What do we know about the ^{229}Th nuclear clock isomer ?

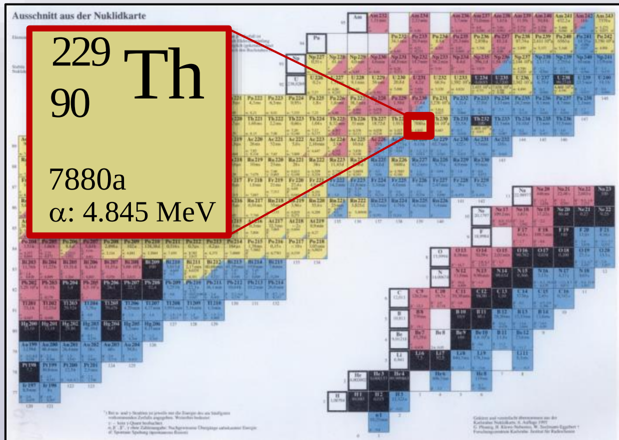
P.G. Thirolf, LMU München

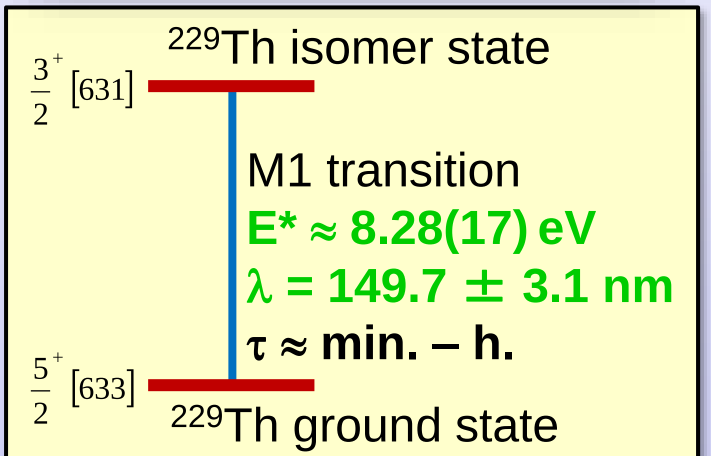
“Thorium story” has reached a pivot point:

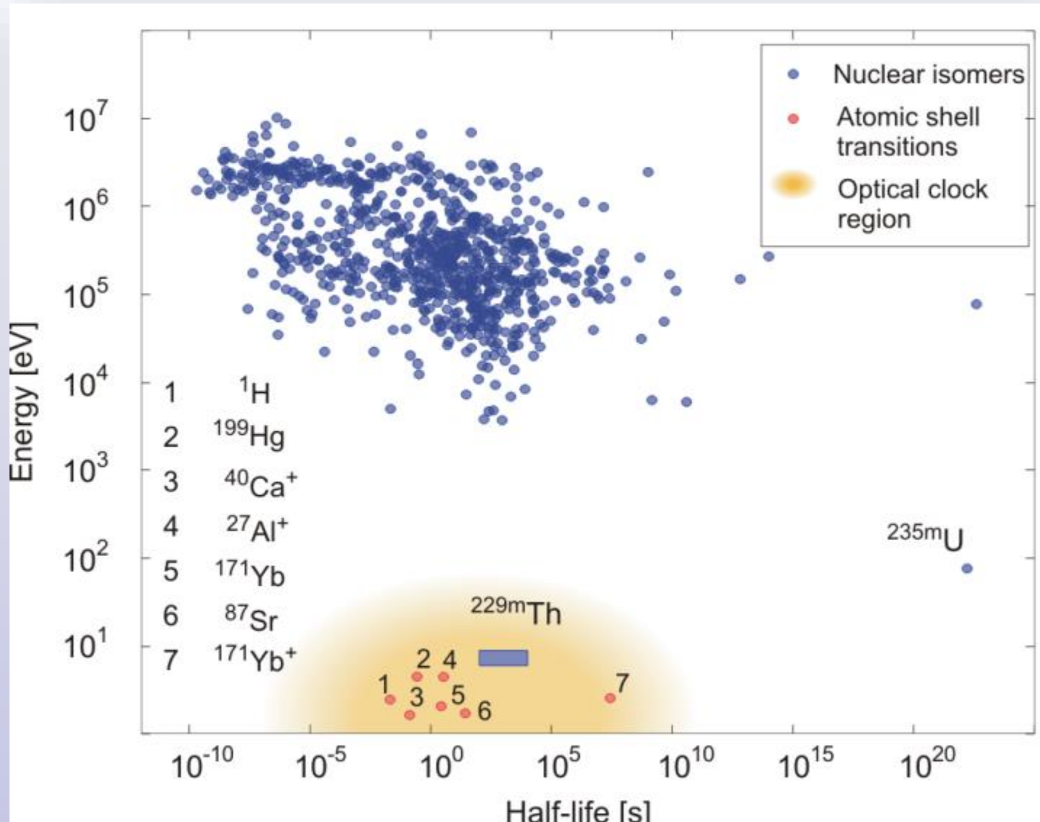
- **Search & Characterization Phase:**
  nuclear physics-driven
  → remind huge progress from last 4 years

- **Consolidation & Realization Phase:**
  laser-driven
  → ongoing efforts and upcoming next steps

Unique properties of the ^{229m}Th Isomer







lowest E* of all ca. 184000 presently known nuclear excited states

→ **ΔE/E ~ 10^{-20}:**
extremely stable nuclear frequency standard: ‘nuclear clock’

Applications of Nuclear Clocks

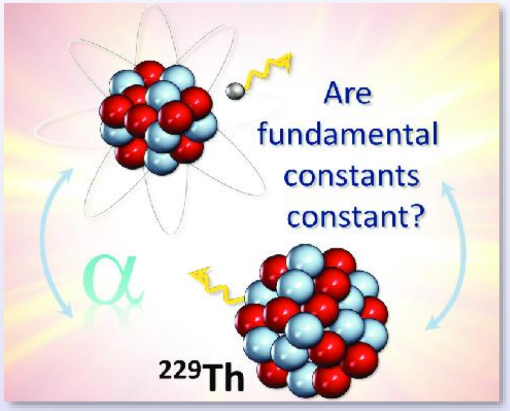
- **Improved precision of satellite-based navigation** (GPS, Galileo..): m → cm (mm ?)

