Probing Nuclear Sizes with Precision Spectroscopy in Bosonic and Fermionic Helium

Yuri van der Werf

LaserLaB VU Amsterdam

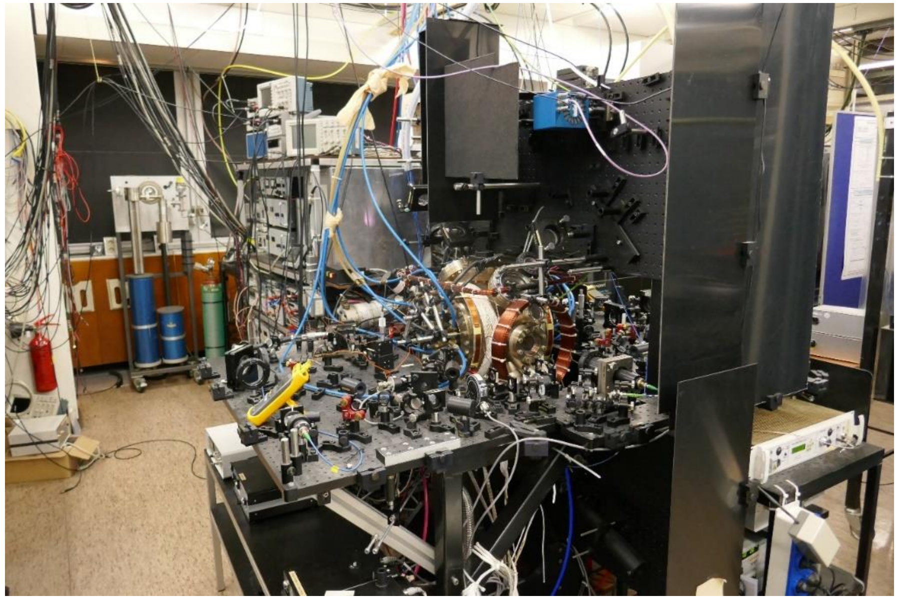
FFK meeting Vienna, 2023

Precision measurements for fundamental physics

Fundamental Physics

Tabletop Experiments

- **High precision measurements**
- Bound-state QED (theory collaborators)



He, He^+, H_2, HD, HT, HD^+, H_2^+, …

Simple, calculable, systems

LaserLaB AMSTERDAM

VU

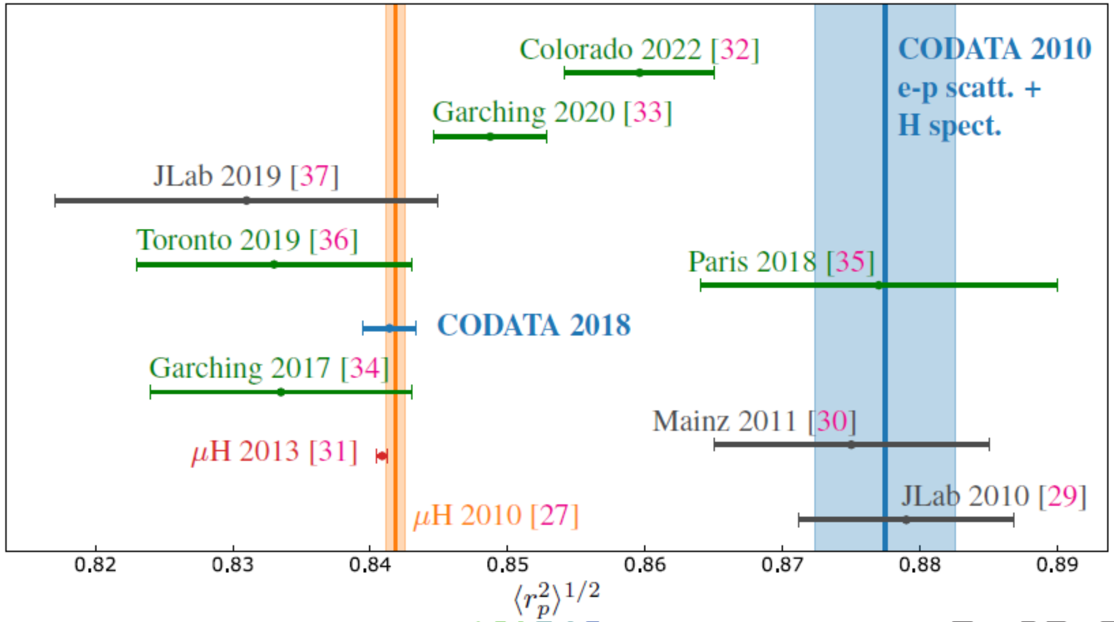
Precision measurements For fundamental physics

Simple, calculable, systems

$^1_1$H
Hydrogen

- H-atom: $1S \rightarrow 2S$ transition
  - $2S$ metastable level: narrow linewidth
  - $4.5 \cdot 10^{-15}$ precision [1]
  - Cornerstone for QED calculation

- Combined with other transitions
  - proton charge radius r_p and R_∞
  - 'proton radius puzzle'

