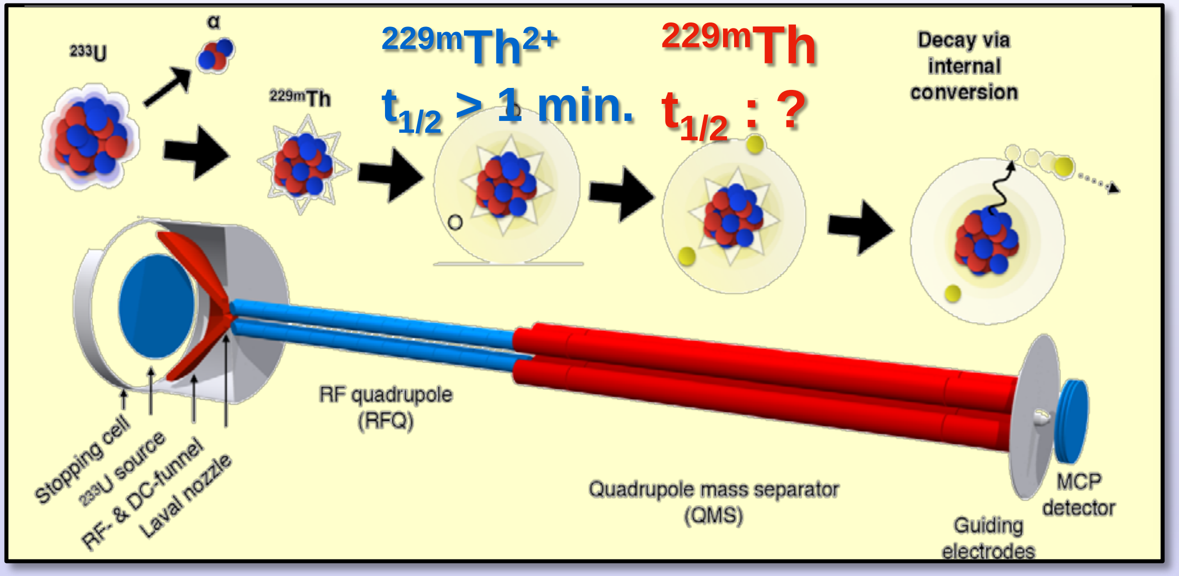


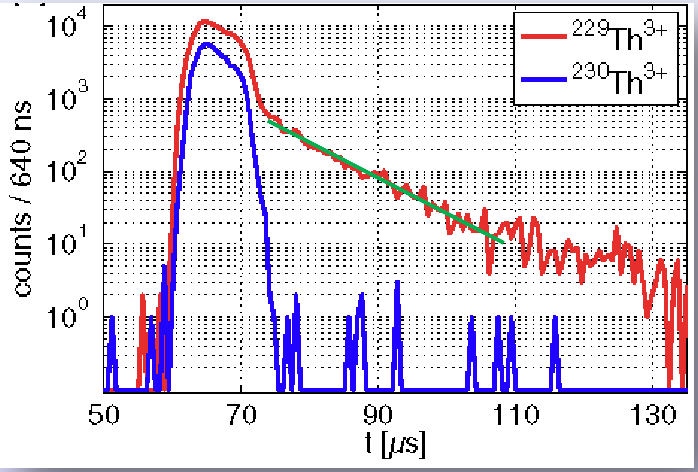
clear signal from Th^{3+}, Th^{2+}
no signal from U^{3+}, U^{2+}

L. v.d. Wense, PT et al., Nature 533, 47-53 (2016)

Halflife of (neutral) ^{229m}Th

- operate segmented RFQ as linear Paul trap: pulsed ion extraction
- ion bunches: width ca. 10 μs, ~ 400 $^{229(m)}Th^{2+,3+}$ ions/bunch
- charged $^{229m}Th^{2+}$: $t_{1/2}$ > 1 min. (limited by ion storage time in RFQ, i.e vacuum quality)





- after neutralization on MCP surface: **$t_{1/2}$ = 7±1 μs**

→ in agreement with expected $\alpha_{IC} = N_e/N_\gamma \sim 10^9$

B. Seiferle, L. v.d. Wense, PT, PRL 118, 042501 (2017)

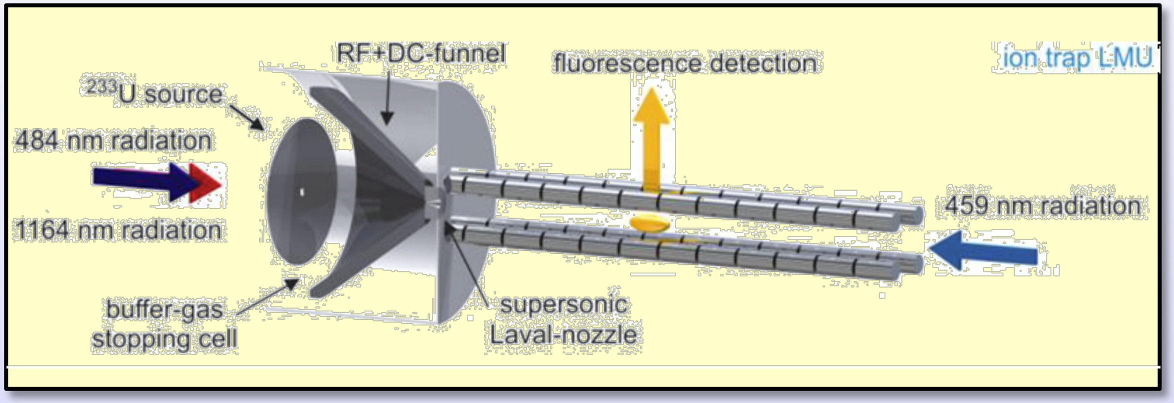
Collinear Laser Spectroscopy on ^{229m}Th