- **Temporal variation of fundamental constants**
  - theoretical suggestion: temporal (spatial) variations of fundamental "constants"

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

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

  - enhanced sensitivity by (10^2 – 10^5) of ^{229m}Th expected



- **Search for Dark Matter**
  - topological dark matter: clumped to point-like monopoles, 1D strings, 2D 'domain walls'
  - use networks of ultra-precise synchronized clocks

- **3D gravity sensor:** 'relativistic geodesy'
  - best present clocks: detect gravitational shifts of ± 1 cm
  - precise, fast measurements of nuclear clock network: monitor volcanic magma chambers, tectonic plate movements

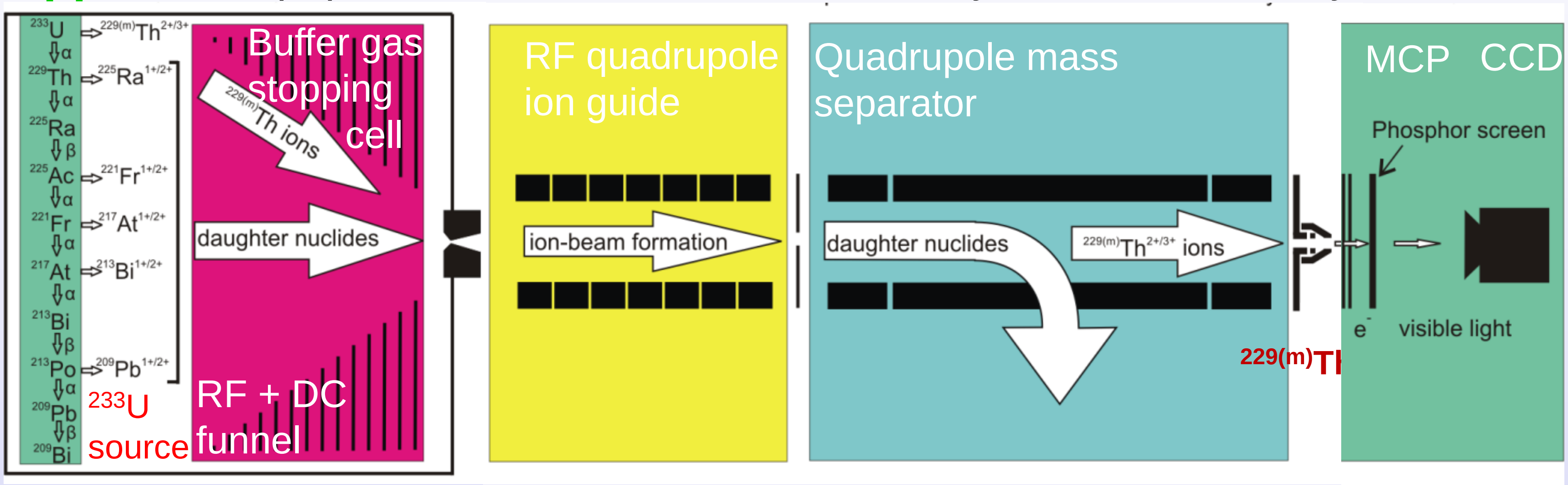
$$\Delta f/f = -\Delta U/c^2$$

f: clock frequency
U: gravitat. potential

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

"Thorium Isomer Factory"

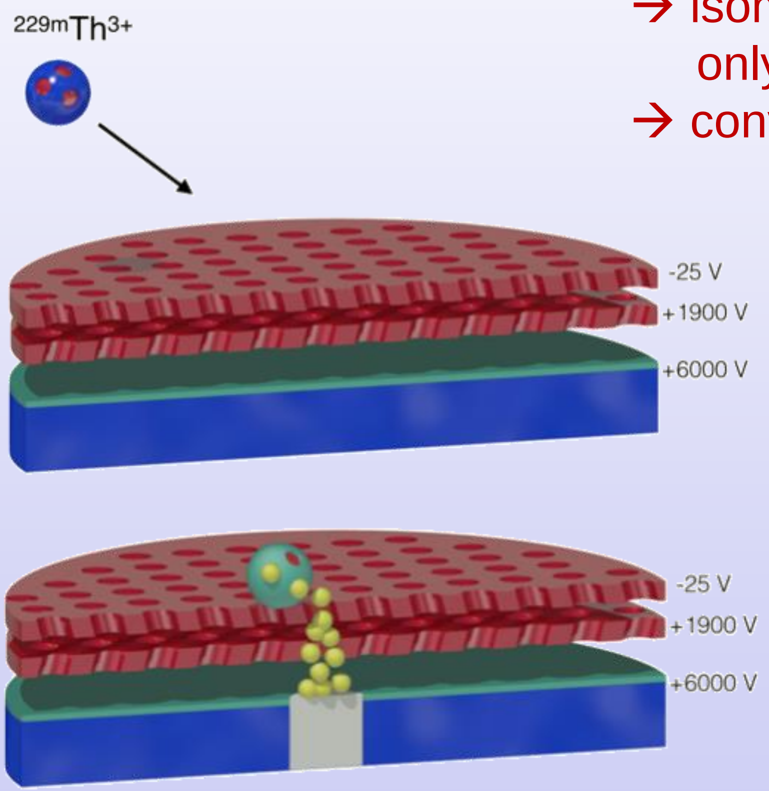
- **approach:** populate isomeric state via 2% decay branch in α decay of ^{233}U