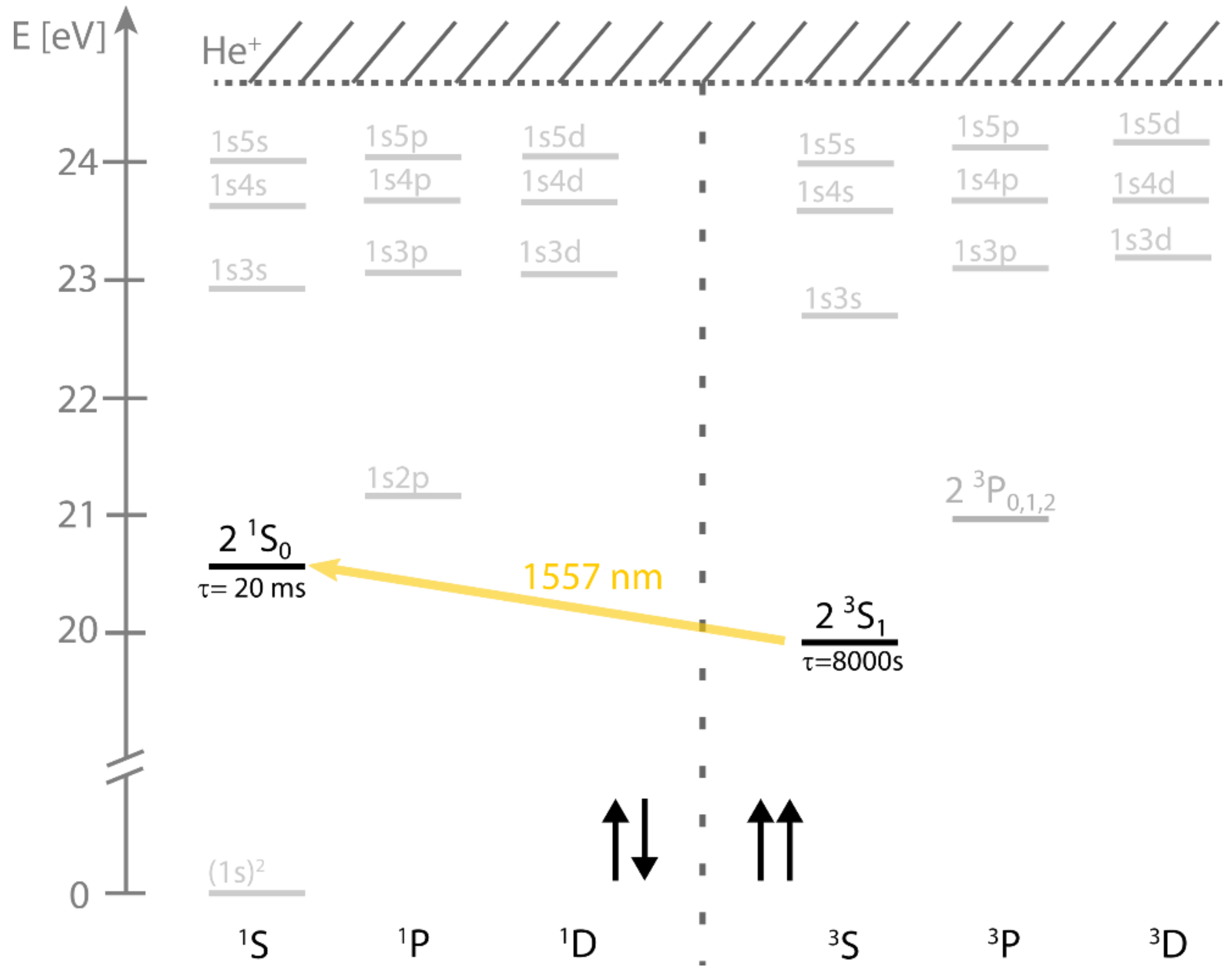


LaserLaB AMSTERDAM

VU

[1] Matveev et al. *Phys. Rev. Lett.* 110, no. 23 (June 2013): 230801.

Precision measurements For fundamental physics



- Next atom, He
- Two electrons:
  - Singlet/Triplet structure
- Two 2S metastable levels:
  - Narrow transition at 1557 nm
  - First measured in 2011 at VU (van Rooij *et al.*)