→ enable 'tagging' nuclear excitation of ^{229m}Th by, e.g., double resonance method

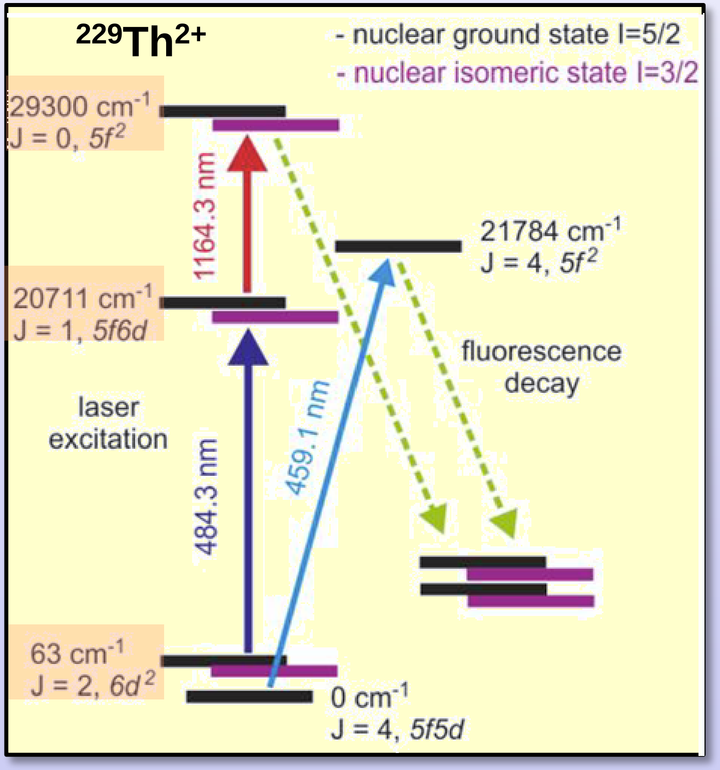
Peik, Tamm, Eur. Phys. Lett. 61 (2003) 181

→ resolve hyperfine structure of $^{229m}Th^{2+}$

→ co- and counter-propagating laser beams



in collaboration with PTB
(E. Peik, M. Okhapkin et al.)



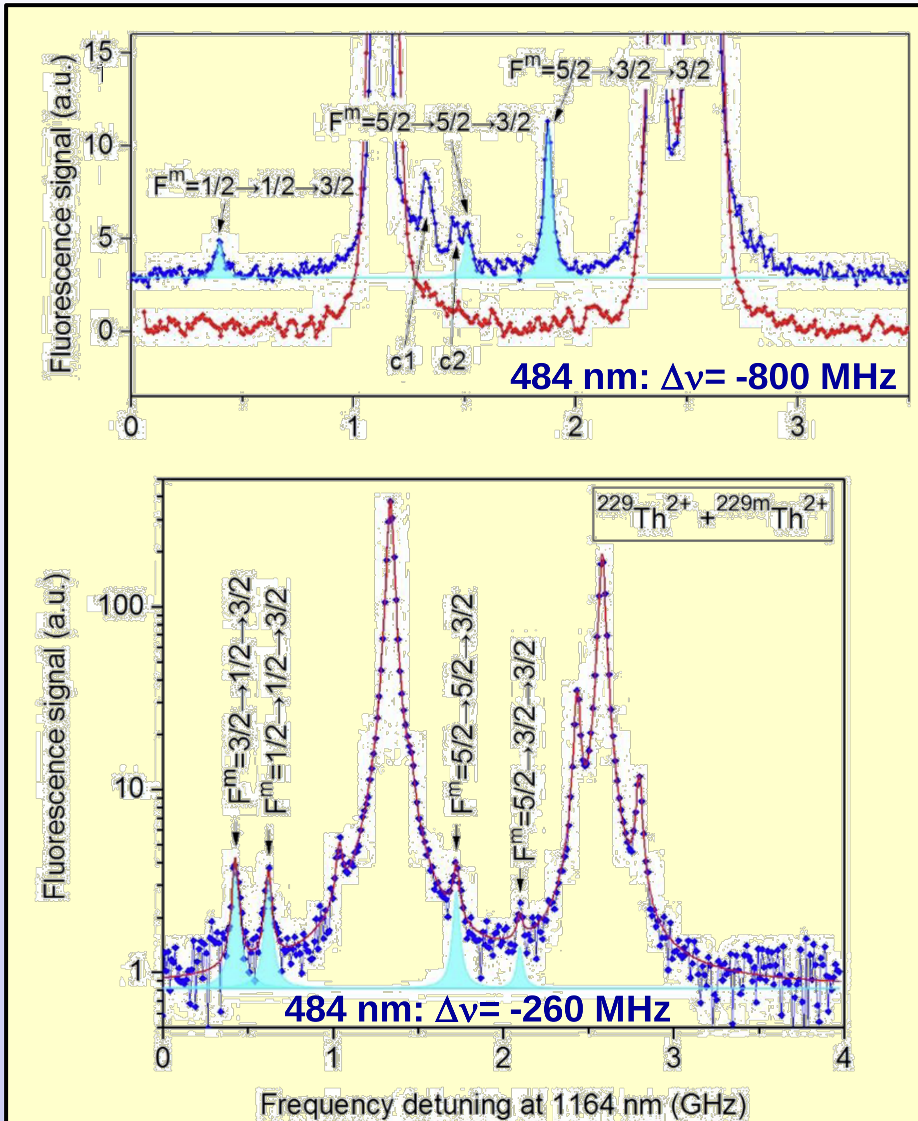
2-photon laser excitation (J=2 → 1 → 0):

