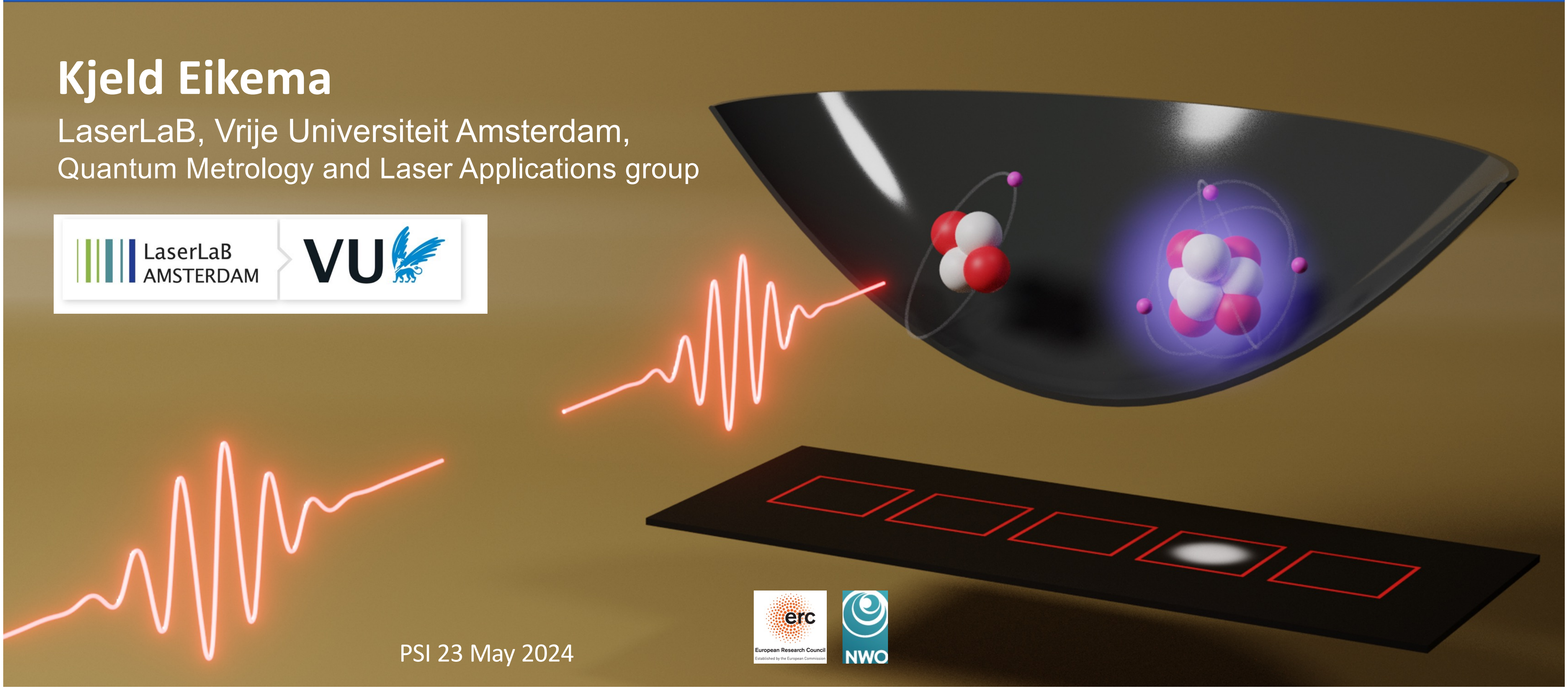
’Extreme’ spectroscopy on helium and helium ions

Kjeld Eikema
LaserLaB, Vrije Universiteit Amsterdam,
Quantum Metrology and Laser Applications group



PSI 23 May 2024

Outline

○ Introduction - precision measurements for fundamental tests

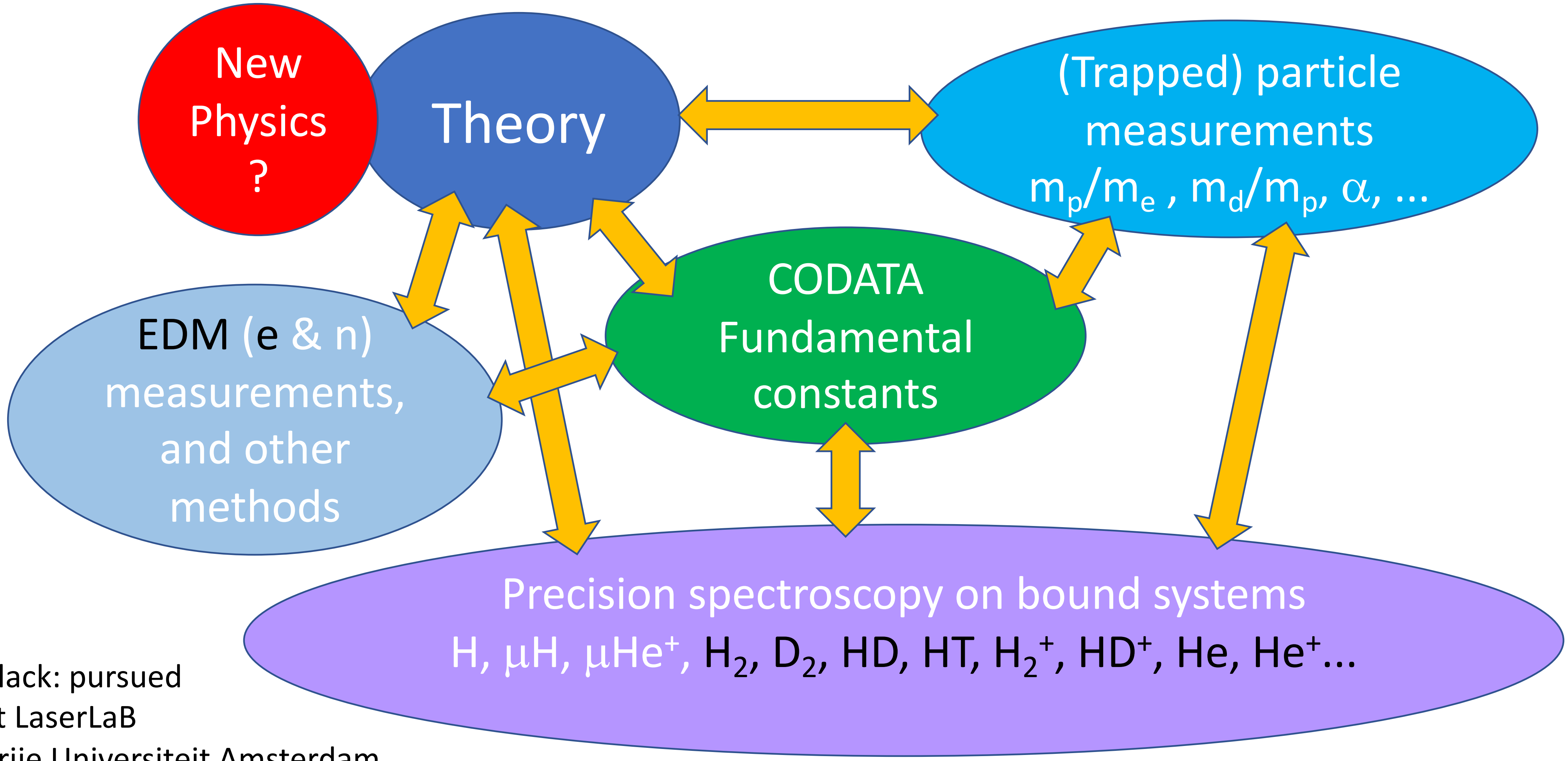
○ Isotope shift measurement in ultra-cold ^{3}He and ^{4}He: nuclear size difference
- quantum differences: cooling, trapping and spectroscopy of ^{3}He and ^{4}He
- results and consequence for charge radius^2 difference
- developments: new ^{4}He measurements in progress

○ He$^+$ 1S-2S precision measurement project: charge radius, Ry constant & QED
- First excitation of the He$^+$ 1S-2S transition in the extreme ultraviolet @ 30 nm
- Challenges and solutions to reach 1 kHz (10^{-13} on the transition)

○ Summary and outlook

Precision measurement for searching new physics

LaserLaB Amsterdam



New Physics ?

Theory

(Trapped) particle measurements m_p/m_e , m_d/m_p, α, ...

CODATA Fundamental constants

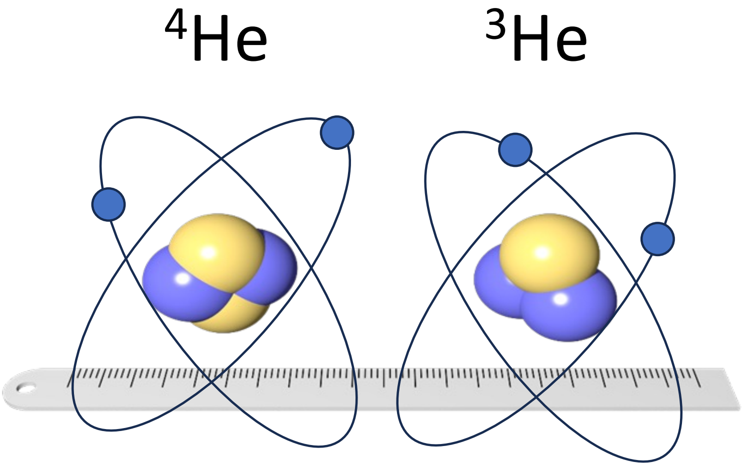
EDM (e & n) measurements, and other methods

Precision spectroscopy on bound systems
H, μH, μHe^+, H_2, D_2, HD, HT, H_2^+, HD^+, He, He^+...