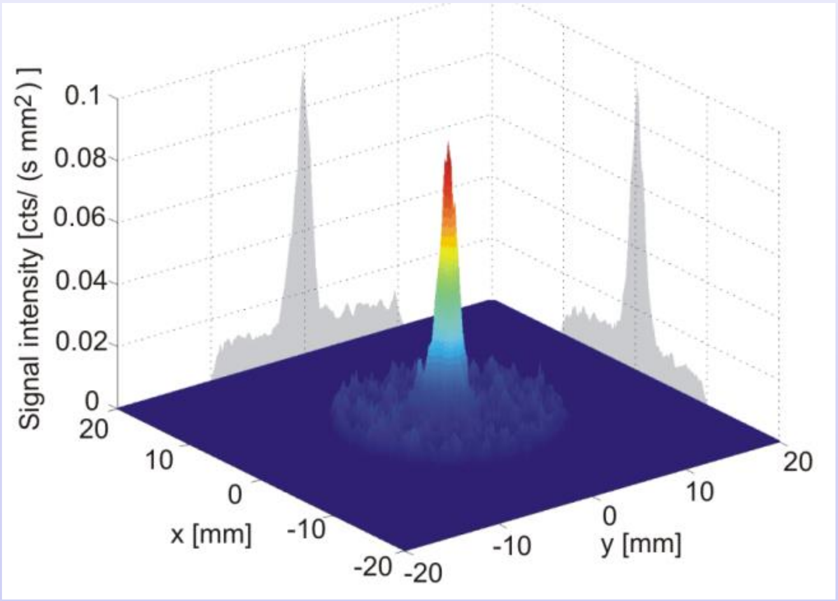


P.G. Thirolf, LMU München 3rd Intern. Workshop on „Shapes and Dynamics of Atomic Nuclei", Sofia, Bulgaria, October 3-5, 2019

Detection of Direct Isomer Decay

- **extracted $^{229(m)}Th^{q+}$ ions:** - impinging directly onto MCP surface
  - 'soft landing' on MCP surface: avoid ionic impact signal
  - neutralization of Th ions
  - → isomer decay by Internal Conversion: only allowed in neutral ^{229}Th: IP(Th^+, 6.31 eV) < E*(^{229m}Th, 8.28 eV)
  - → conversion electron emission





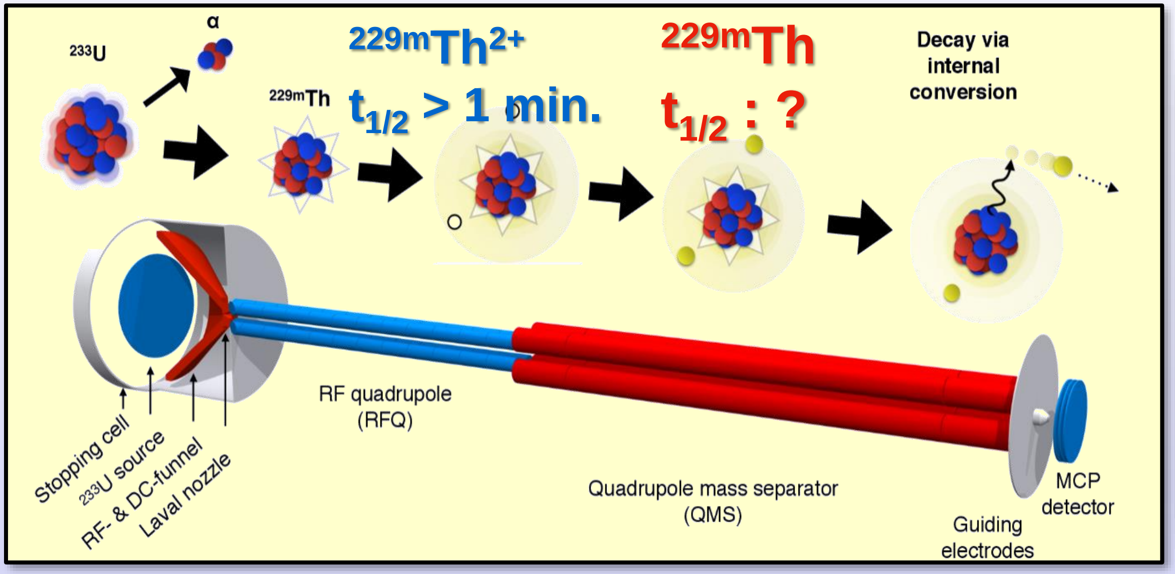
L. v.d. Wense, PT et al., Nature 533, 47-51 (2016)

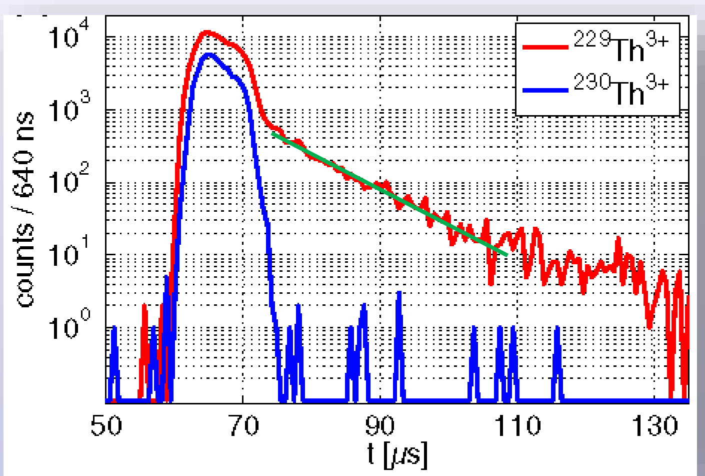
- **isomer lifetime:** reduction expected by ca. 10^{-9} (from ~10^4 s → ~ 10 μs): $\alpha_{IC} \sim 10^9$

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: $t_{1/2} = 7 \pm 1\ \mu s$