i) 484.3 nm: excitation of ions from thermal distribution into intermediate state
- 35 steps across frequency profile

ii) 1164.3 nm: excitation from intermediate state with variable excitation into final state
- for each step of i): continuous frequency scan

Hyperfine Structure of ^{229m}Th

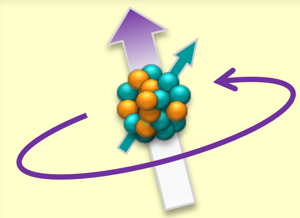
J. Thielking,.., PT et al., Nature 556, 321-325 (2018)



ground state: (I=5/2): 9 transitions

isomeric state: (I=3/2): 8 transitions

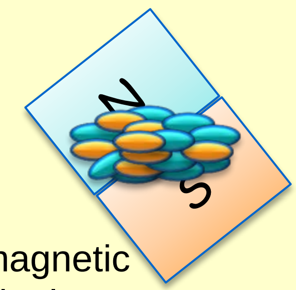
$$E_{HFS}(JIF) = \frac{1}{2} A K + B \frac{(3/4)K(K+1) - I(I+1)J(J+1)}{2I(2I-1)J(2J-1)}$$



$F = J + I$

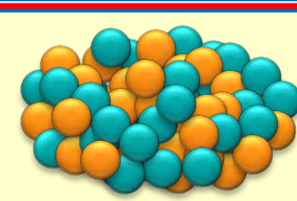
nuclear spin

I = 3/2



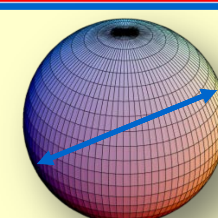
magnetic dipole moment

μ^m **= - 0.37(6)** μ_N



electrical quadrupole moment

Q_0^m **= 8.7(3) eb**



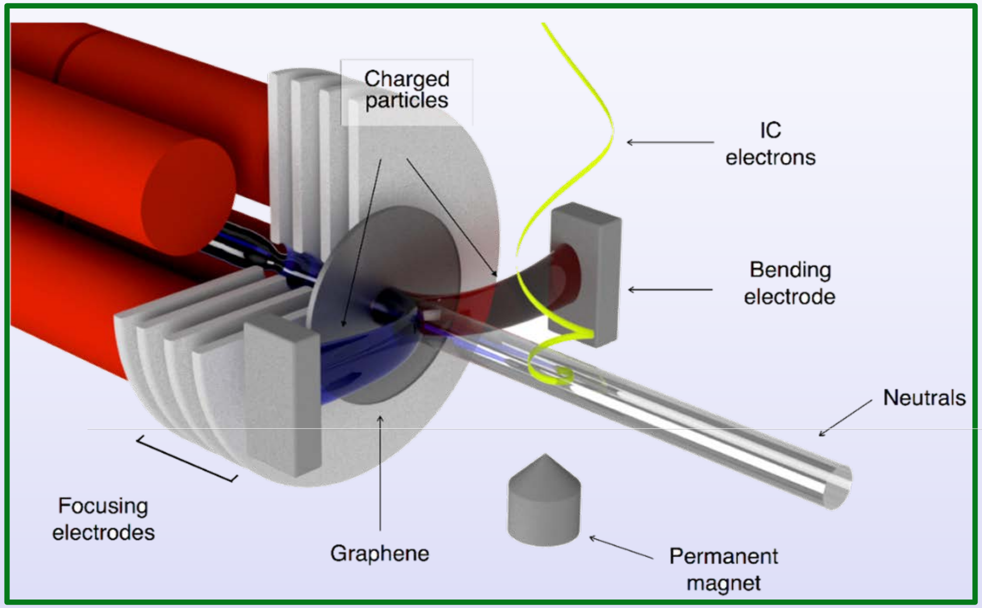
charge radius

$\langle r^2\rangle^{229m} - \langle r^2\rangle^{229}$ **= 0.012(2) fm²**

→ sensitivity enhancement **$K=\Delta E_c/E^*$**

Berengut et al., PRL 102, 210801 (2009)