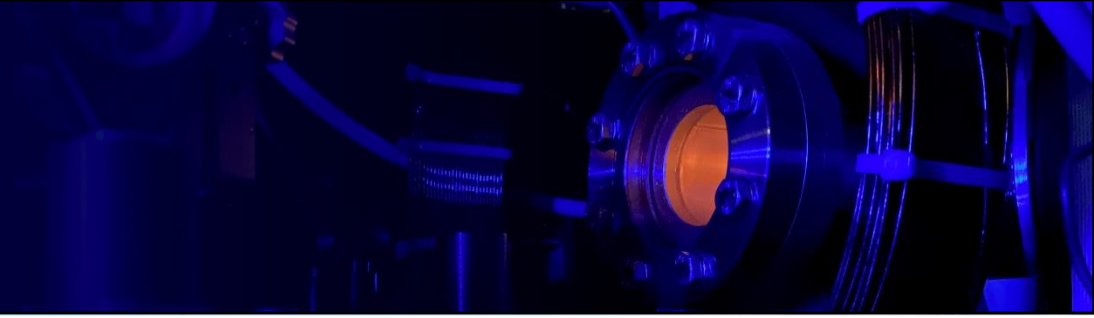
$^{4}_{2}He$

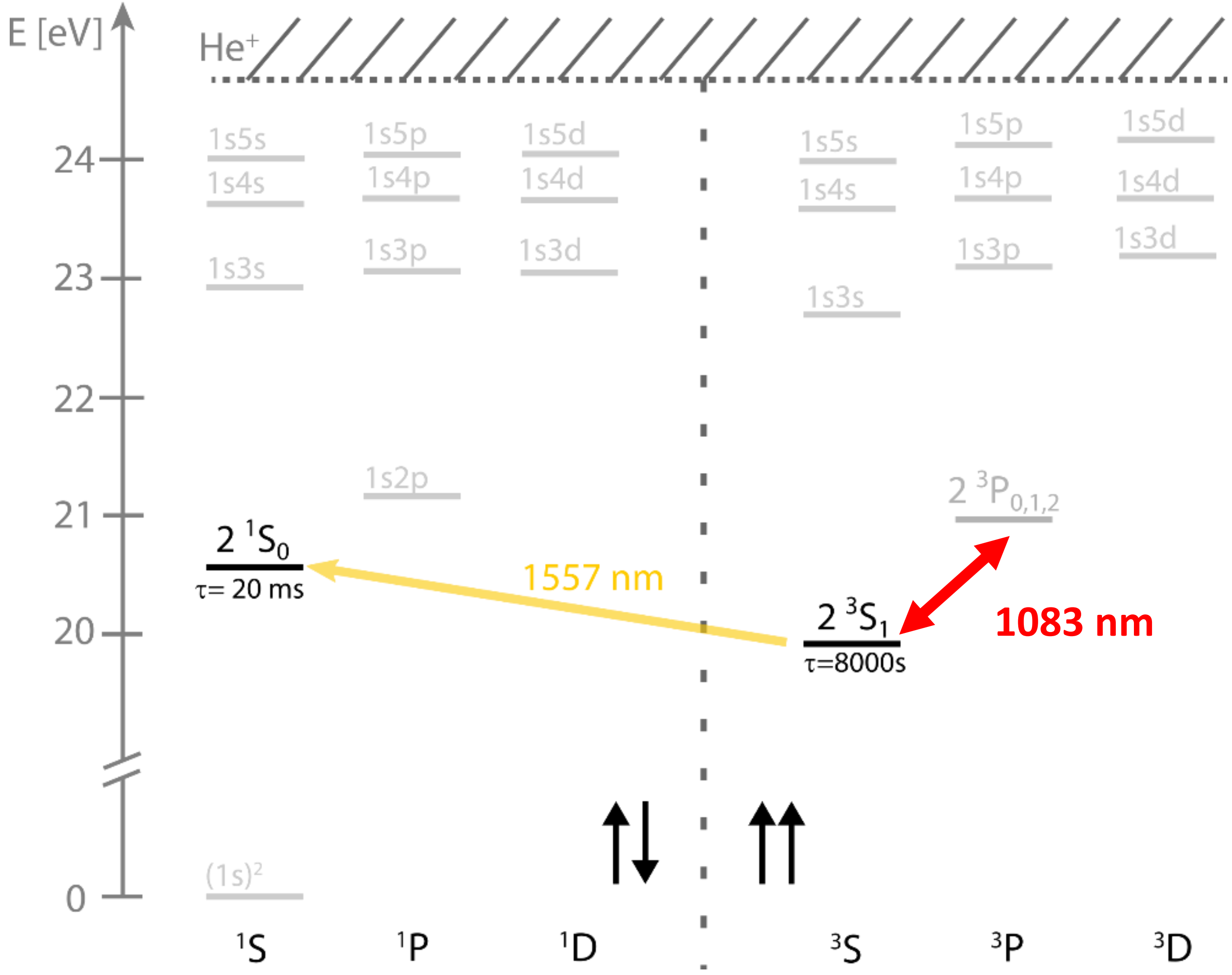
Helium

LaserLaB AMSTERDAM

VU

Precision measurements
For fundamental physics



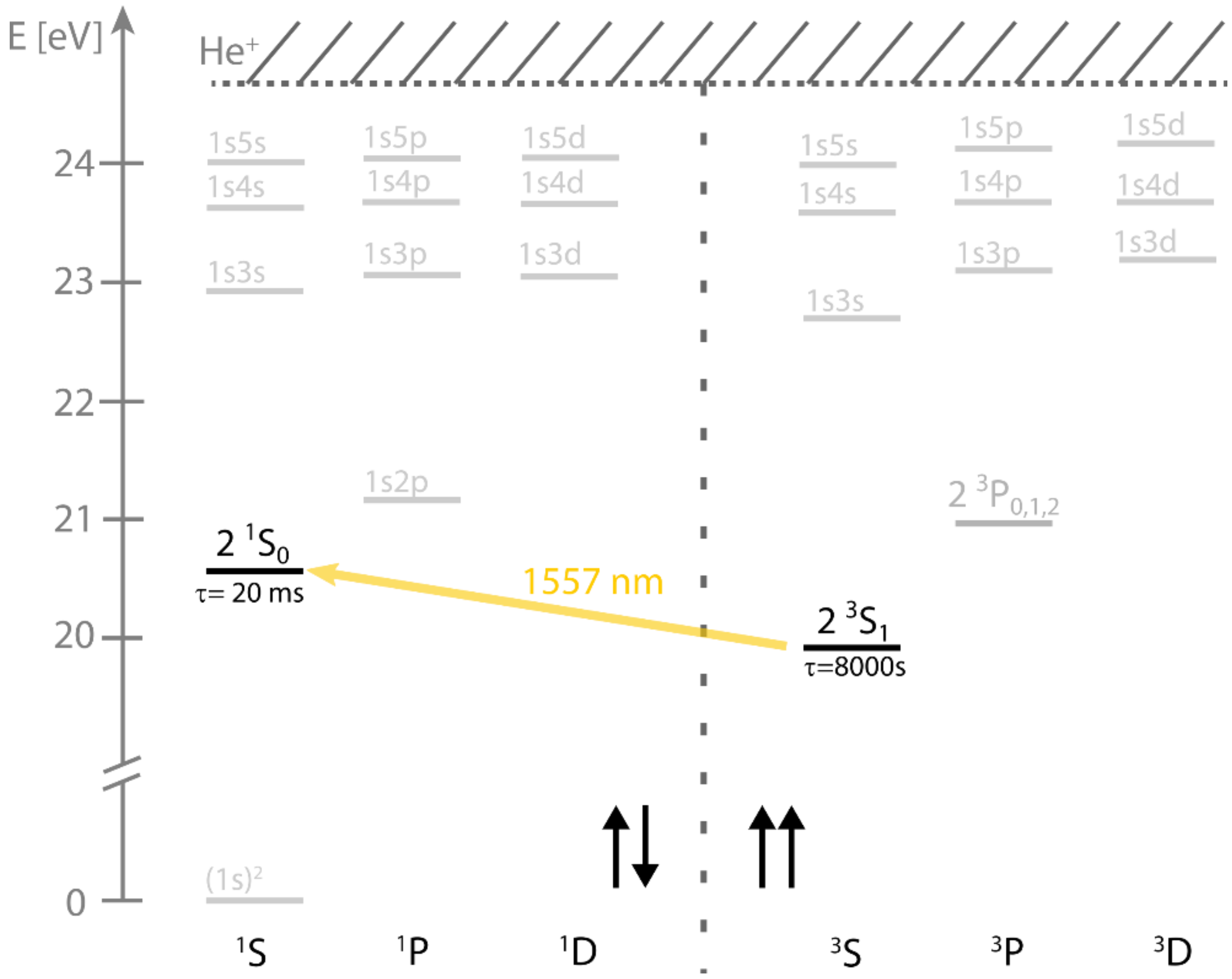


- Next atom, He
- Two electrons:
  - Singlet/Triplet structure
- Two 2*S* metastable levels:
  - Narrow transition at 1557 nm
- 2^3S_1 state:
  - Laser cooling and trapping
  - Degree of control
  - Reduce Doppler