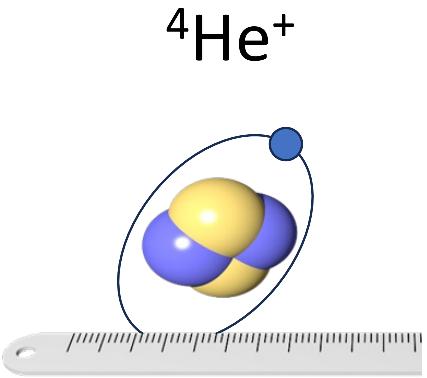
Black: pursued
at LaserLaB
Vrije Universiteit Amsterdam

Spectroscopy targets: He and He^+

Goal: nuclear **charge radius² difference** between ^3He and ^4He

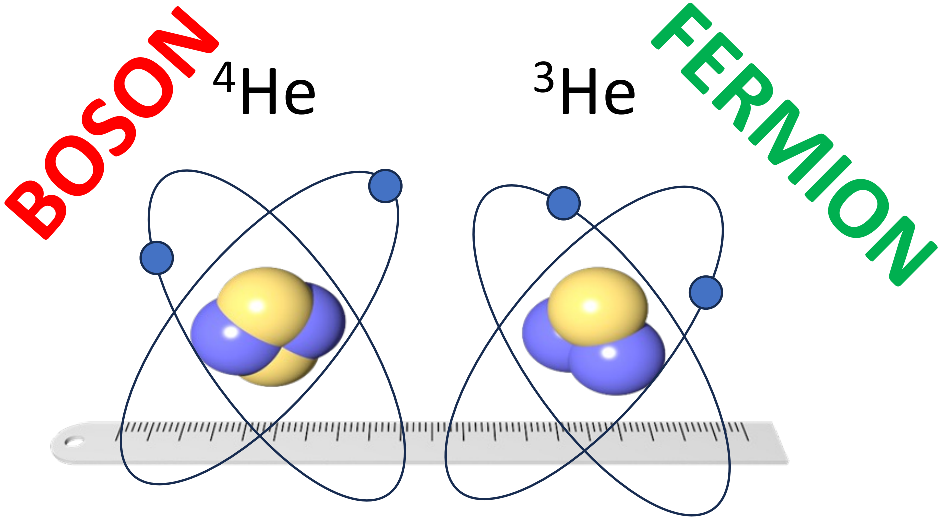


Goal: absolute nuclear charge radius² of $^4He^+$, test of **QED & Rydberg constant**



Spectroscopy targets: He and He$^+$

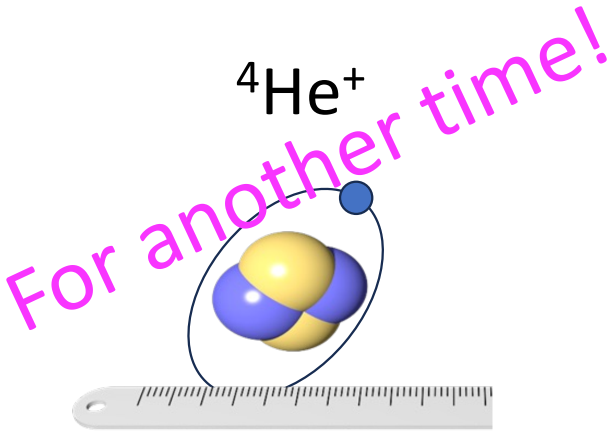
Goal: nuclear **charge radius² difference** between ^{3}He and ^{4}He



Isotope measurement on the **doubly-forbidden 2 ^{3}S – 2 ^{1}S transition** at 1557 nm, **acc. <200 Hz (10^{-12})**

Required: ultra-cold ^{3}He and ^{4}He
& trapping in magic wavelength trap

Goal: absolute nuclear charge radius² of ^{4}He$^+$, test of **QED & Rydberg constant**



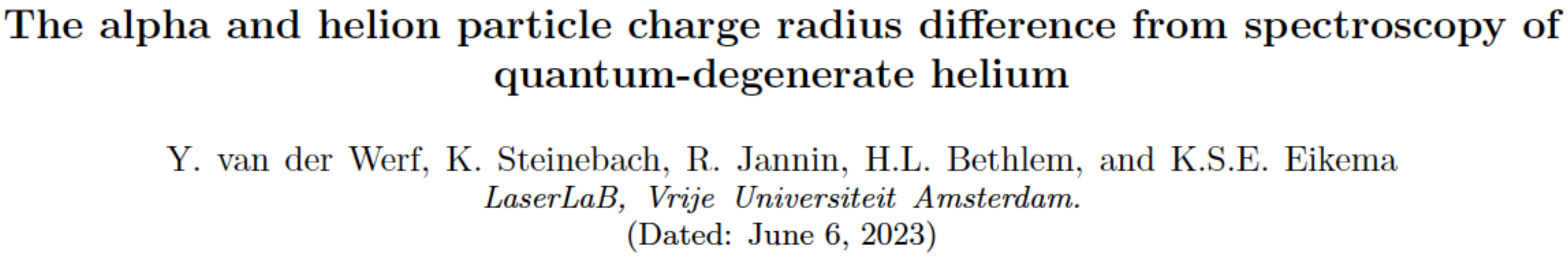
Two-photon transition involving 30 nm on 1S-2S transition, acc. target < 1 kHz (10^{-13})

Required: single trapped & cooled He$^+$,
enough power at 30 nm, and a whole lot more!

Alpha and helion charge radius^2 measurements

LaserLaB Amsterdam

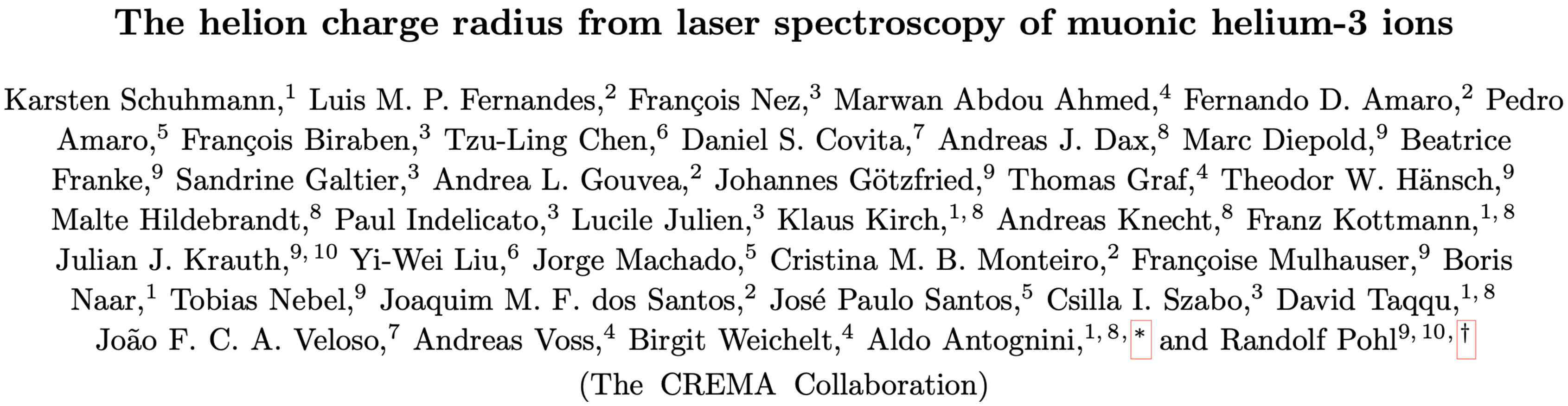
arXiv: 2305.02333v1



The alpha and helion particle charge radius difference from spectroscopy of quantum-degenerate helium

Y. van der Werf, K. Steinebach, R. Jannin, H.L. Bethlem, and K.S.E. Eikema
LaserLaB, Vrije Universiteit Amsterdam.
(Dated: June 6, 2023)

arXiv: 2305.11679v2



The helion charge radius from laser spectroscopy of muonic helium-3 ions

Karsten Schuhmann,[1] Luis M. P. Fernandes,[2] François Nez,[3] Marwan Abdou Ahmed,[4] Fernando D. Amaro,[2] Pedro Amaro,[5] François Biraben,[3] Tzu-Ling Chen,[6] Daniel S. Covita,[7] Andreas J. Dax,[8] Marc Diepold,[9] Beatrice Franke,[9] Sandrine Galtier,[3] Andrea L. Gouvea,[2] Johannes Götzfried,[9] Thomas Graf,[4] Theodor W. Hänsch,[9] Malte Hildebrandt,[8] Paul Indelicato,[3] Lucile Julien,[3] Klaus Kirch,[1,8] Andreas Knecht,[8] Franz Kottmann,[1,8] Julian J. Krauth,[9,10] Yi-Wei Liu,[6] Jorge Machado,[5] Cristina M. B. Monteiro,[2] Françoise Mulhauser,[9] Boris Naar,[1] Tobias Nebel,[9] Joaquim M. F. dos Santos,[2] José Paulo Santos,[5] Csilla I. Szabo,[3] David Taqqu,[1,8] João F. C. A. Veloso,[7] Andreas Voss,[4] Birgit Weichelt,[4] Aldo Antognini,[1,8,*] and Randolf Pohl[9,10,†]
(The CREMA Collaboration)

Introduction He*

Metastable helium (He*)

2^3S_1 state

Accessible narrow transition

Precision spectroscopy

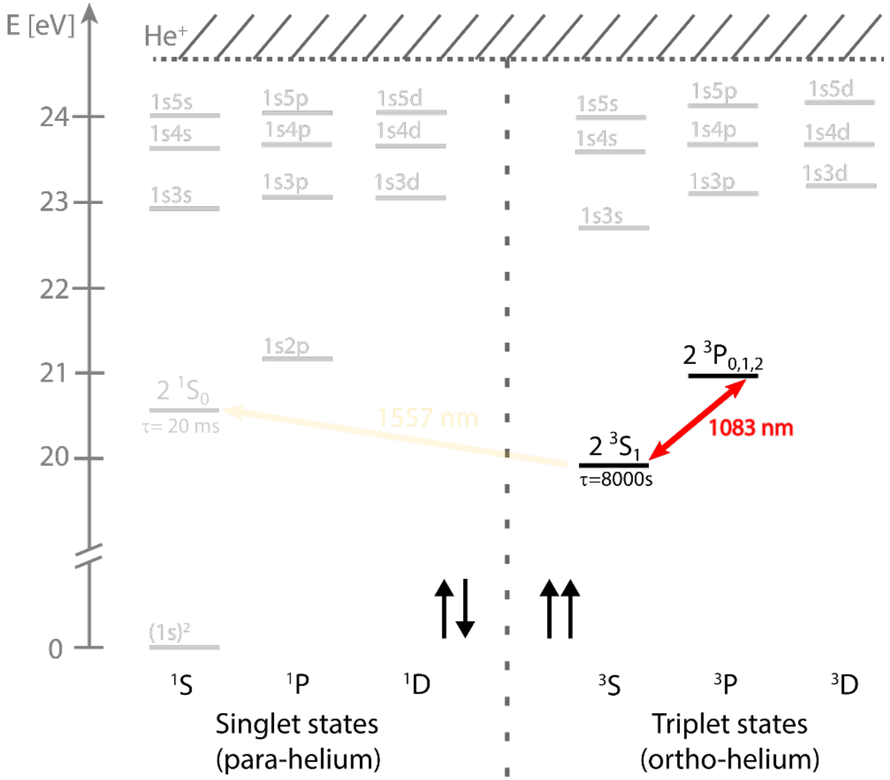
Laser cooling & trapping

High experimental control

ab initio calculations

Fundamental physics tests

Metastable helium (He*)



Metastable 2^3S_1 state:

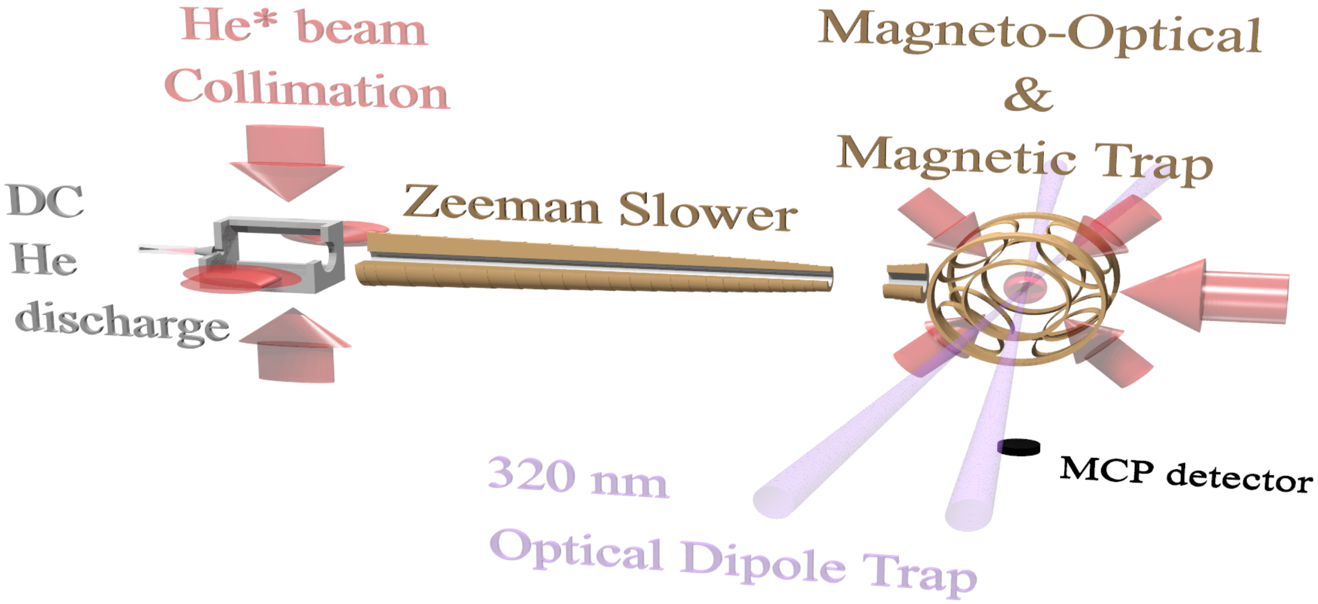
Accessible narrow transition:

Laser cooling

***ab initio* calculations**

- Two-electron correlations
- Measure ^{4}He – ^{3}He isotope shift
- Fundamental constants:
  (differential) nuclear charge radius^2
- *^{4}He measured,* 10^{-12} *level* *[Nat Phys 14, 2018]*

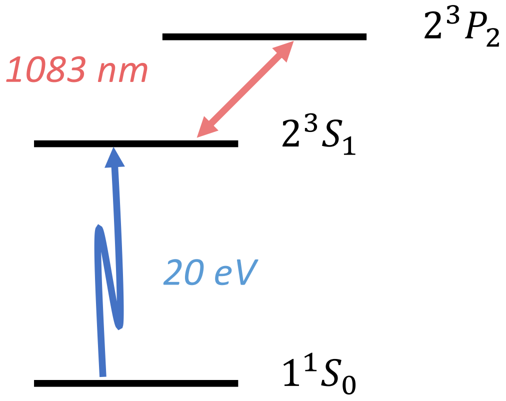
Making quantum degenerate He*

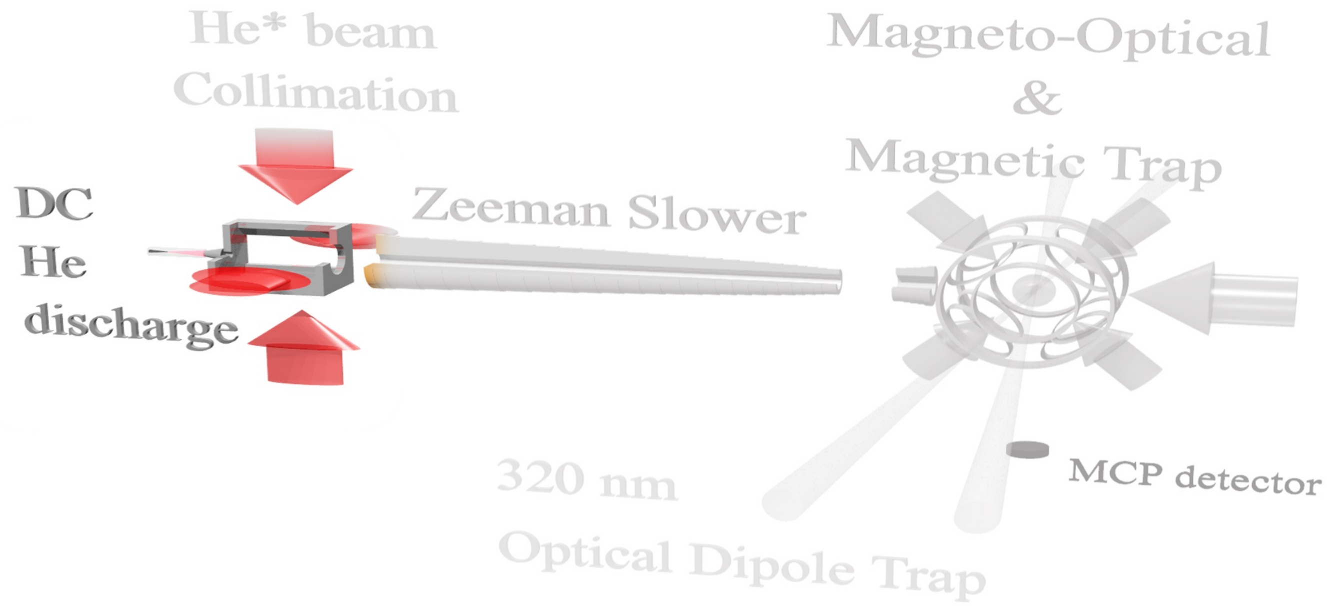


Making quantum degenerate He*

Populating the 2^3S_1 state

- DC discharge source
- Liquid nitrogen cooling
- ^{3}He recycling

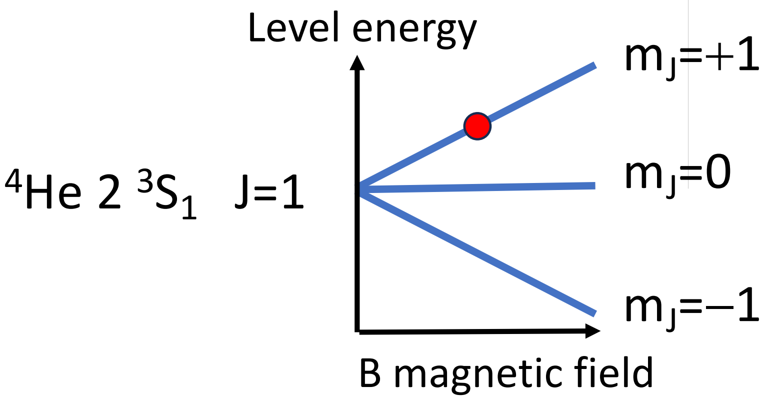


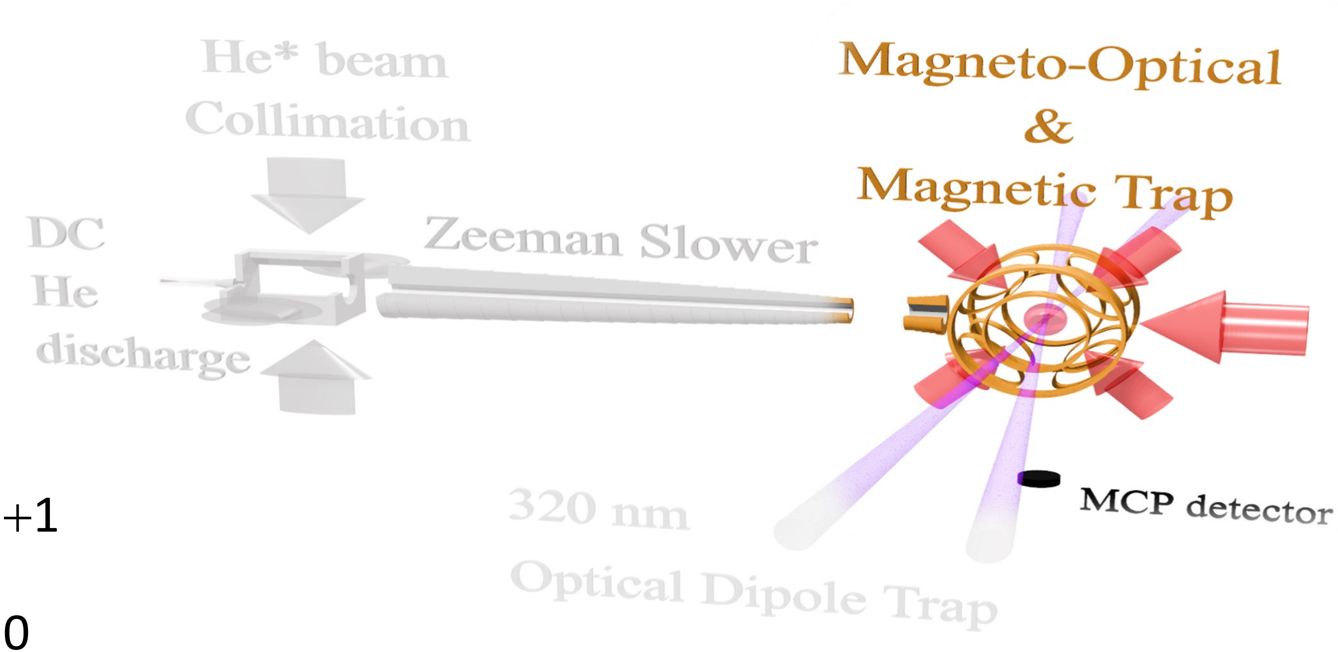


Initial trapping of He* and cooling to degeneracy

Laser cooling

- 1083 nm laser red detuned
- Zeeman slower: detuning from velocity change compensated with tapered magnetic field
- Magneto-optical trap: 0.5 mK
- Magnetic trapping
- Suppression Penning ionization by spin polarization: max m_J