Excitation Energy Measurement

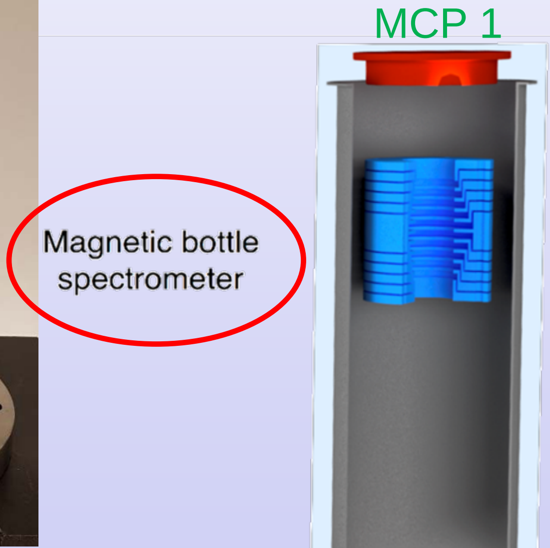


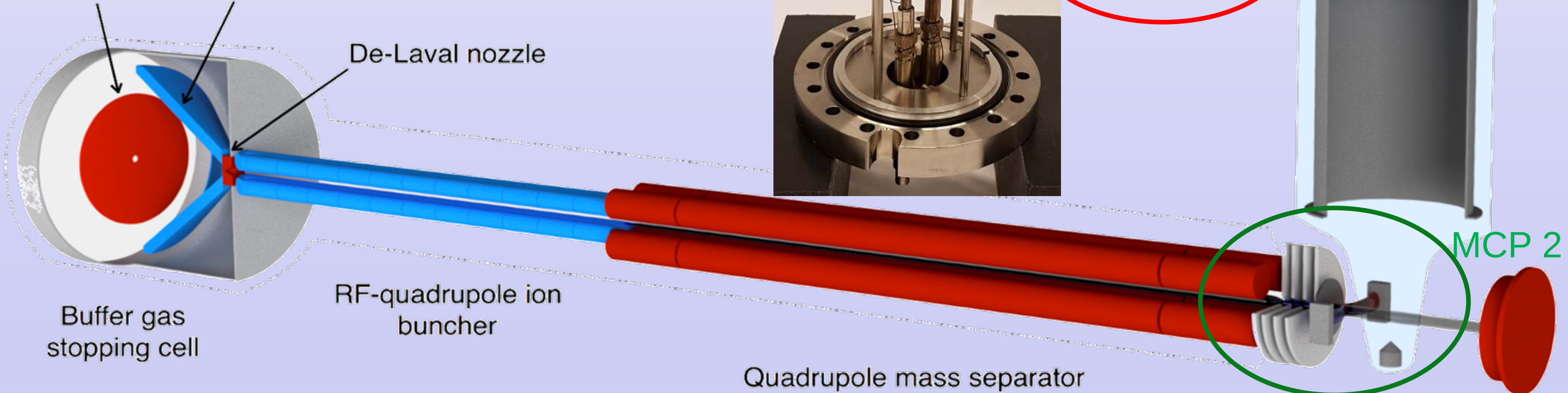
neutralization of $^{229m}Th^{q+}$ in graphene foil:

→ contact-free IC decay

→ measure E_{kin} (e)

→ spectrometer resolution: 30 -50 meV



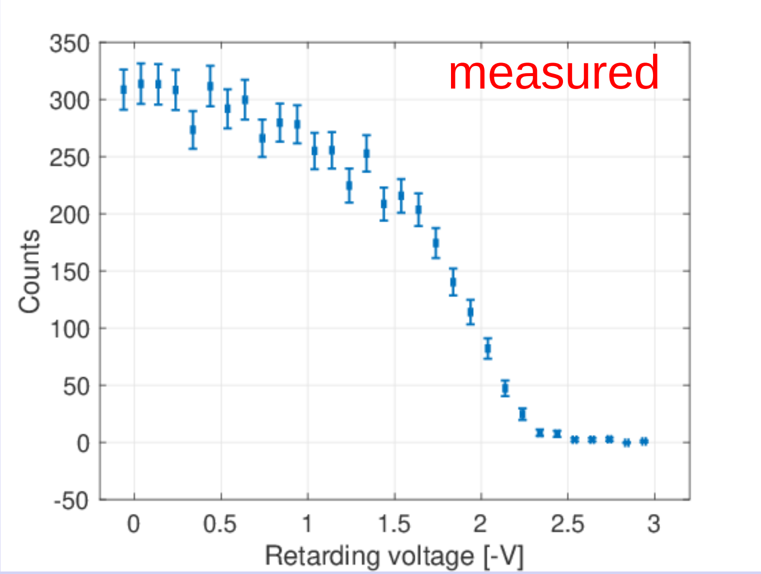


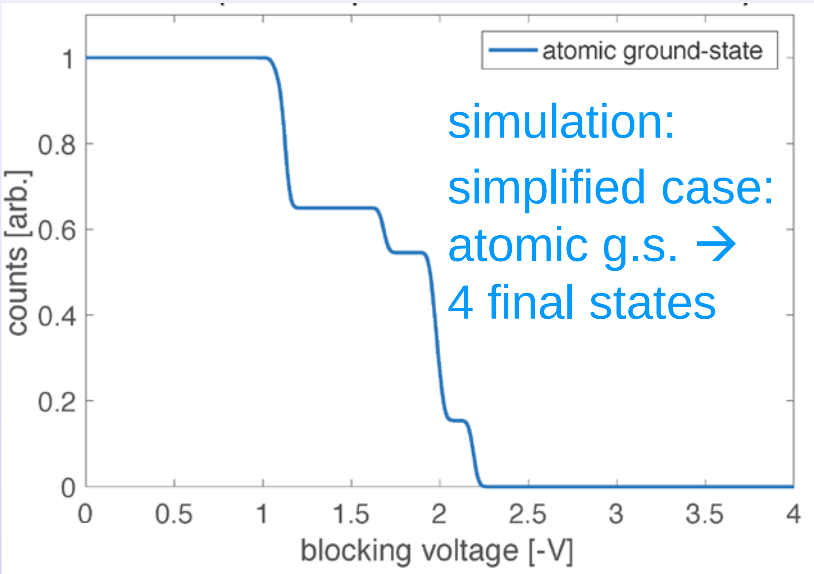
Excitation Energy: Analysis

- **Experimental challenge:**

  - resonant neutralization of $^{229m}Th^{q+}$ ends in excited atomic state and IC decay leads to excited electronic states

$$E_{kin}(e) = E^*(iso) - IP - E_{ion,final} + E_{atom,initial}$$ (IP(Th) = 6.308(3) eV)