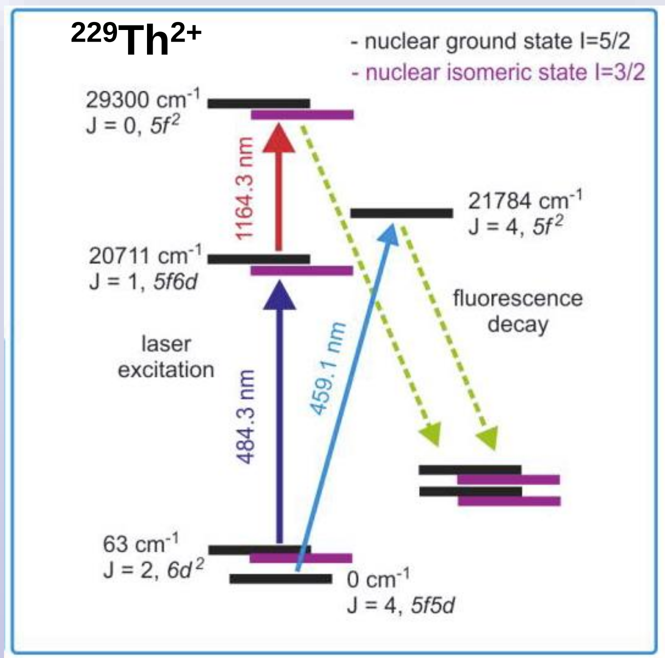
→ in agreement with expected $\alpha_{IC} \sim 10^9$

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

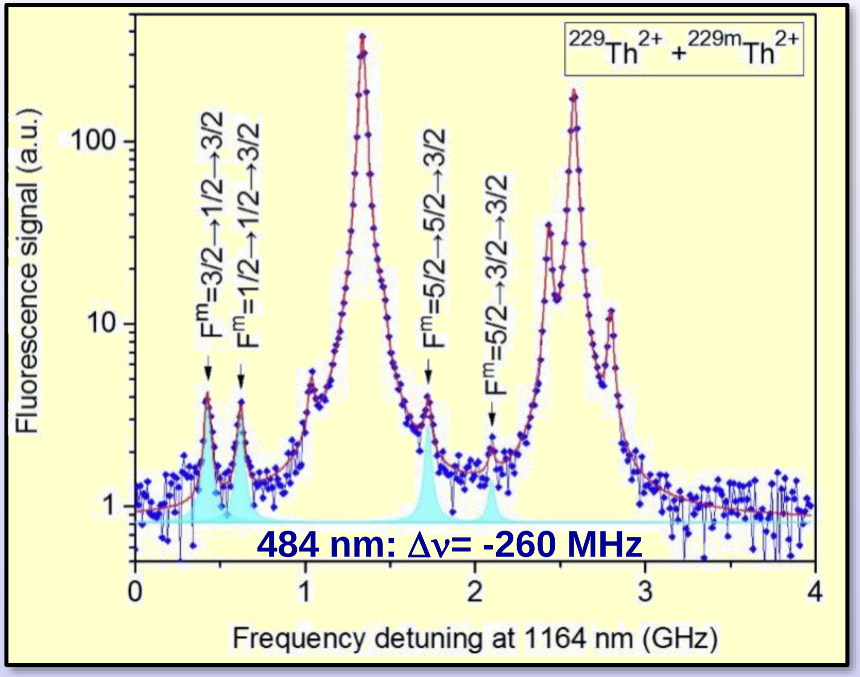
Resolve Hyperfine Structure of ^{229m}Th

Collaboration with PTB Braunschweig

- Doppler-free two-step laser excitation (J=2→1→0) of $^{229m}Th^{2+}$:



scan co- & counter-propagating lasers



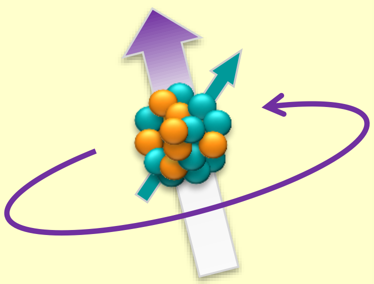
ground state: (I=5/2): 9 transitions

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

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

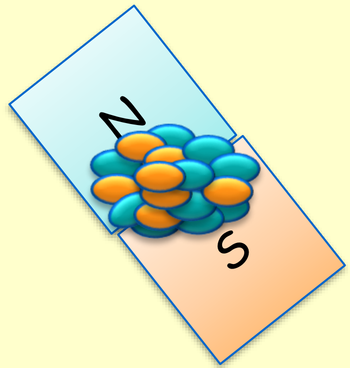
J. Thielking,.., PT et al., Nature 556, 321-325 (2018)

What does HFS teach about ^{229m}Th ?