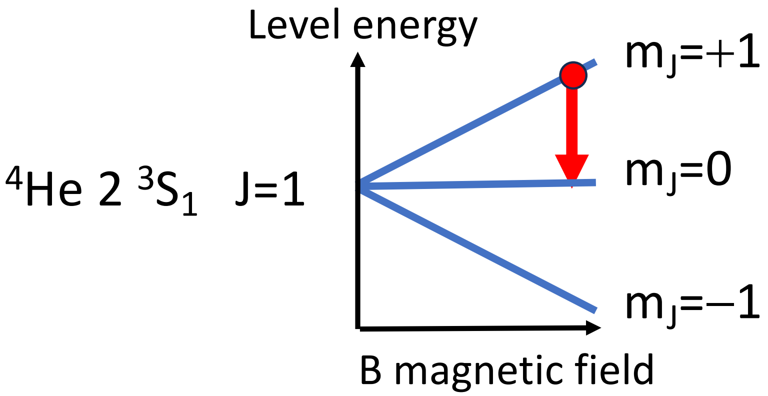
Penning ionization:

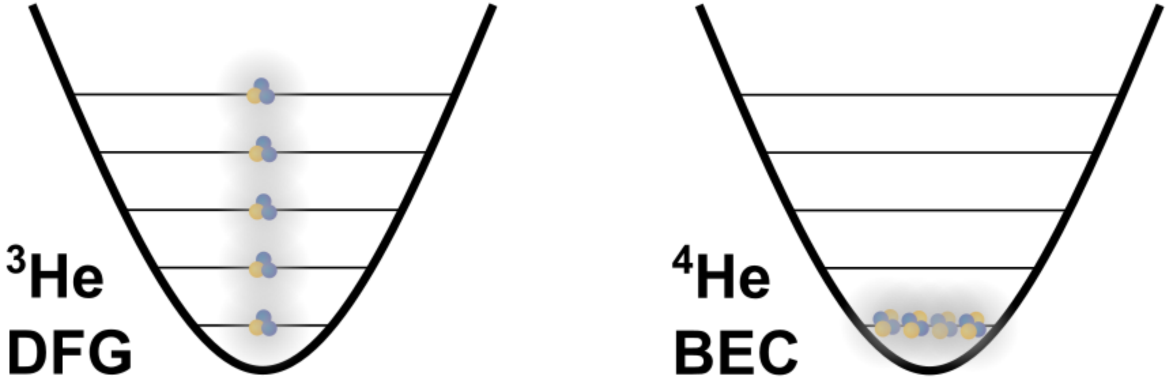
He* + He* → He + He^+ + e^-

Fermions and Bosons: very different!

Evaporative cooling to quantum degeneracy

- ^{4}He collides, re-thermalizes and forms a Bose condensate
- ^{3}He does not collide at μK temperatures; only S-wave collisions, which is forbidden for fermions. Solution mix ^{3}He and ^{4}He!



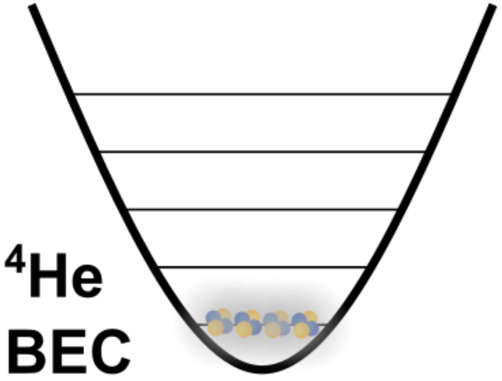


^{3}He and ^{4}He in a trapping potential

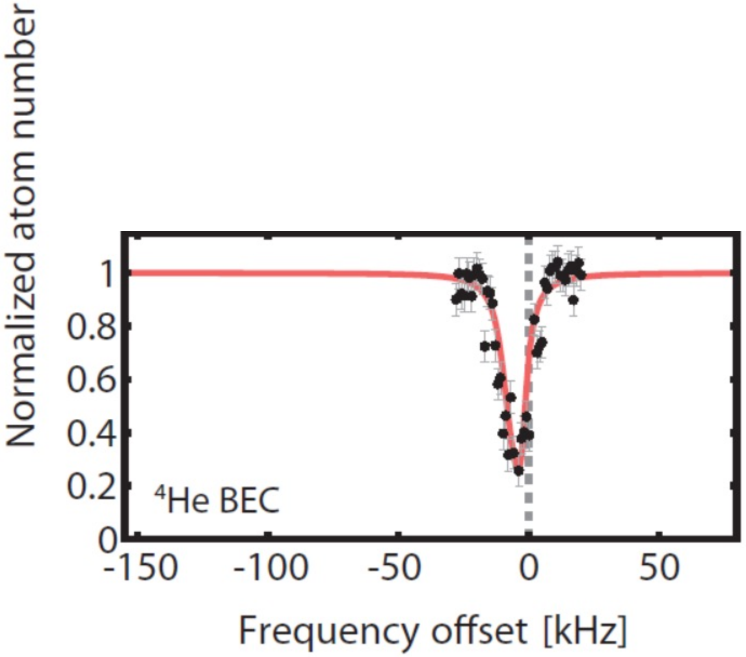
Spectroscopy also very different!

- Trapped bosonic ^{4}He: all atoms in ground state
  No Doppler, but 'mean field' shift & broadening

Spectroscopy 2 ^{1}S - 2 ^{3}S @ 1557 nm

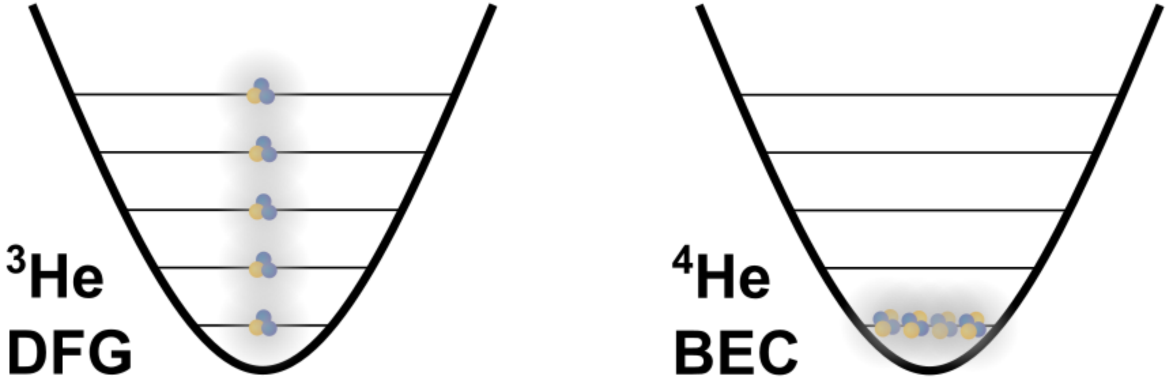


^{4}He in a trapping potential



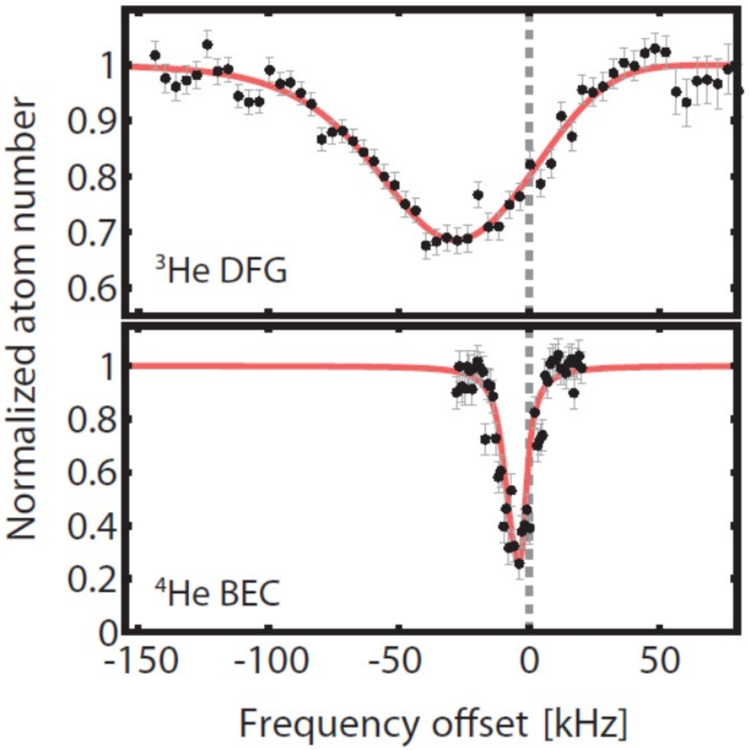
Fermions and Bosons: very different!

- Trapped bosonic ^{4}He: all atoms in ground state
  No Doppler, but 'mean field' shift & broadening
- Trapped fermionic ^{3}He: Fermi-Dirac distribution
  - Many motional states in the trap occupied
  - Doppler broadening ($T_F \sim 1\ \mu K$)



^{3}He and ^{4}He in a trapping potential

Spectroscopy 2 ^{1}S - 2 ^{3}S @ 1557 nm



Trapping in a focused laser beam: "ODT"

Cancel magnetic field influence:
switch between opposite m states

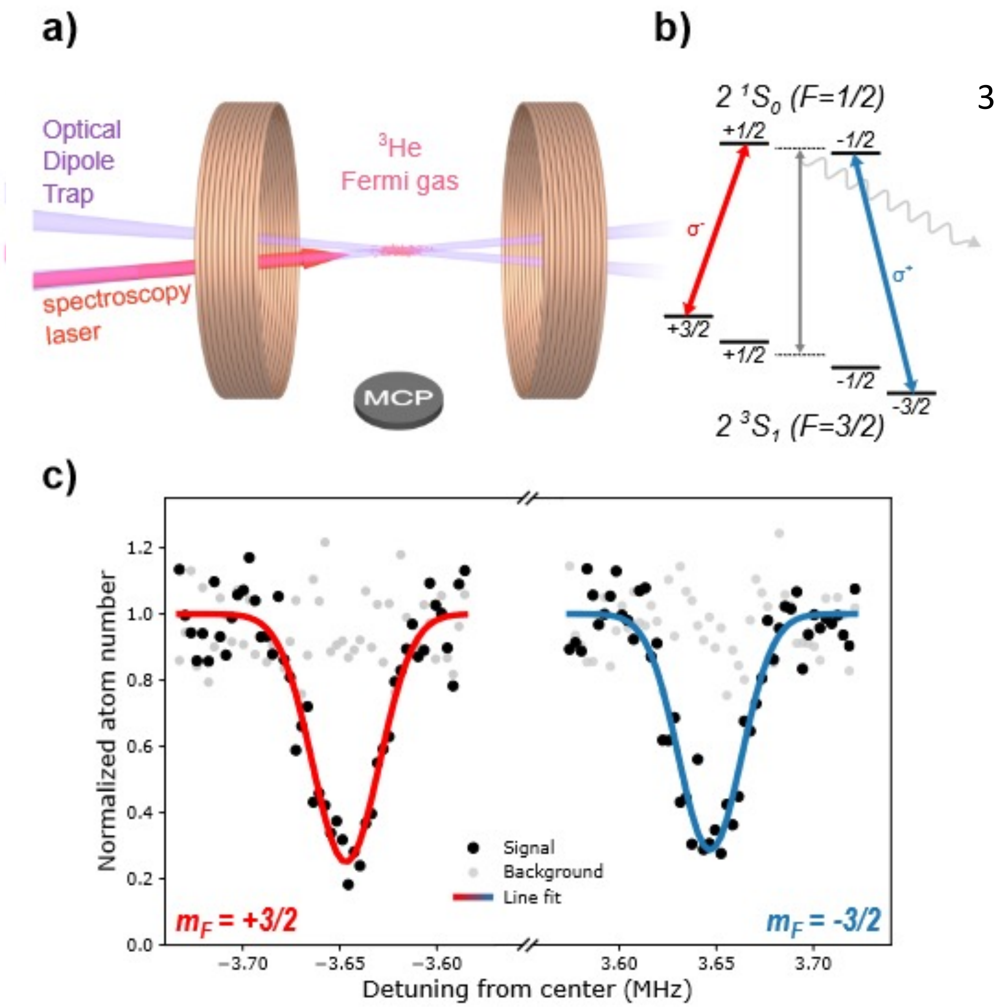
Required: magnetic state independent trapping