- IC transitions from ≤ 4 excited atomic states could be resolved
- measurement: no steps clearly identified: ≥ 5 initial states must contribute
- 82 states can contribute in relevant energy range (below 20000 cm^{-1}, ≈ 2.5 eV)
- individual population unknown

atomic calculations:
P. Bilous, A. Palffy (MPIK Heidelberg)
F. Libisch, C. Lemell (TU Wien)

Excitation Energy

B. Seiferle, PT et al., Nature 573 (2019)

- **Statistical analysis:**

$f(U) = a\,(1 – \mathrm{erf}\,[\,(U - E_{defl})\,/\,b\,])$

- fit error function to measured data:

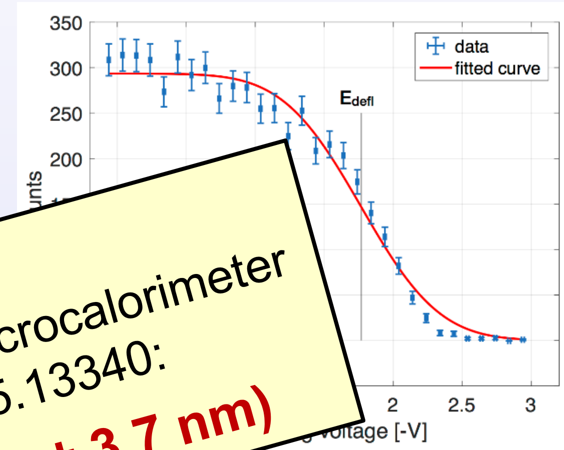
→ deflection point E_{defl} = 1.77(3) eV

→ $E^*(iso) = E_{defl} + E_0$

→ predict E_0 from simulated sp

- simulate 20000 per

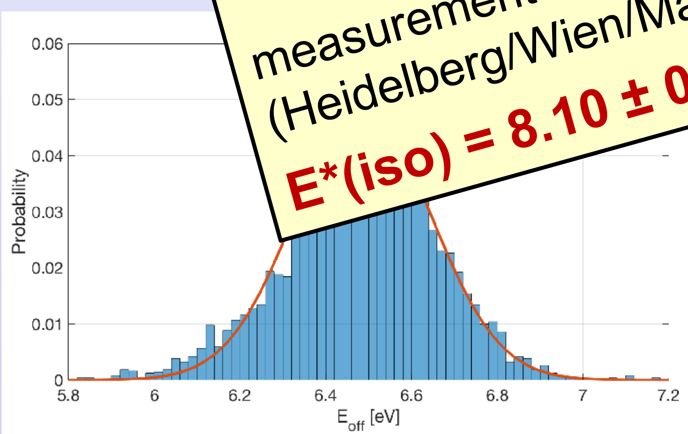
any 5 (of 8

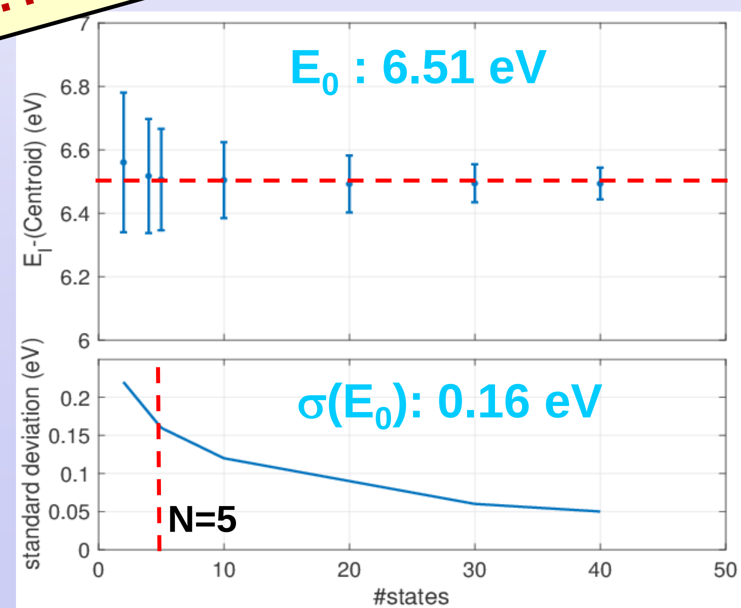


'hot of the press':

measurement of E* with magnetic microcalorimeter (Heidelberg/Wien/Mainz), arXiv:2005.13340:

E*(iso) = 8.10 ± 0.17 eV (= 153.1 ± 3.7 nm)





E*(iso) = 8.28 ± 0.17 eV (= 149.7 ± 3.1 nm)