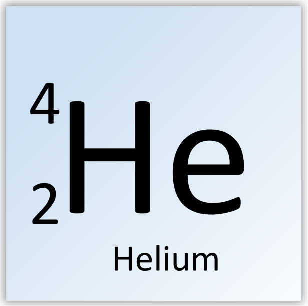
$^4_2$He
Helium

LaserLaB AMSTERDAM
VU

Precision measurements For fundamental physics



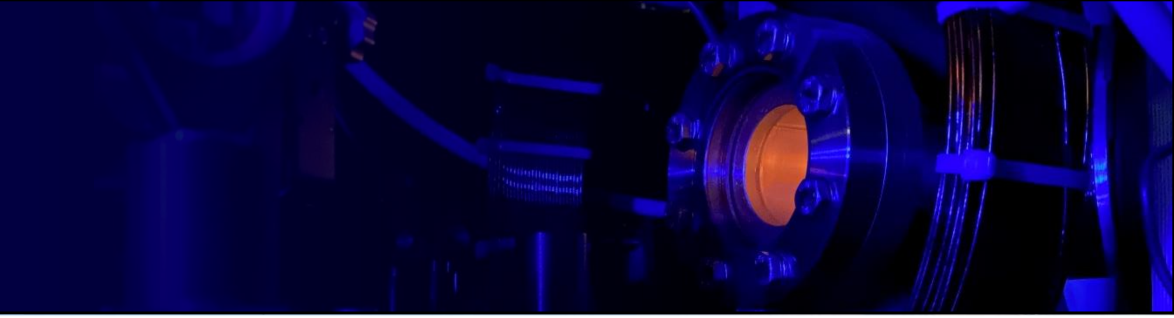
- Next atom, He
- Two electrons:
  - Singlet/Triplet structure
- BUT: complicated QED theory from electron-electron terms



- SOLUTION: ^{3}He-^{4}He isotope shift
  - Most difficult terms drop out
  - Nuclear sizes: $\delta r^2 = r_3^2 - r_4^2$