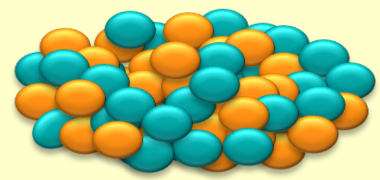


F=J+I

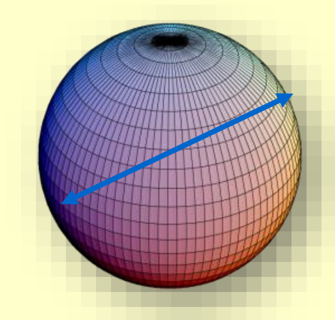
nuclear spin



magnetic
dipole moment



electrical
quadrupole moment



charge radius

I = 3/2

⇓

confirms level scheme

μ^m = - 0.37(6) μ_N

⇓

confirmed by recent theory

Q_0^m = 8.7(3) eb

⇓

prolate deform.; $\dot{\alpha}$ sensitivity

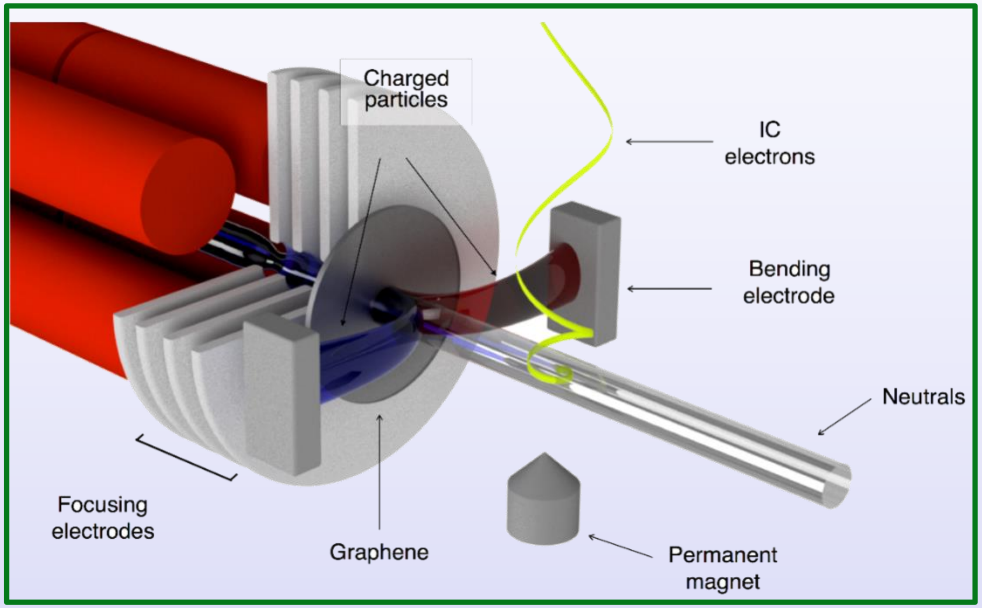
$\langle r^2\rangle^{229m}$ - $\langle r^2\rangle^{229}$ = 0.012(2) fm^2

⇓

sensitivity for $\dot{\alpha}$

⇒ **HFS: important for detection (tagging) of isomer excitation**

Excitation Energy Measurement



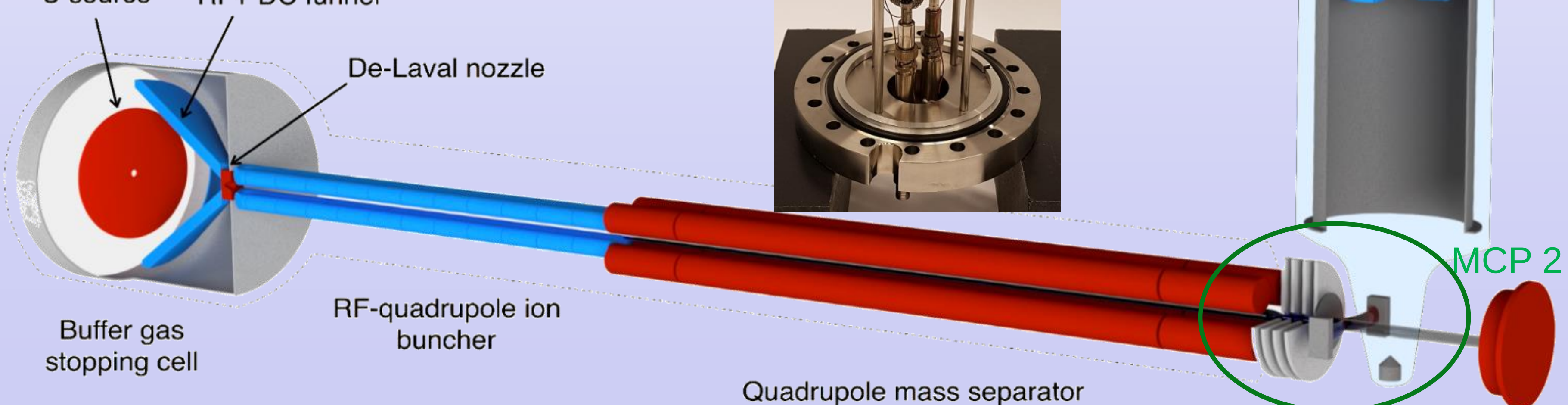
neutralization of $^{229m}Th^{q+}$ in graphene foil:

→ contact-free IC decay

→ measure E_{kin} (e)