→ constrains laser technology

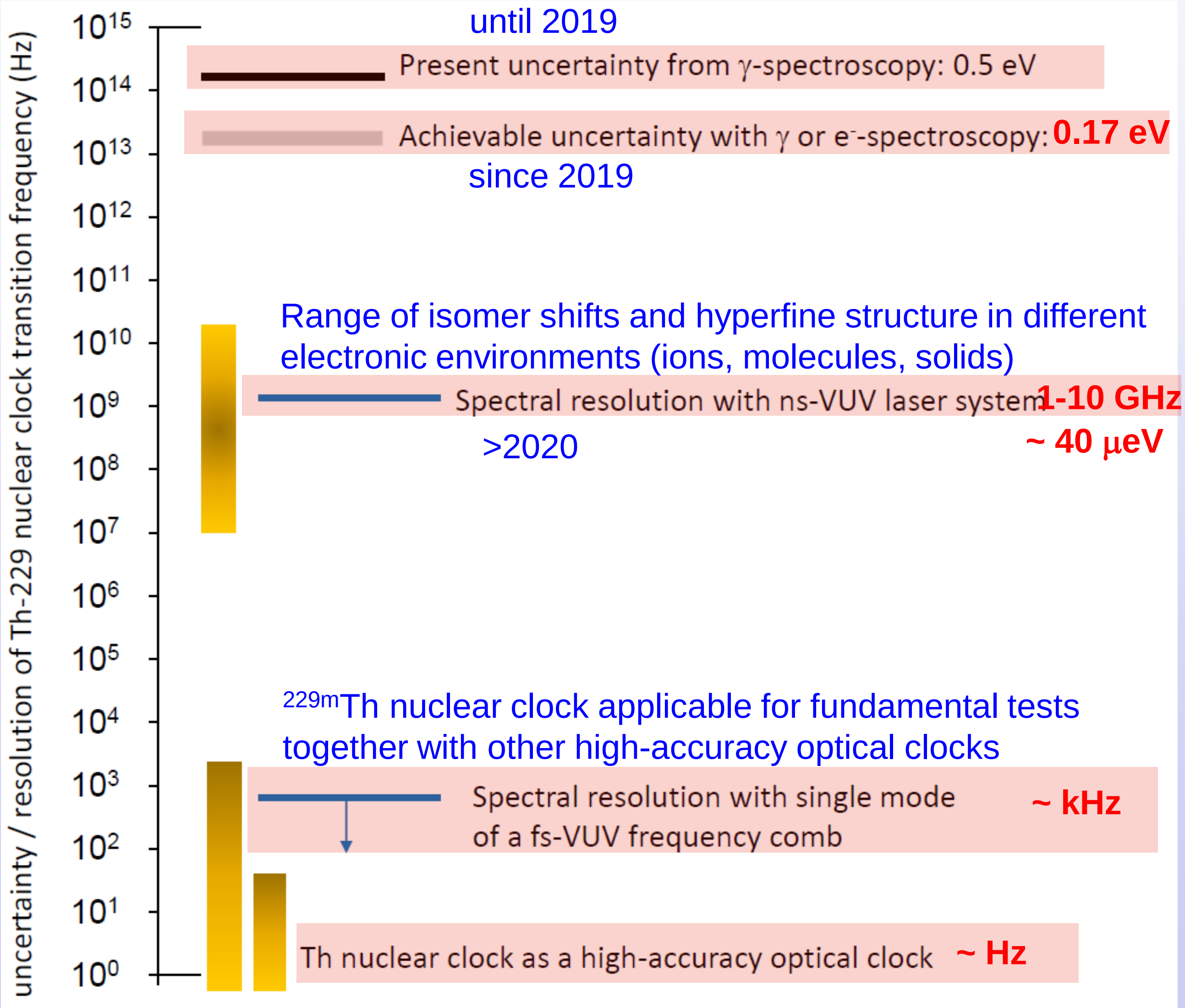
Perspectives towards the Nuclear Clock

- **still to bridge: ca. 14 orders of magnitude:**

already feasible with existing laser technology

concept:

L. v.d. Wense, PT et al, PRL 119 (2017)

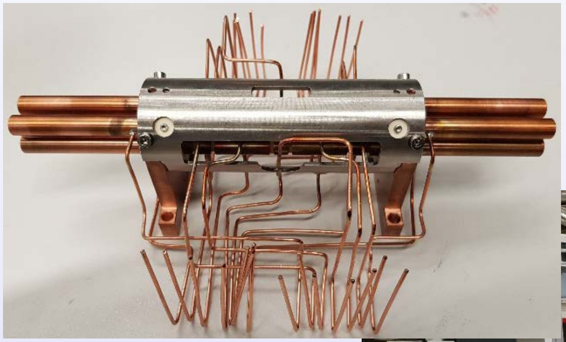


Experimental Platform

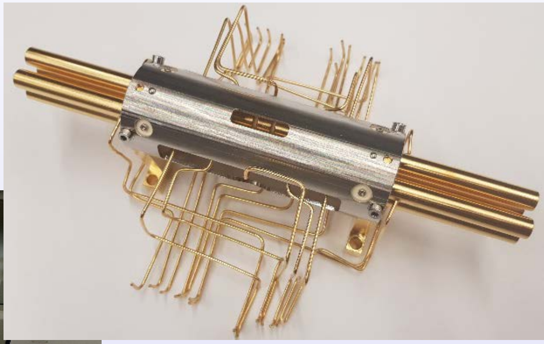
Ionic lifetime: needs longer storage time (= better vacuum)