LaserLaB AMSTERDAM

VU



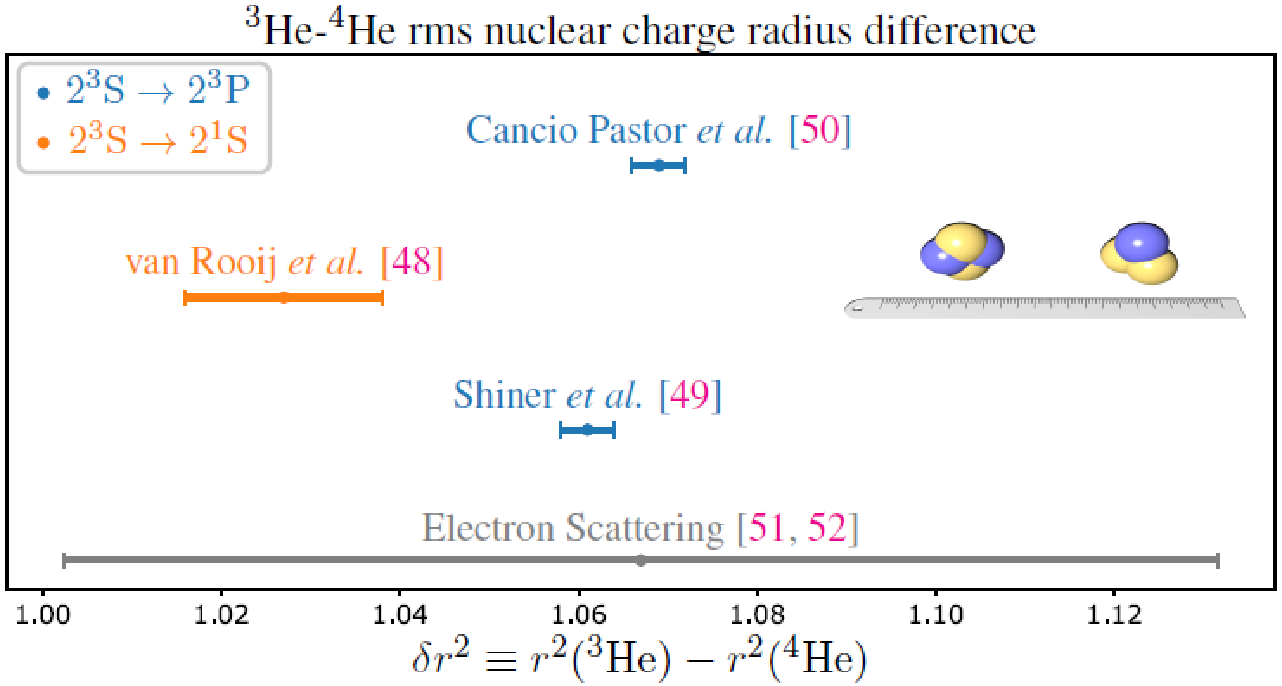
The helium atom

- Measure **isotope shift:**
  - Electron-electron terms drop out
  - *Finite nuclear size remains*
  - Scattering data too inaccurate

- Approach:
  - Measure ^{3}He-^{4}He isotope shift
  - Extract differential charge radii $r_3^2 - r_4^2$ using QED theory
  - Compare with other measurements:

    Spectroscopic, scattering, μHe^+

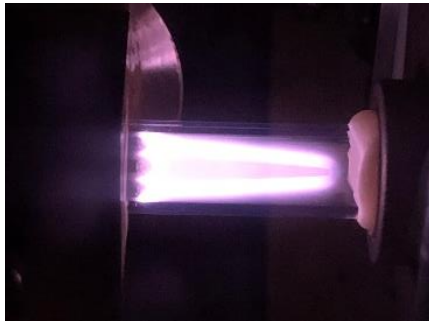
    Consistency check

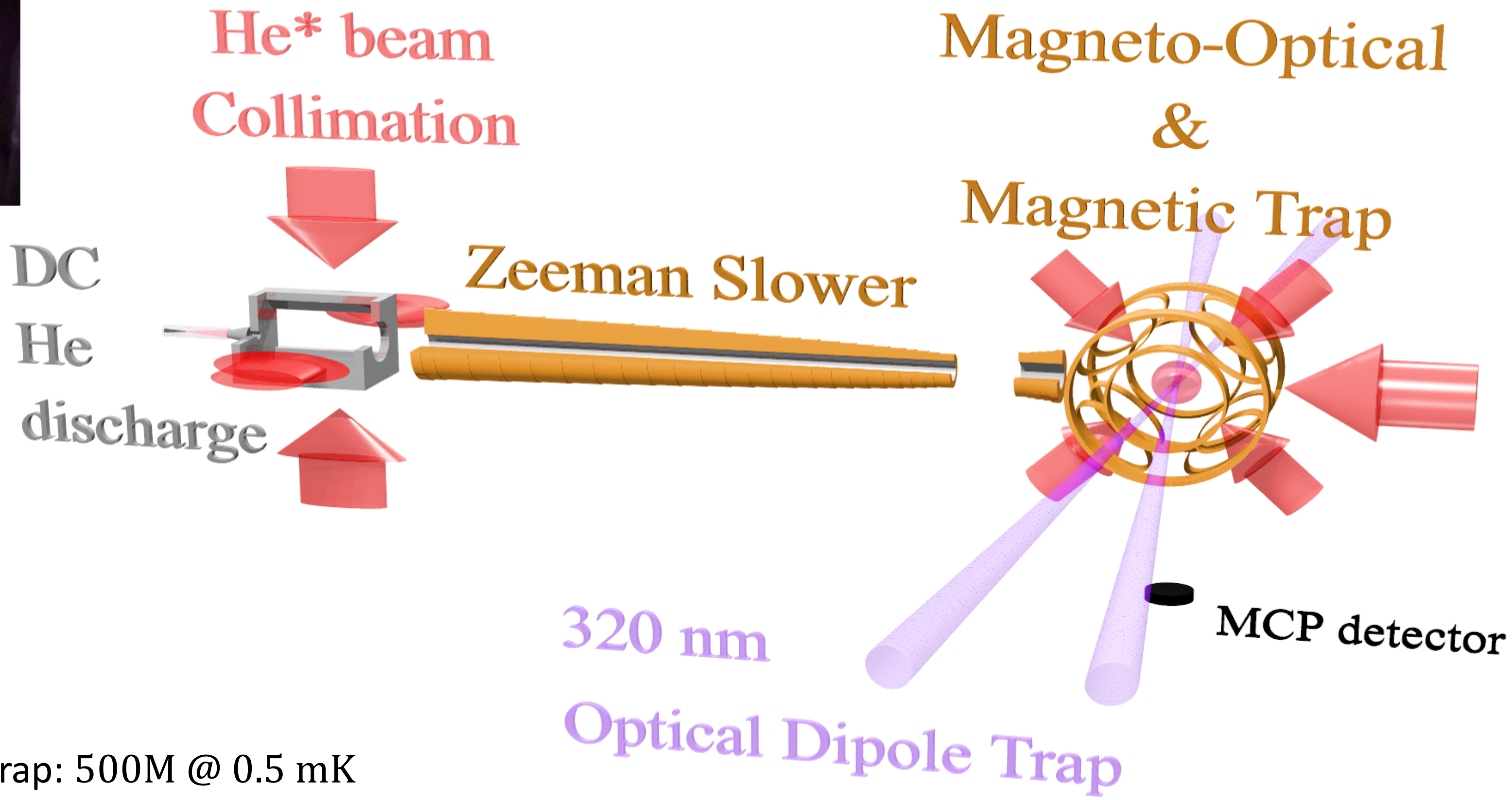


LaserLaB AMSTERDAM

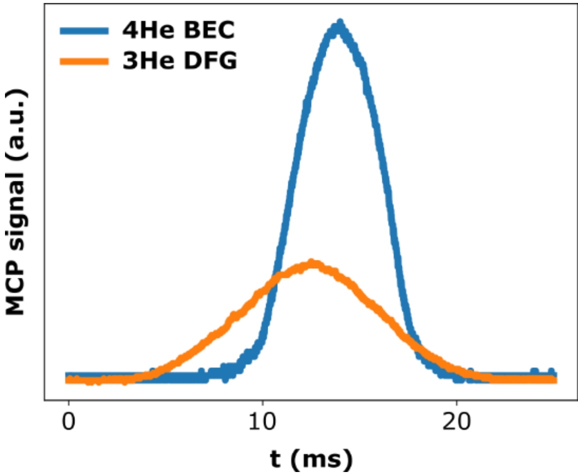
VU

Quantum degenerate He*





Atom detection
- Microchannel plate
- 20 eV internal energy
- Time-of-flight fitting: N, μ, T



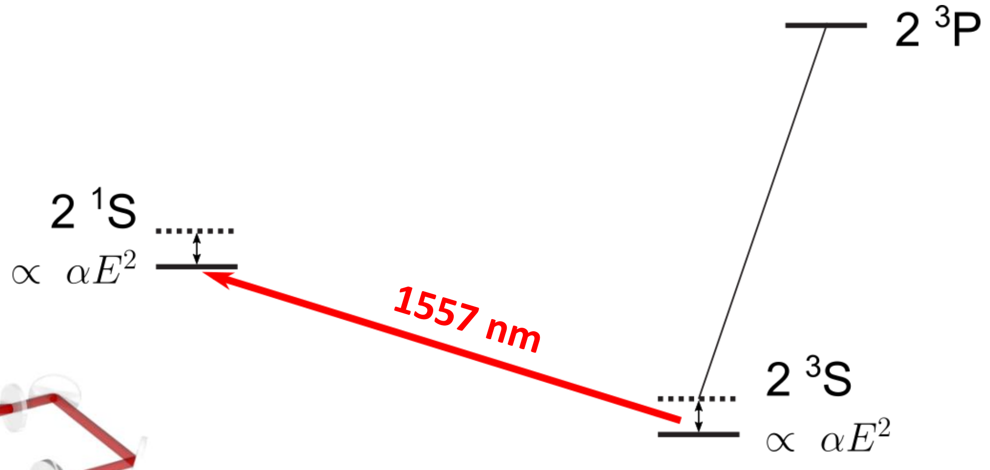
Cooling sequence:
- Magneto-optical trap: 500M @ 0.5 mK
- Doppler cooling in Magnetic Trap: 200M @ 130 μK
- Evaporative cooling: quantum degenerate gas ≤ 1 μK
- Transfer to Optical Dipole Trap (ODT)