→ spectrometer resolution: 30 -50 meV

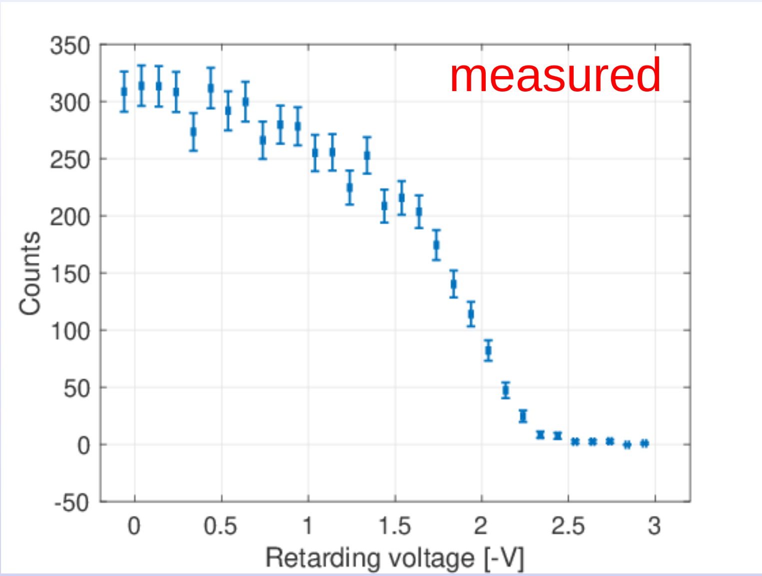
Magnetic bottle spectrometer

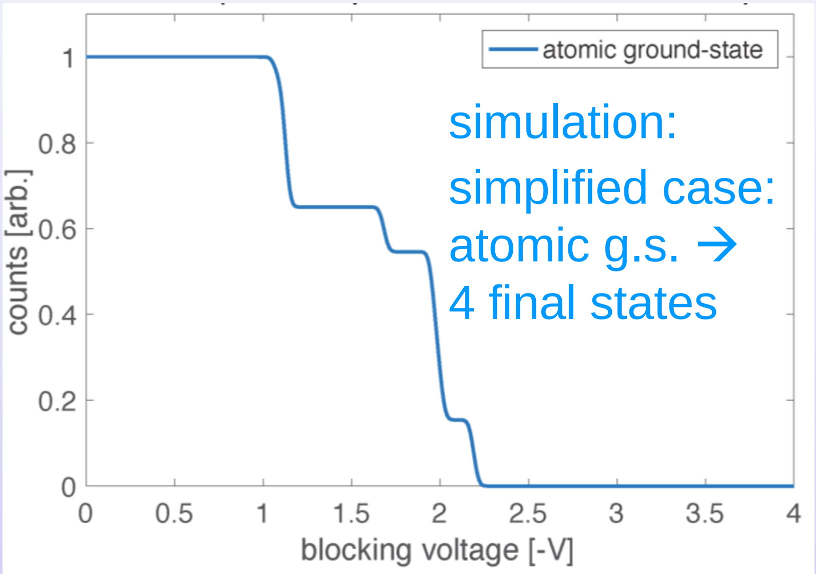


Excitation Energy: Analysis

- **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)

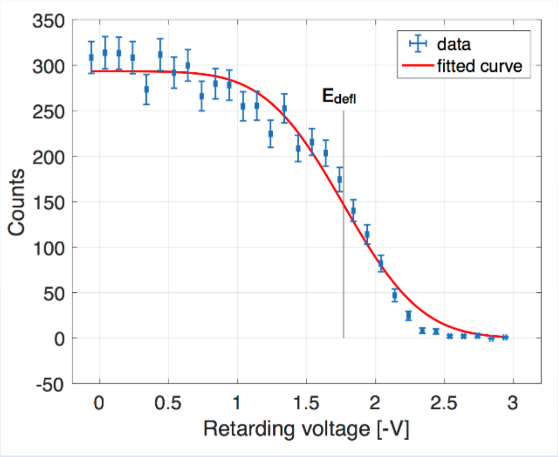
Excitation Energy: Analysis

- **fit error function to measured data:** $f(u) = a\,(1 - \mathrm{erf}\,[\,(U - E_{defl}) / b\,])$

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

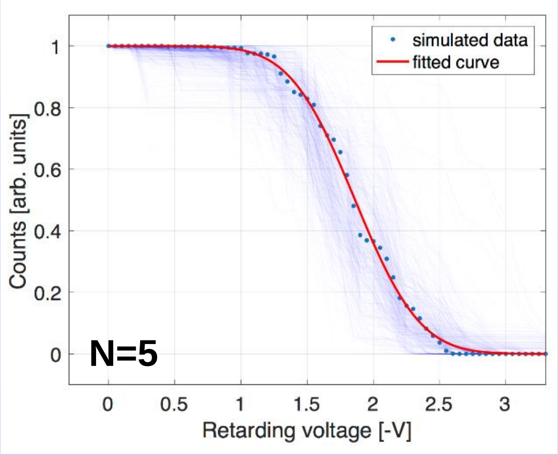
→ $E^*(iso) = E_{defl} + E_0$

→ predict E_0 from simulated spectra

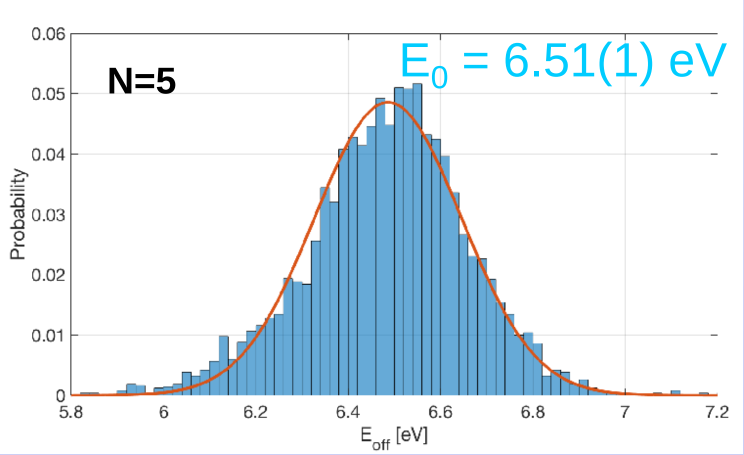


→ create simulated data from combinations of (N=5) initial atomic states:

Expected IC electron energy spectra



20000 population distributions: any 5 (of 82) E_i to all possible final E_f



Excitation Energy: Analysis

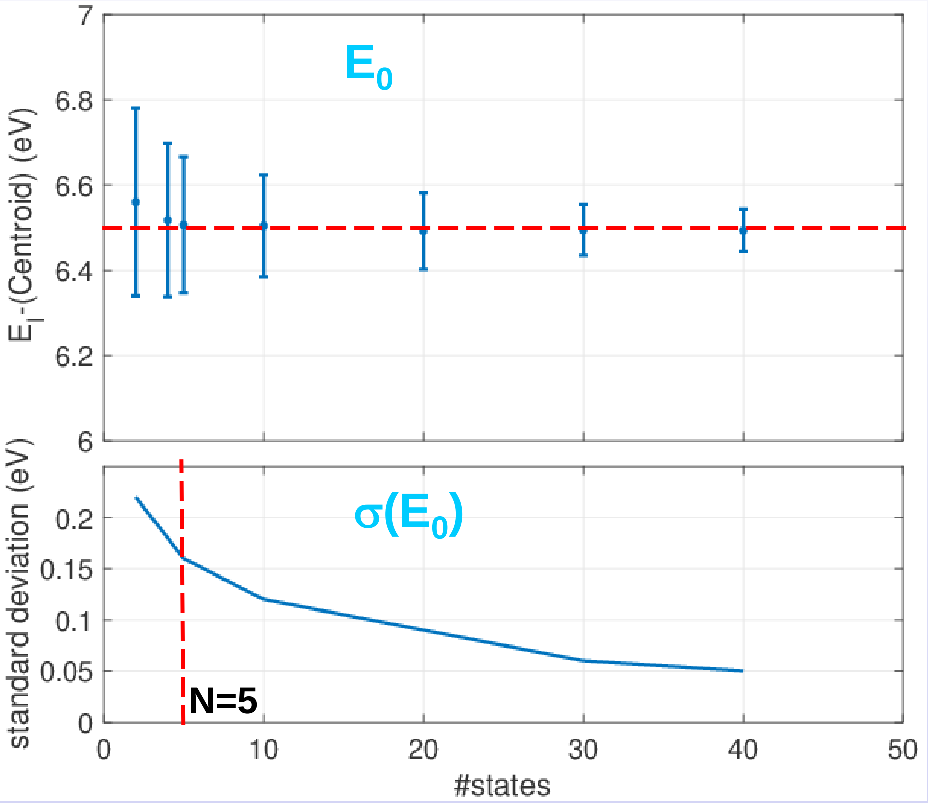
- **Findings from simulated spectra:**

robust position of E_0 → $E_0 = 6.51(1)$ eV

larger N : smaller uncertainty of E_0

→ N=5: conservative estimate of experimental uncertainty

→ **$E_0 = 6.51 \pm 0.16$ eV**



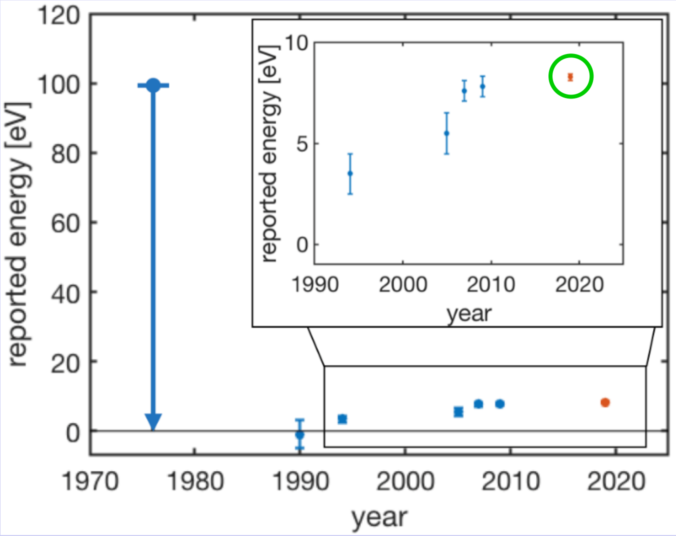
- **First direct measurement:**

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

B. Seiferle, PT et al., Nature 575 (2019)

Achievements in "Search & Characterization Phase"

- Existence of ^{229m}Th: first direct detection via IC decay — Nature 533 (2016)
- Half-life of neutral ^{229m}Th: $t_{1/2}$ = 7 μs → $\alpha_{IC} \sim 10^9$ — PRL 118 (2017)
- Hyperfine structure of ^{229m}Th
  → via collinear laser spectroscopy — Nature 556 (2018)
  → nuclear moments, charge radius
- isomeric excitation energy: — method: EPJ A53 (2017)
  → via retarding field magnetic bottle electron spectrometer
  first direct measurement: Nature 575 (2019)



E* = 8.28 ± 0.17 eV

λ = 149.7 ± 3.1 nm

→ clarifies regime of laser technology for optical control (excludes laser crystal approaches)