Solution: "optical dipole trap"
Based on a focused laser beam

320 nm 'magic wavelength'

- Same trap for 2^3S_1 and 2^1S_0
- No AC Stark shift on transition

- Homebuilt 1 W cw UV laser
  [Appl. Phys. B (2016) 122:122]

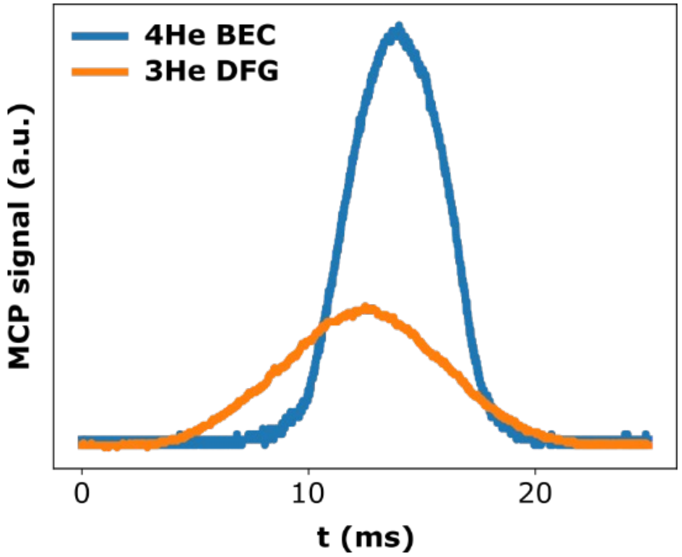


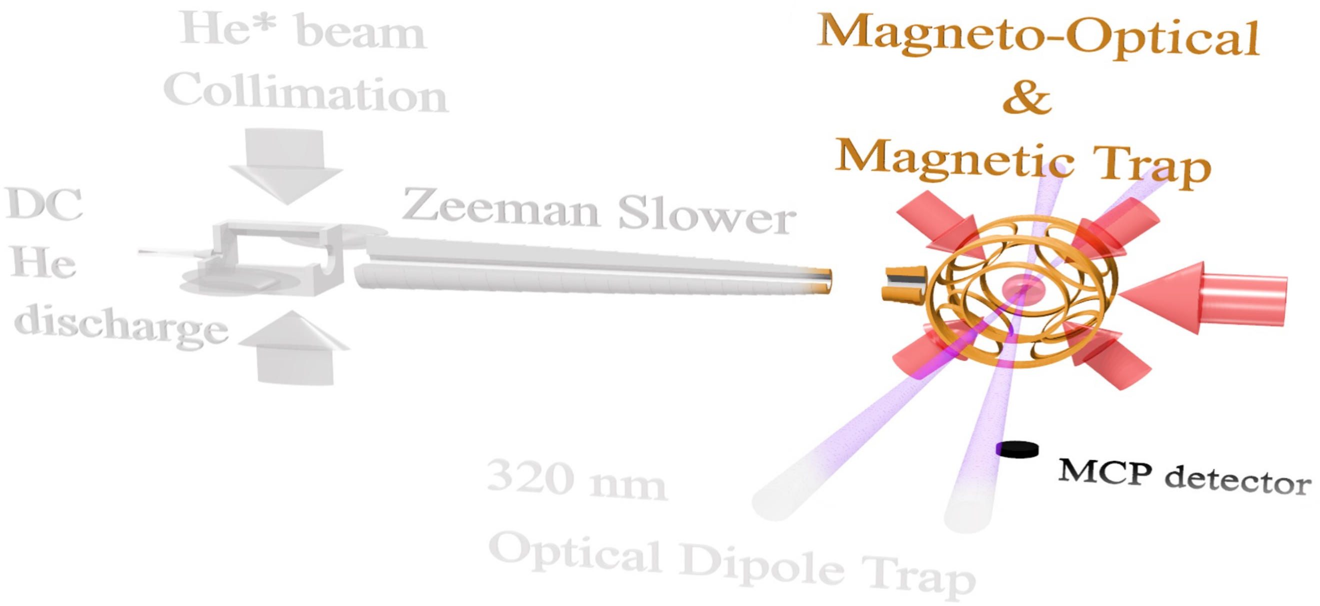
^{3}He

Detection

Atom detection (loss of atoms)

- Microchannel plate
- 20 eV internal energy
- Time-of-flight fitting: N, μ, T
- Spectroscopy: $N_{atom}(f_{laser})$

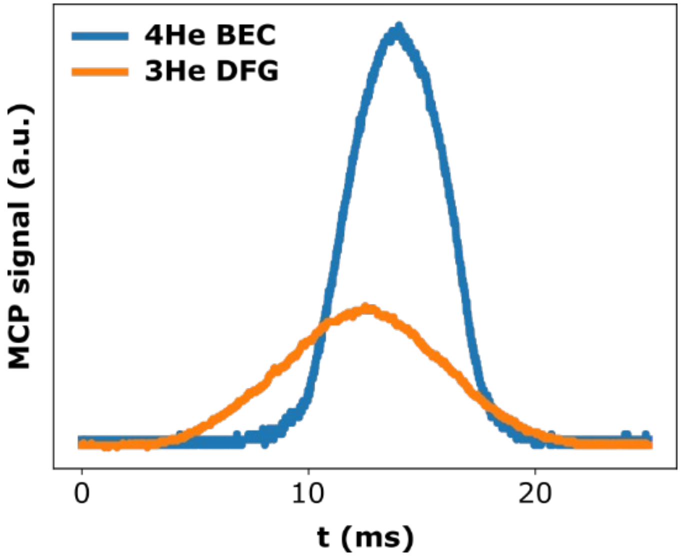




Detection and measuring spectrum (^{3}He)

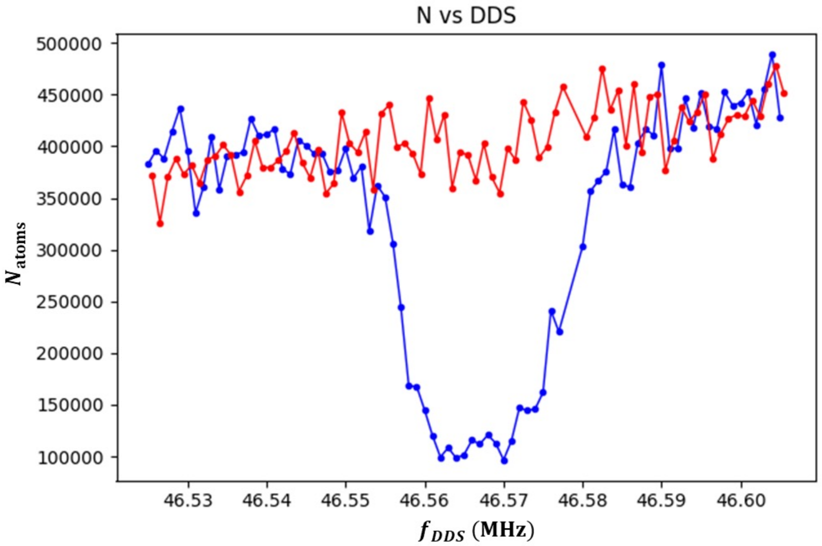
Atom detection (loss of atoms)

- Microchannel plate
- 20 eV internal energy
- Time-of-flight fitting: N, μ, T
- Spectroscopy: $N_{atom}(f_{laser})$



Measuring the 2 $^3S_1$ – 2 $^1S_0$ at 1557 nm

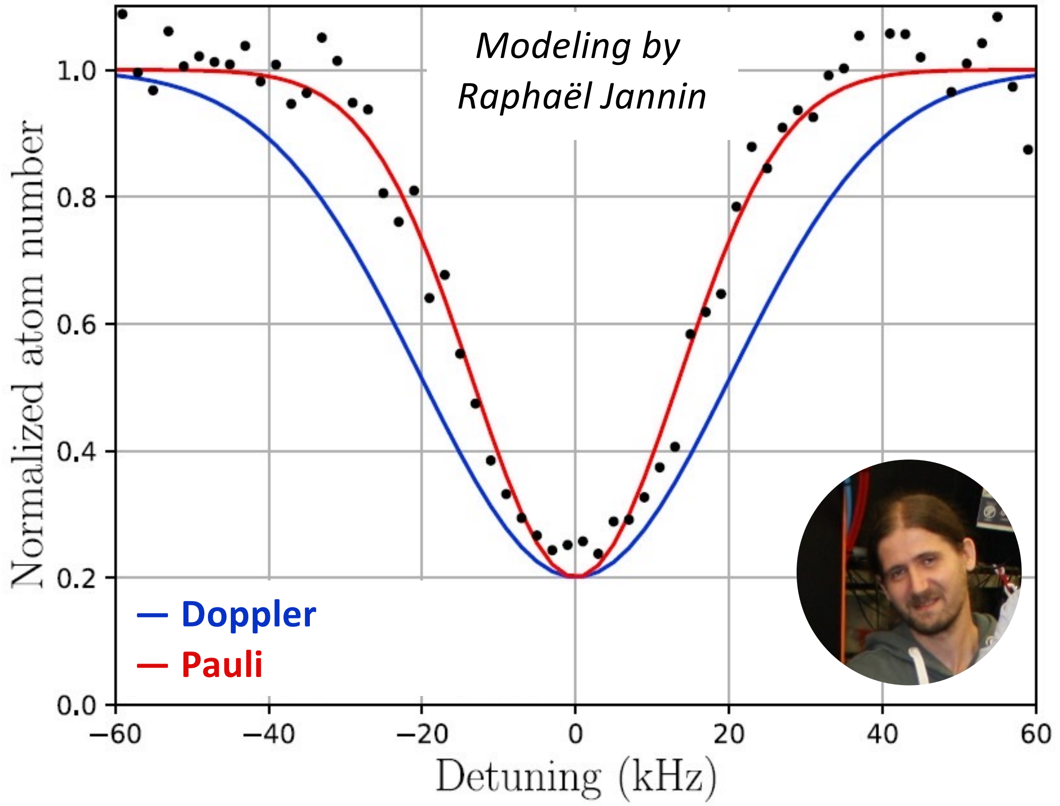
- Sample preparation
- Set laser, 3s exposure
- Alternate background shots
- Measure remaining atoms