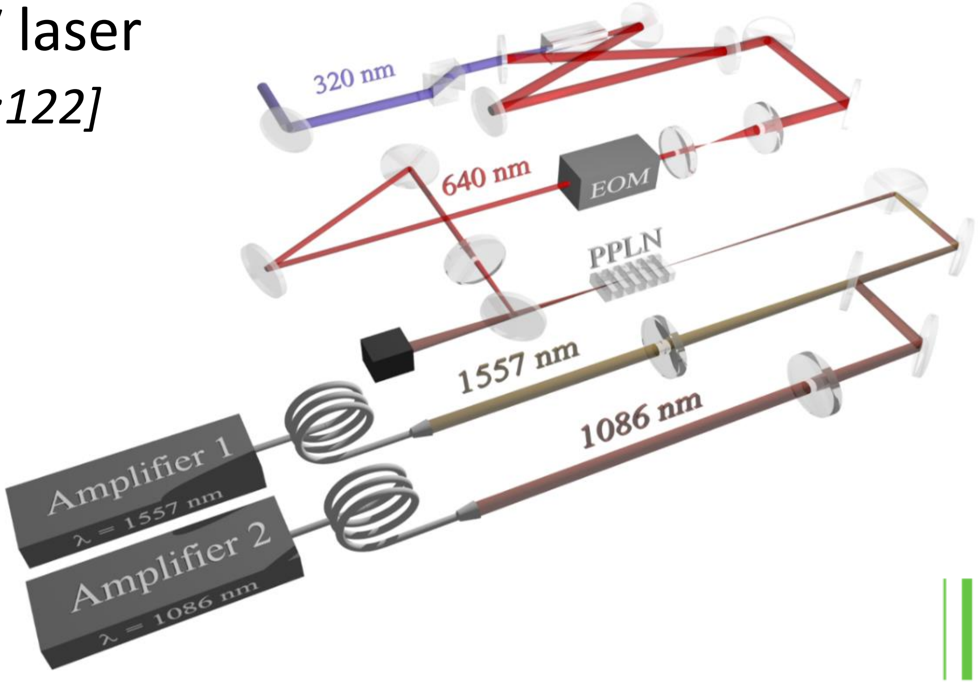
LaserLaB AMSTERDAM VU

Precision Spectroscopy

- **Magic wavelength Optical Dipole Trap**
  - ‘magic wavelength’ @ **320 nm**
  - Same trap potential for 2^3S_1 and 2^1S_0
  - No ac-Stark shift
  - Homebuilt 2 W cw UV laser

    [Appl. Phys. B (2016) 122:122]

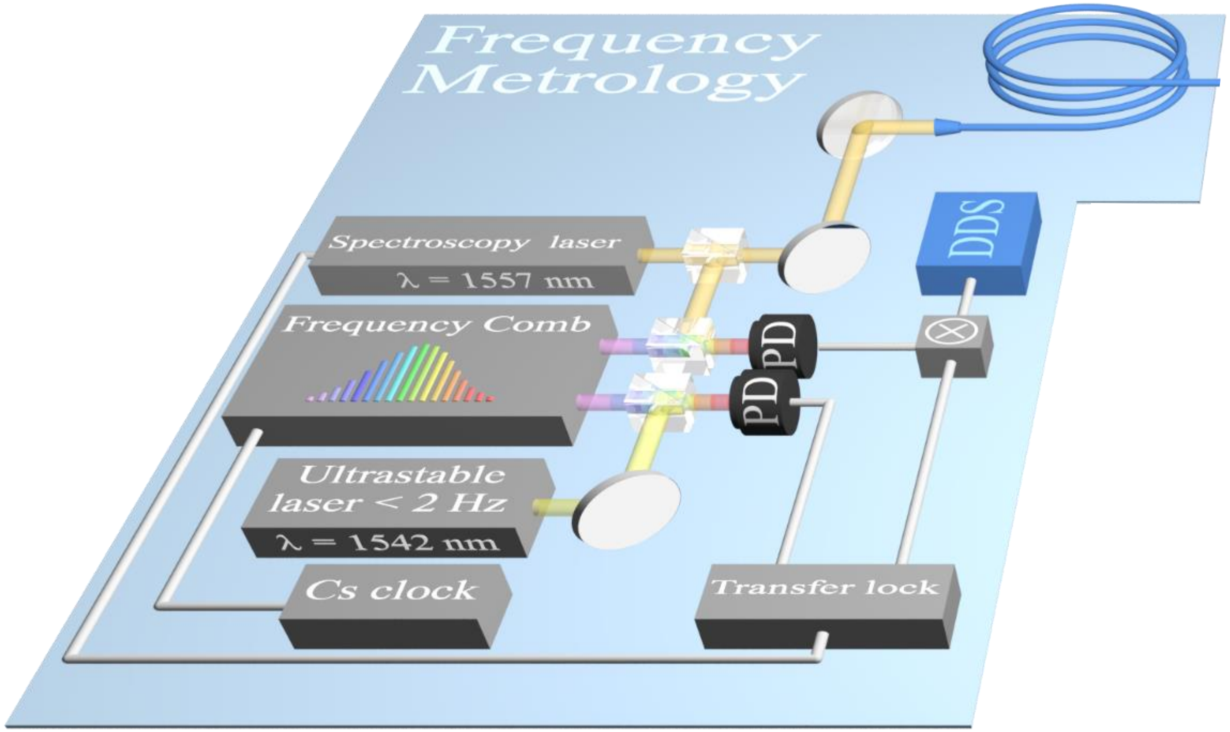




Precision spectroscopy

Two ingredients for precision spectroscopy:

- **Magic wavelength dipole trap**
- **Frequency metrology:**
  - Cs clock frequency standard
  - Optical frequency comb
  - Ultra stable (< 2 Hz) reference laser