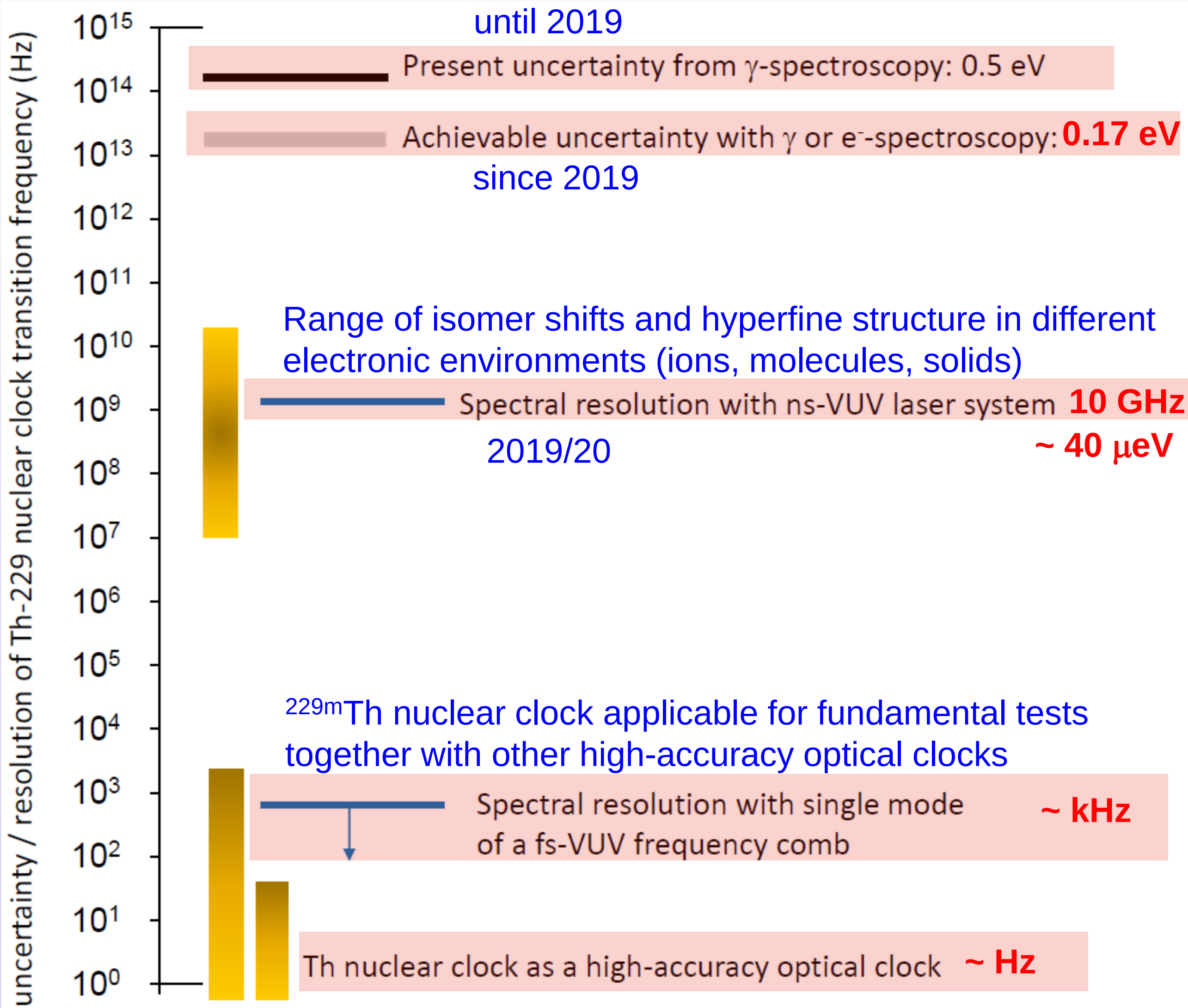
The long way towards the Nuclear Clock

- still to bridge: 14 orders of magnitude:

already feasible with existing laser technology {

concept:

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



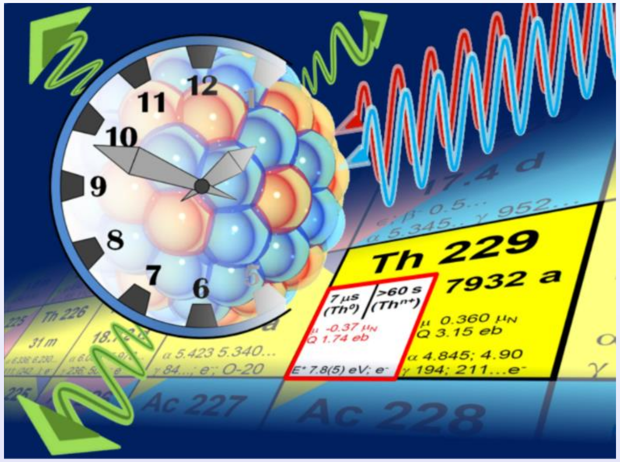
Summary

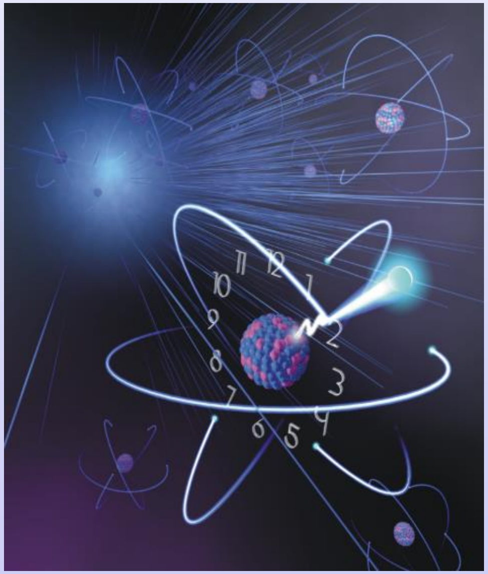
look back: huge progress in last 4 years:

- 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 …

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:
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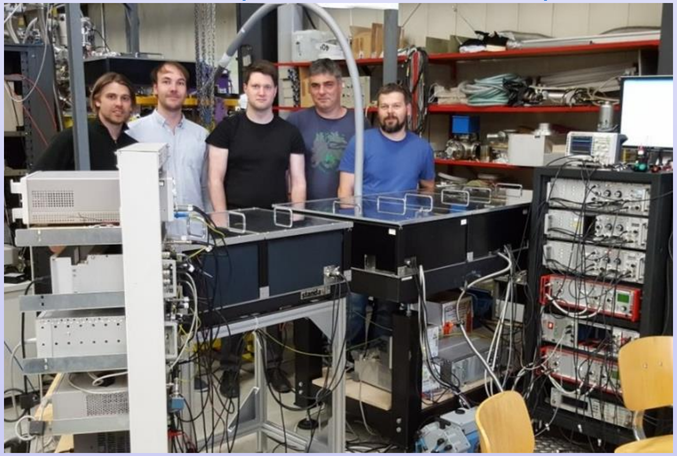
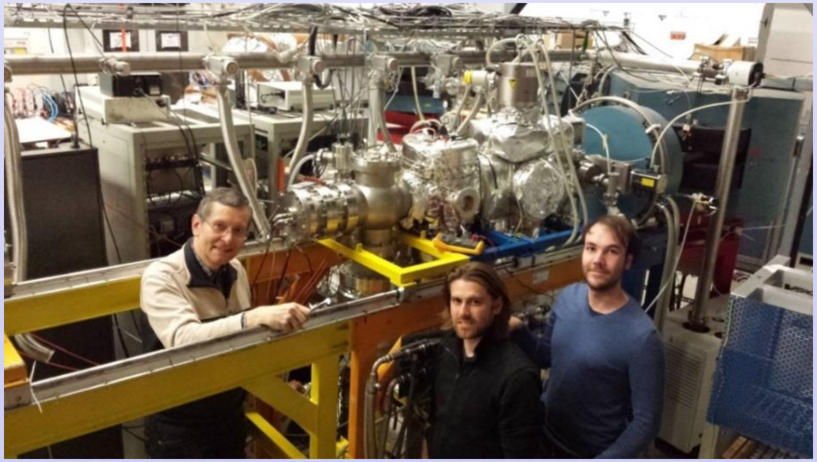
MPI-HD: A. Pàlffy, P. Bilous, N. Minkov, J. Crespo
NIST: S. Nam, G. O'Neill
UCLA: E. Hudson, C. Schneider, J. Jeet





Thank you for your attention !