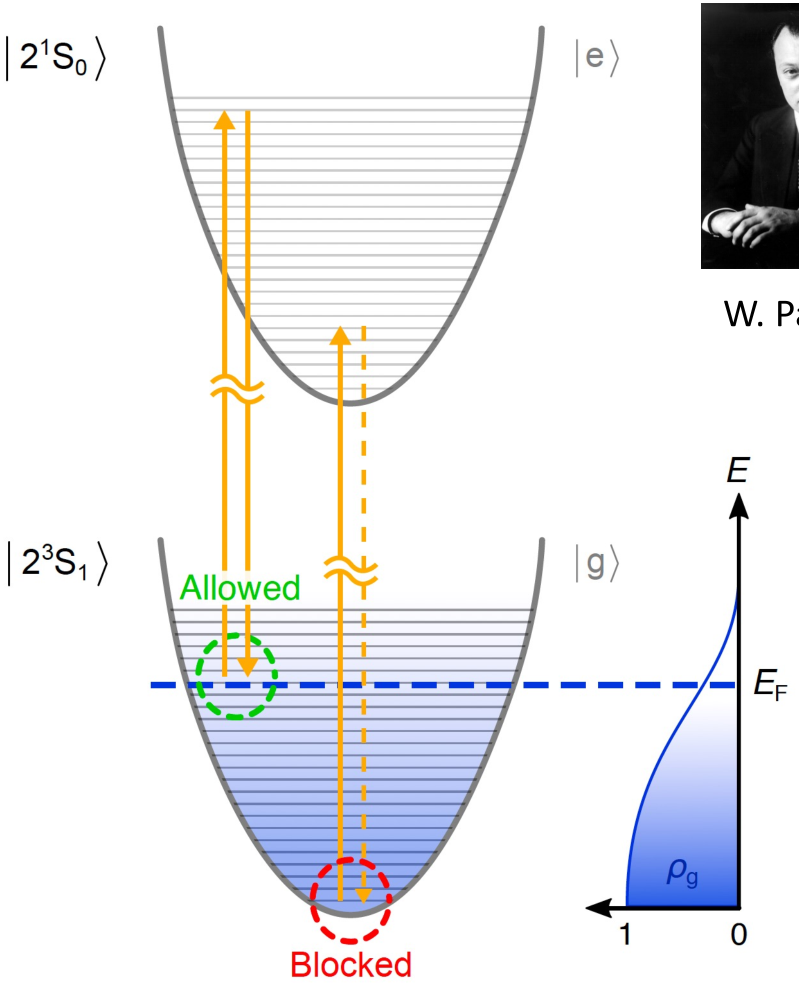
^{3}He quantum effect: Pauli blocking

Pauli-blocking of stimulated emission

R. Jannin et al., Nat. Comm. 13, 6479 (2022)

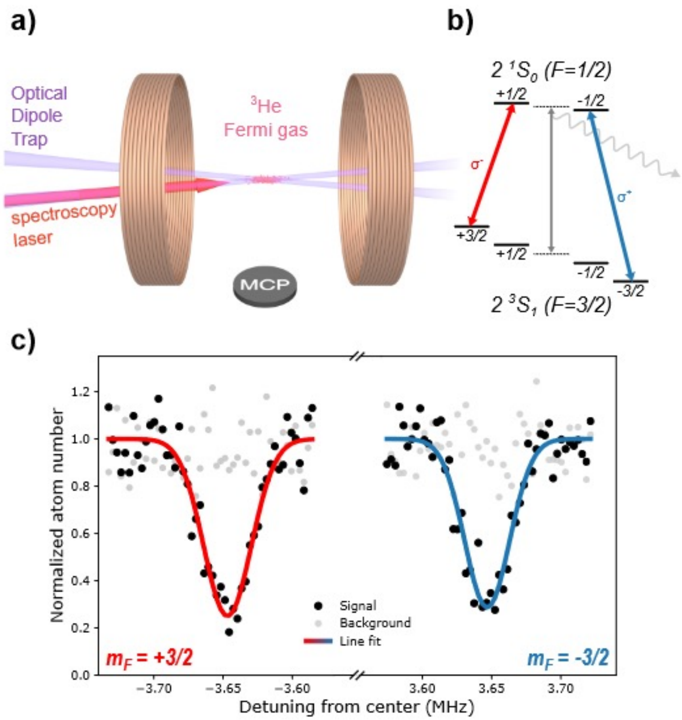


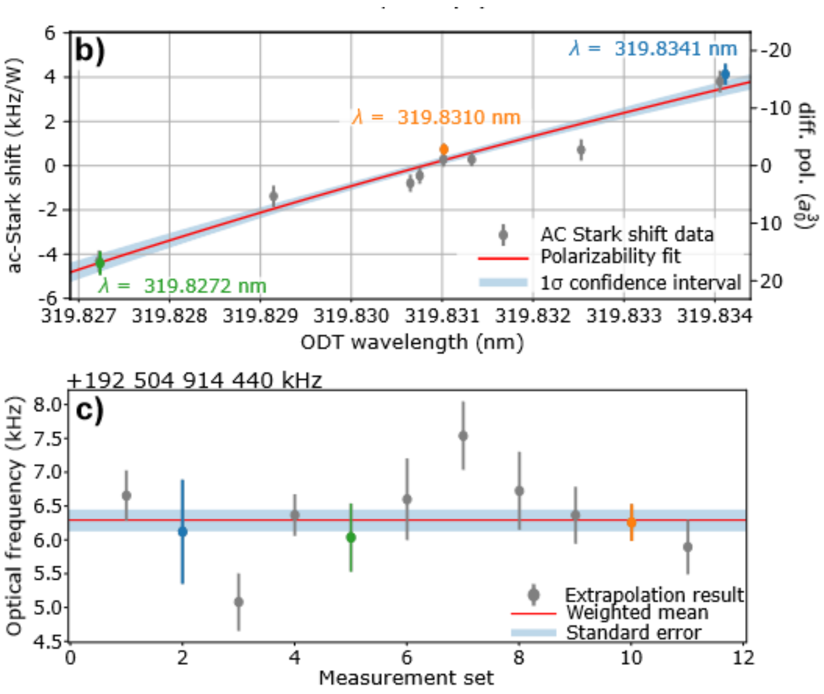
Modeling by Raphaël Jannin



W. Pauli

^{3}He spectroscopy result (under review)





^{3}He Transition Frequency: 192 504 914 418.96(17)kHz

^{3}He spectroscopy result: radius

^{3}He Transition Frequency: 192 504 914 418.96(17)kHz

Then with:

☐ previous measurement of ^{4}He in 2018

☐ theory from K. Pachucki et al., Phys. Rev. A 95, 062510 (2017)

we determine a new improved value for the charge radius^2 difference:

Our result: $r^2_h - r^2_a = 1.0757(12)_{exp}(9)_{theo}\ \mathrm{fm}^2$

Theory: $r^2_h - r^2_a = 1.084(40)\ \mathrm{fm}^2$

Agrees, but experiment 27x better, therefore compare different experiments

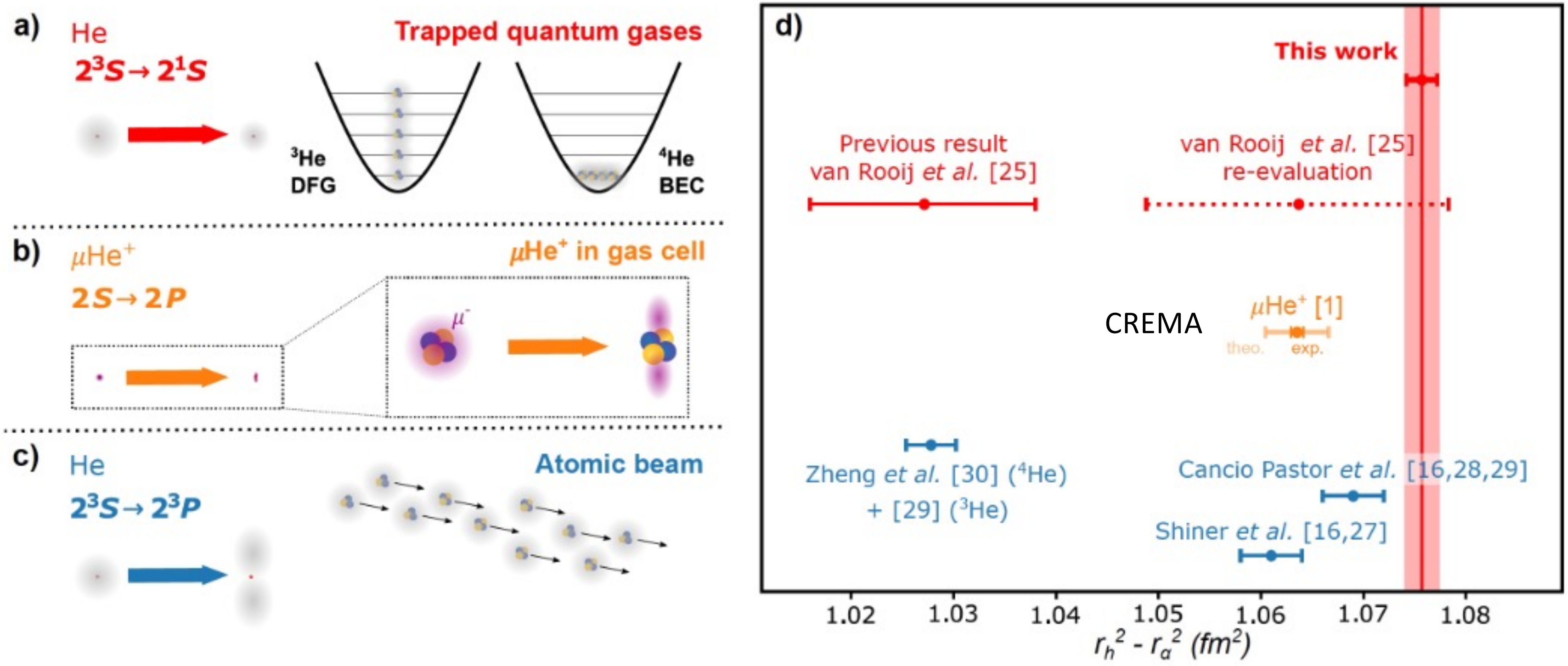
Theory value based on the values/publications below; common mode error cancellation in the difference is not considerd