- setup of a cryogenic Paul trap
- new small buffer gas cell
- QMS at injection/extraction side

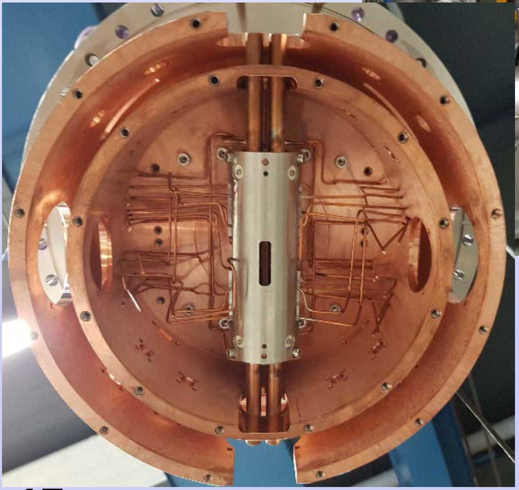
→ platform for laser manipulation



Cu basis



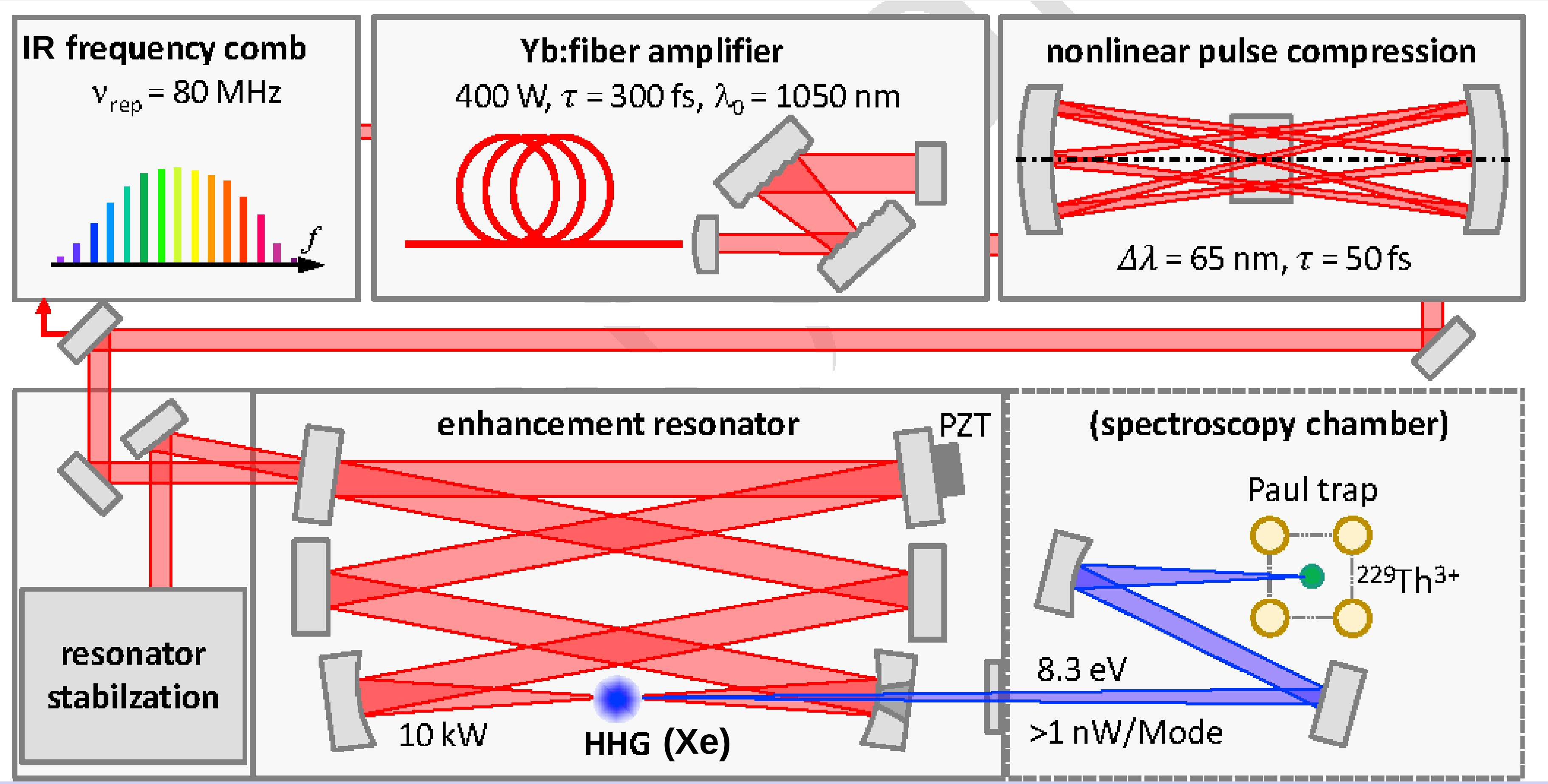
Au plated



ready for commissioning

VUV laser source for the
^{229m}Thorium - Nuclear Clock transition

7th harmonic of VUV frequency comb: (central wavelength 150 nm)