$r_{\alpha,\ theory} = 1.663(11)\ \mathrm{fm}$ L.E. Marcucci et al. J. Phys. G43, 023002 (2016)

$r_{h,\ theory} = 1.962(4)\ \mathrm{fm}$ M. Piarulli et al., Phys. Rev. C 87, 014006 (2013)
& L.E. Marcucci et al. J. Phys. G43, 023002 (2016)

Helion-alpha particle charge radius^2 difference

LaserLaB Amsterdam



Our He* result on arXiv: 2305.02333v1

CREMA μHe⁺ result on arXiv: 2305.11679v2

⇒ **3.6 σ difference**

New ^{4}He measurements started: improvements

Recent improvements for ^{4}He new measurement:

1. Reduced linewidth

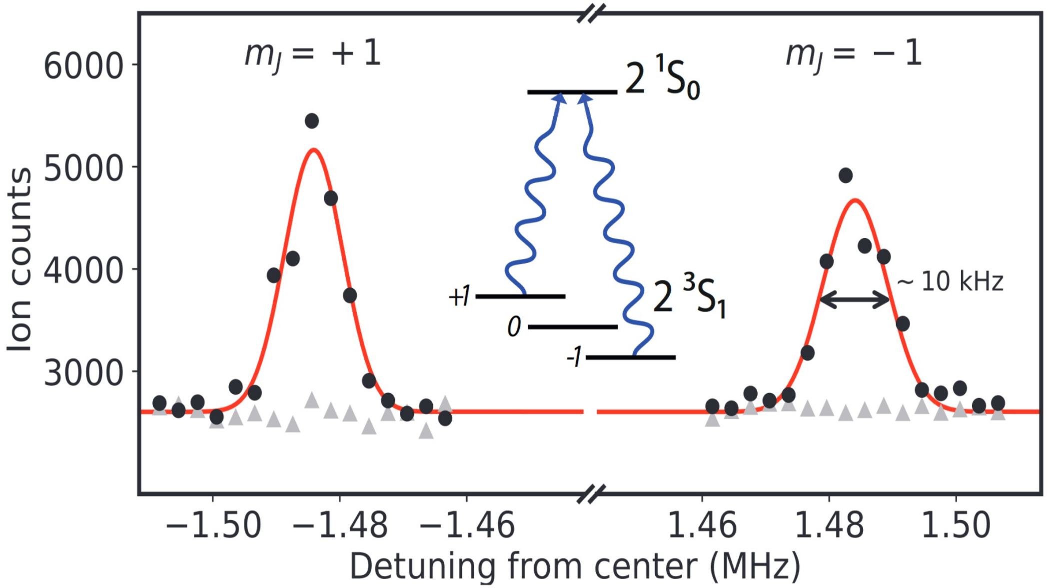
-> Increased stability of the ODT, removed AC-magnetic field sources

2. Speed up measurement

-> Reduced measure time by factor 5

3. Stabilization of magnetic field

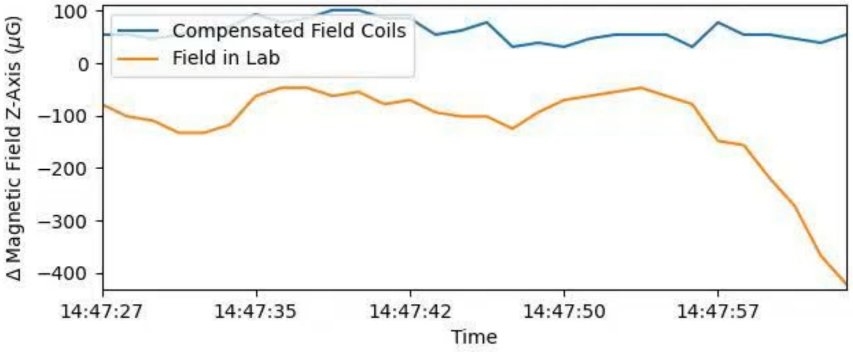
-> Observed random jumps magnetic field of 2-3mG; now stabilized to 100 μG



Magnetic field jumps...

Camera Feed

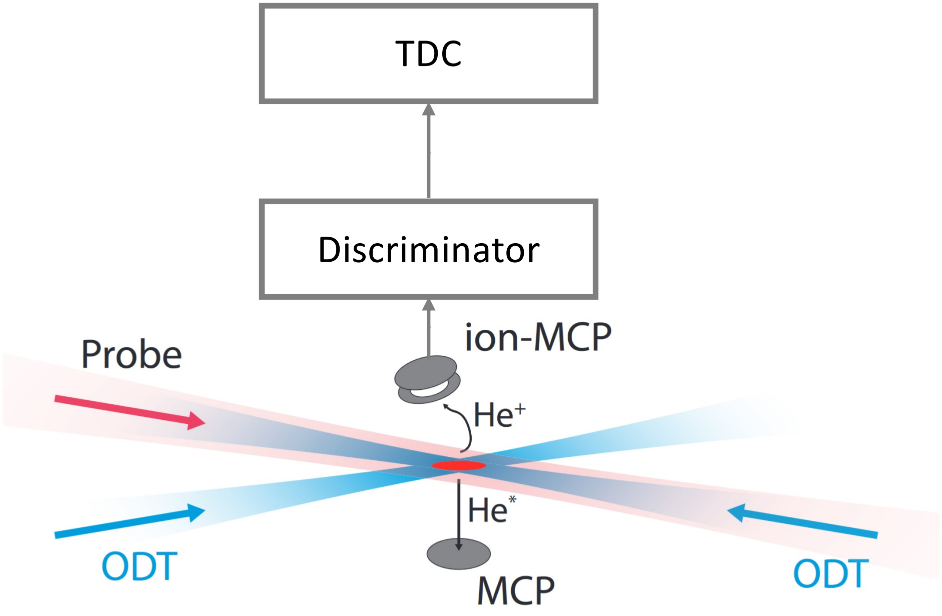
Magnetic Field He* Lab



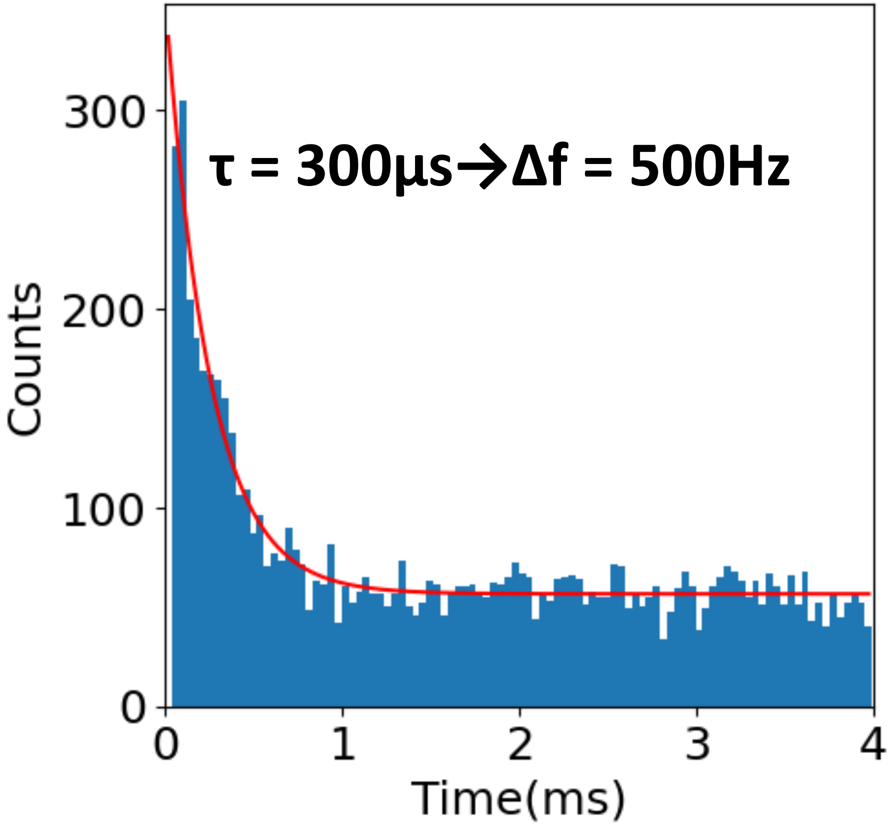
^{4}He ion signal + TDC = much more information

Measurement via ion production

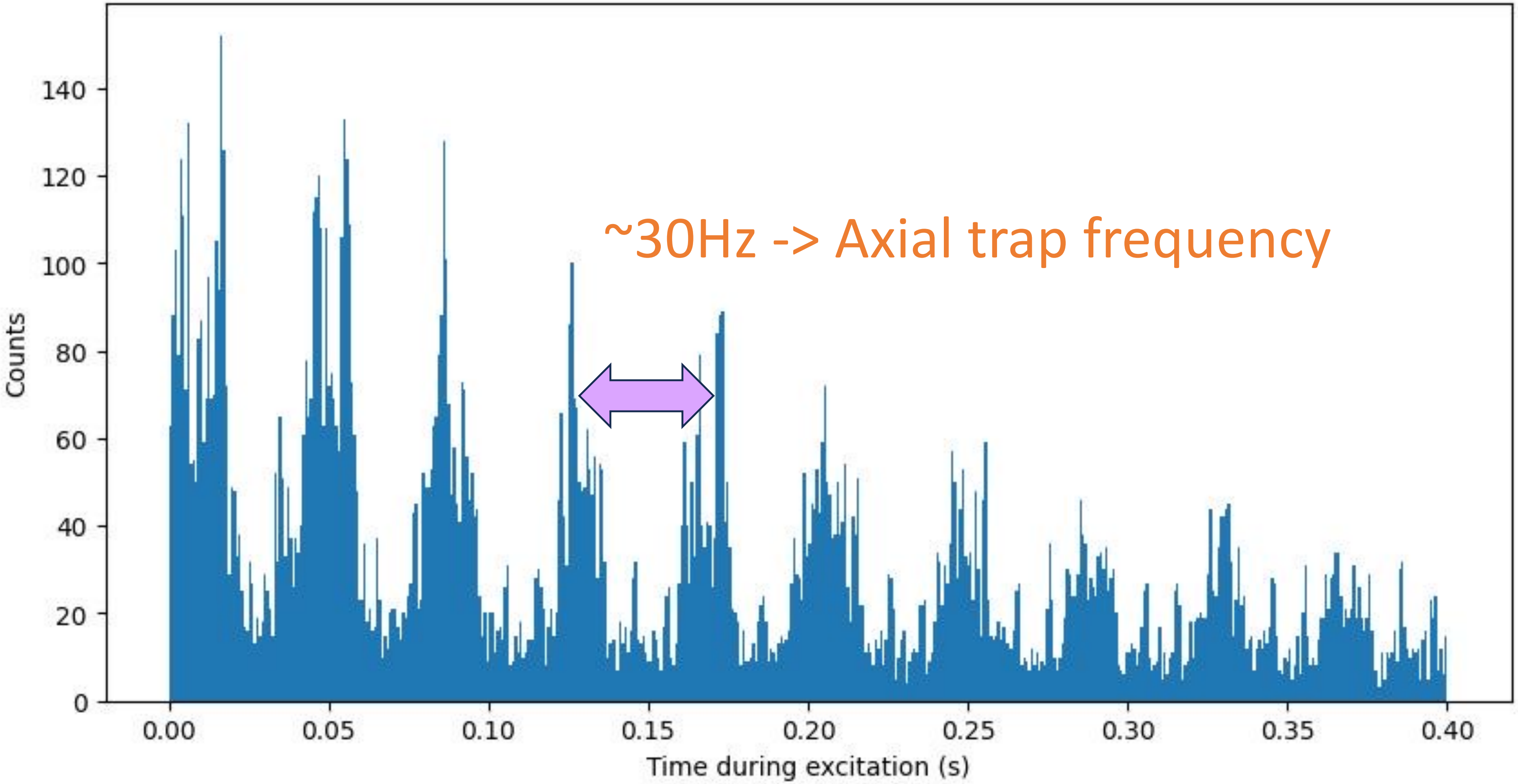
$He^*(2\,^3S_1) + He^*(2\,^1S_0) \rightarrow He\,(1\,^1S_0) + \mathbf{He^+} + e^-$



Lifetime 2 $^1S_0$

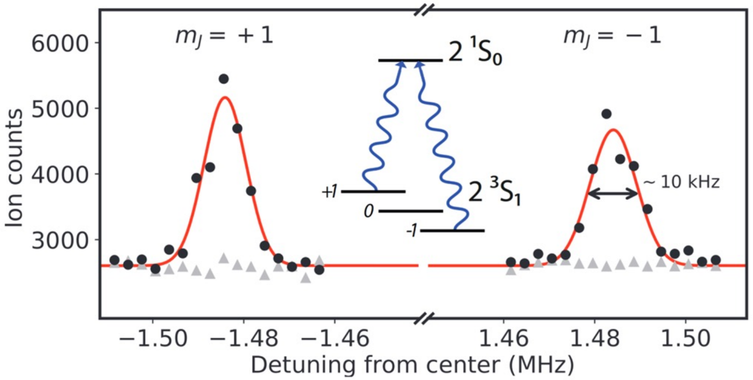


BEC is oscillating in the optical dipole trap...

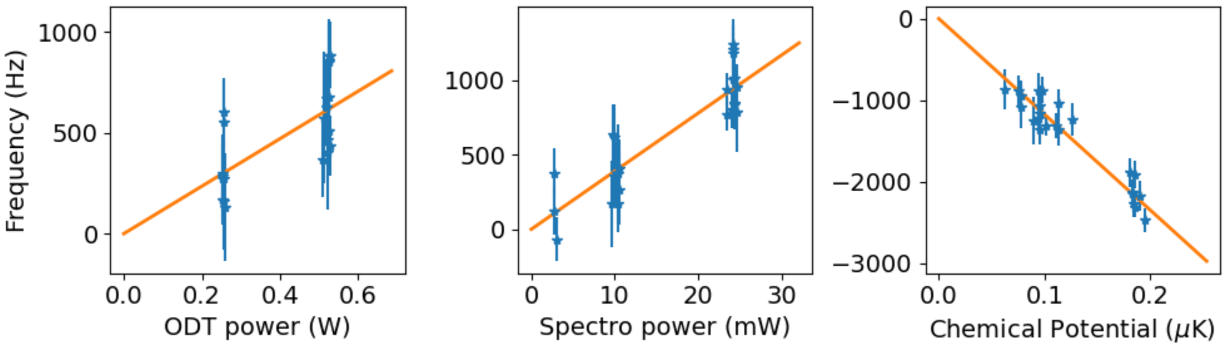


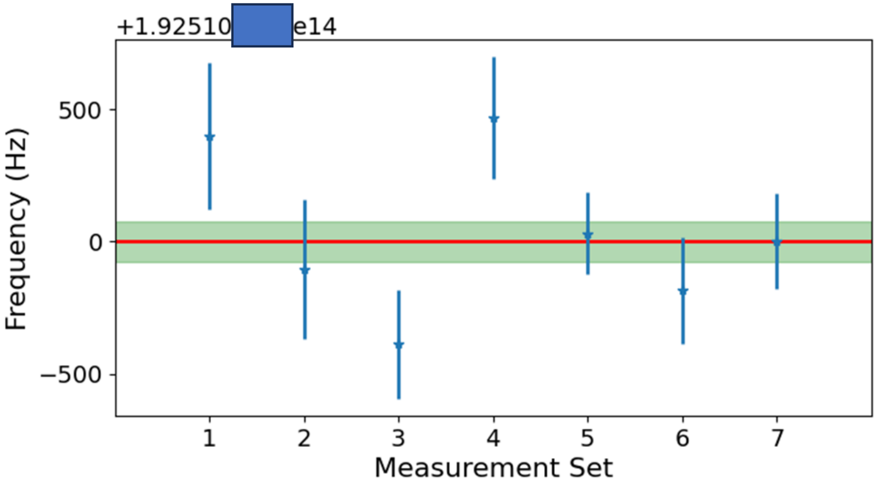
~30Hz -> Axial trap frequency

Early test measurements promising



$$f_{measured} = f_0 + AP_{Spectro} + BP_{ODT} + C\mu_{chem.pot.}$$





70Hz ‘uncertainty’ in only 7 days of measuring!

Summary He* - nuclear charge radius

- ❑ Remarkable what 1 neutron difference can make: ^{3}He vs. ^{4}He

- ❑ Most precise transition measurement in helium (1 : 10^{12})
  ^{3}He 2 $^3S_1$ – 2 $^1S_0$ transition frequency: 192 504 914 418.96(17)kHz

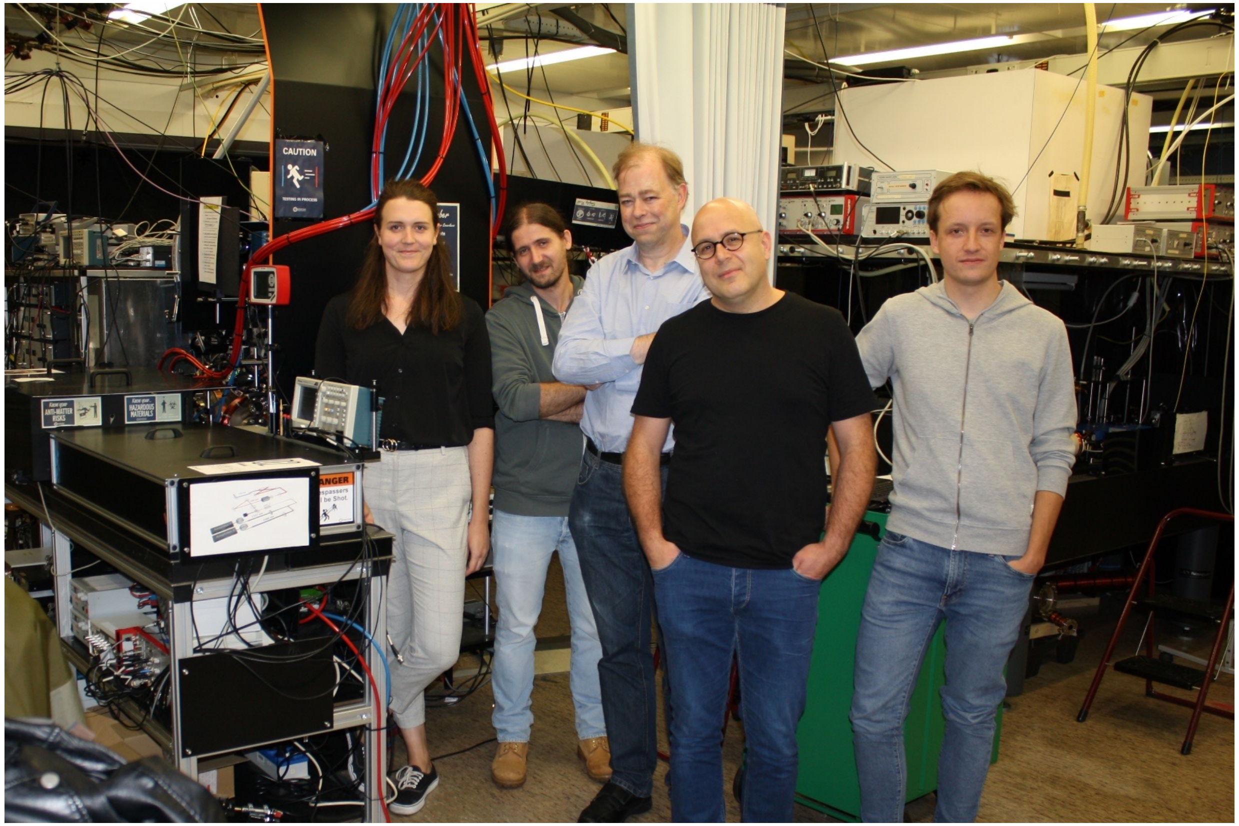
- ❑ Resulting charge radius squared difference most precise, but 3.6 σ difference with μHe+
  $r^2_h - r^2_\alpha = 1.0757(12)_{exp}(9)_{theo}\ fm^2$

Outlook:

- ❑ New ^{4}He measurement in progress and promising; target ~ 50 Hz
- ❑ Expected charge radius^2 difference (with updated theory) factor of 2 better

Thanks to the He* team

LaserLaB Amsterdam



He* team:

- Kees Steinebach
- Yuri van der Werf
- Raphael Jannin
- Rick Bethlem
- Kjeld Eikema

Technical support:

- Rob Kortekaas
- Ronald Buijs
- Lex van der Gracht

Funding:

NWO

Wim Vassen:
† *11-2-2019*