J. Weitenberg, ILT Fraunhofer/ RWTH Aachen & MPQ Garching

(Online) GPMFC Workshop, Portland/Oregon, 1.6.2020

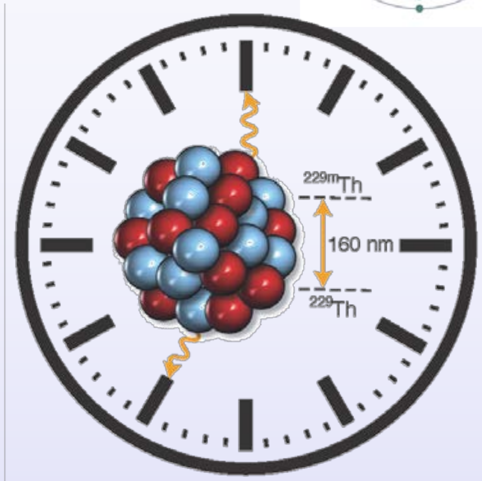
Summary

look back: large progress in last 4 years:

- identification & characterization of the thorium isomer

look ahead: ongoing consolidation & next steps

- excitation energy from complementary techniques
- cryogenic Paul trap, sympathetic (Sr^+) laser cooling
- ^{229m}Th ionic lifetime
- determine sensitivity enhancement for $\dot{\alpha}$
- doped-crystal approach: radiative, IC branches
- laser spectroscopy: resonance search



ambitious, exciting, important research topic:

- excite for the first time ever the nuclear transition by laser
- build clocks based on completely new principles
- ability to drastically improve sensitivity to new physics
- ability to search for dark matter candidates not accessible by any other means

the door is open for the realization of a nuclear clock …

"ThoriumNuclearClock"

- ERC Synergy project: 2020-2026
- Team: PI: PTB (E. Peik et al.), TU Wien (T. Schumm et al.),
  LMU Munich (P. Thirolf et al.), U Delaware (M. Safronova et al.)
  + A. Palffy (MPIK-HD), J. Weitenberg (Fraunhofer ILT/RWTH Aachen)
- long road to go:

Fundamental and technology goals

- Perform the first laser excitation of a nuclear transition
- Precisely determine ^{229}Th nuclear structure parameters
- Development of a < kHz-level linewidth VUV laser
- Quantify the sensitivity to fundamental constants
- Measure isomer energy to > 12 digits
- Demonstrate nuclear clock with Th^{3+} ions
- Demonstrate completely new solid-state clock scheme
- Test fundamental concepts of physics
- Search for dark matter

Scientific advances in many fields

- Precision metrology
- Nuclear physics
- Atomic physics
- Laser physics
- Particle physics
- Solid-state physics
- Radiochemistry

Thanks to ….

LMU Munich: **L. v.d. Wense, B. Seiferle**, N. Arlt, B. Kotulski, I. Amersdorffer

PTB Braunschweig: J. Thielking, P. Glowacki, D.M. Meier M. Okhapkin, ***E. Peik***

GSI Darmstadt & Helmholtz-Institut Mainz: M. Laatiaoui

Helmholtz-Institut Mainz & Johannes Gutenberg-Universität Mainz:
C. Mokry, J. Runke, K. Eberhardt, N.G. Trautmann, C.E. Düllmann

TU Wien: ***T. Schumm***, S. Stellmer, K. Beeks, C. Lemell, F. Libisch

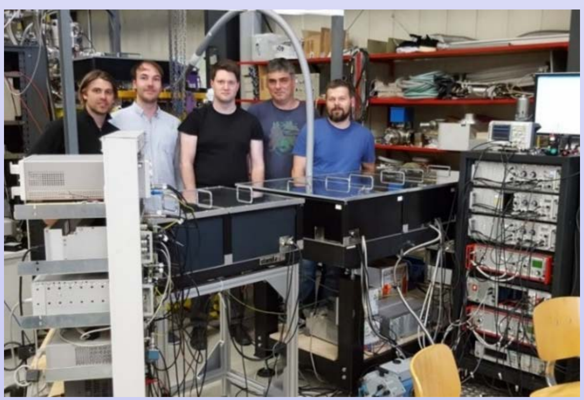
MPQ: J. Weitenberg, T. Udem

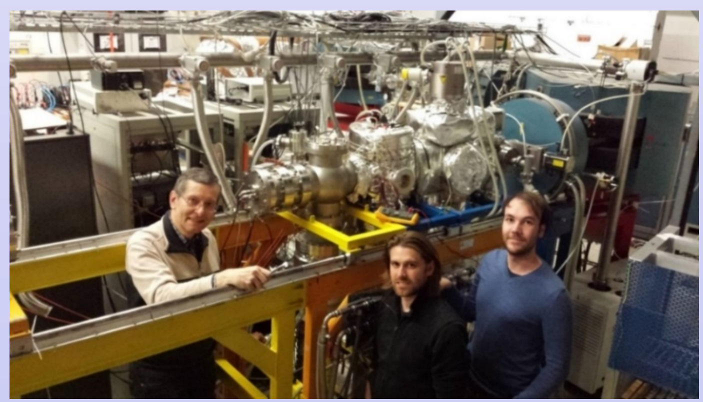
MPI-HD: ***A. Pàlffy***, P. Bilous, N. Minkov, J. Crespo

NIST: S. Nam, G. O'Neill

UCLA: E. Hudson, C. Schneider, J. Jeet

U Delaware: ***M. Safronova***





Thank you for your attention !