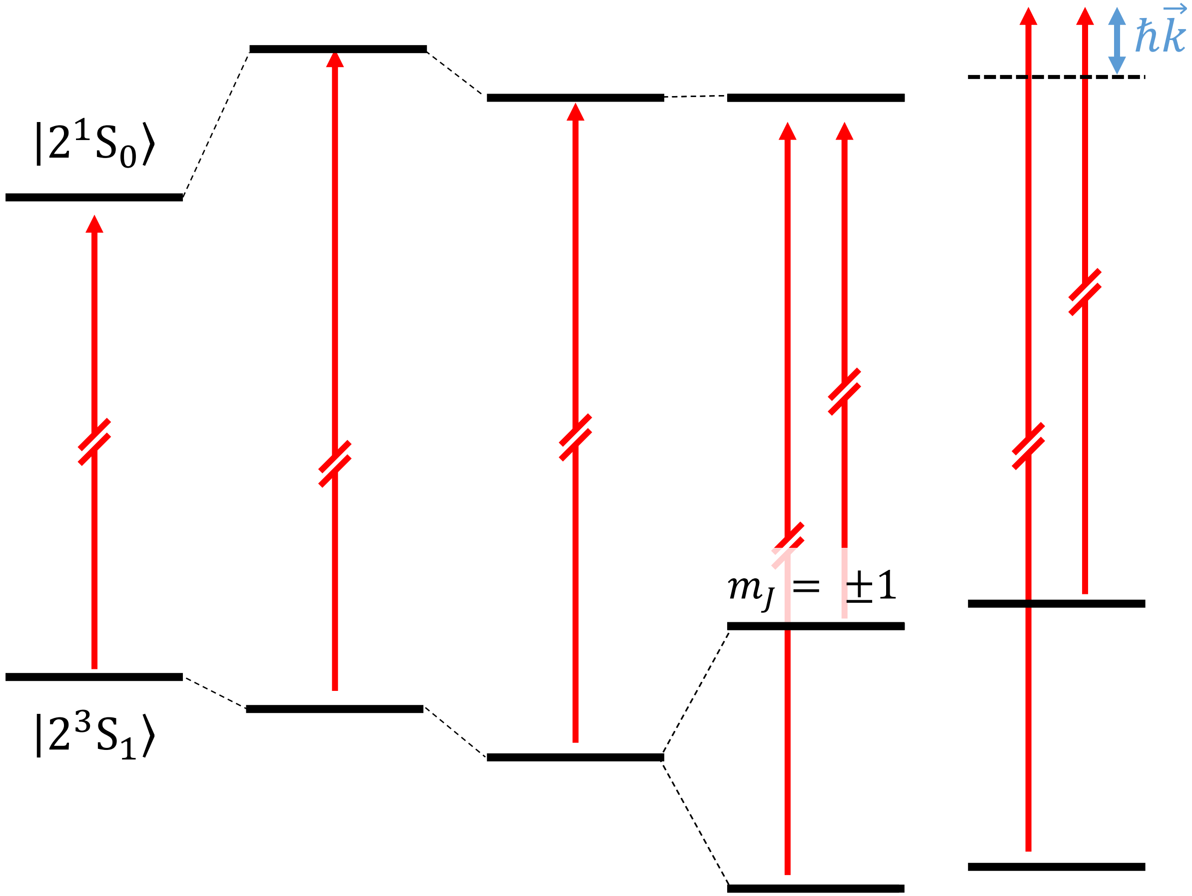


LaserLaB AMSTERDAM

VU

Precision spectroscopy

- Measure *unperturbed* $2^3S_1 \rightarrow 2^1S_0$ transition
- Systematics effects:
  - Spectroscopy Stark shift: extrapolate
  - Dipole trap Stark shift: magic λ
  - Zeeman shift: spin-stretched states
  - photon recoil: exactly known
  - Interactions: **mean-field shift**



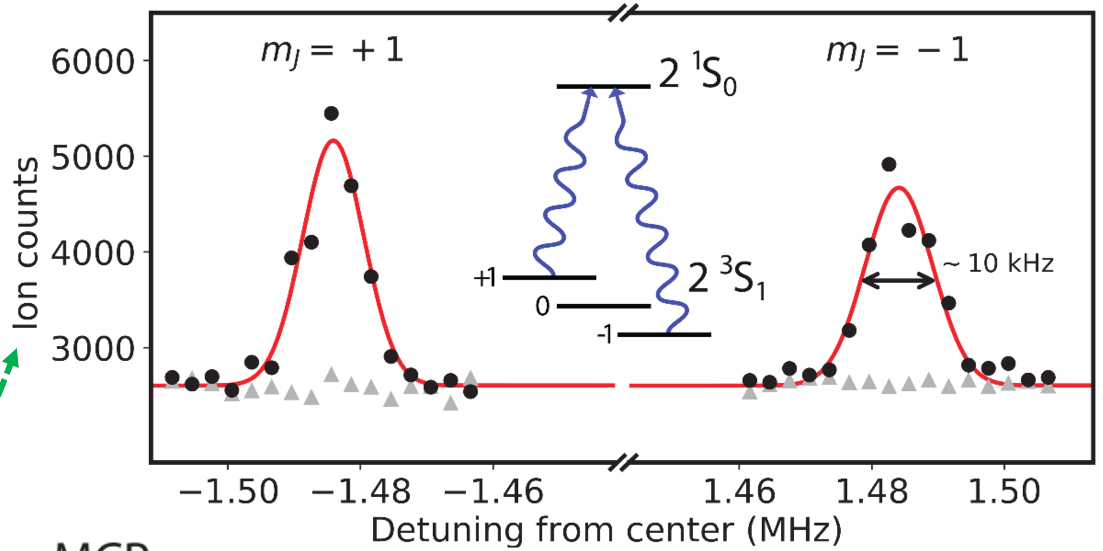
Spectroscopy of a ^{4}He BEC

- Dominated by collisions:
  - Penning ionization signal

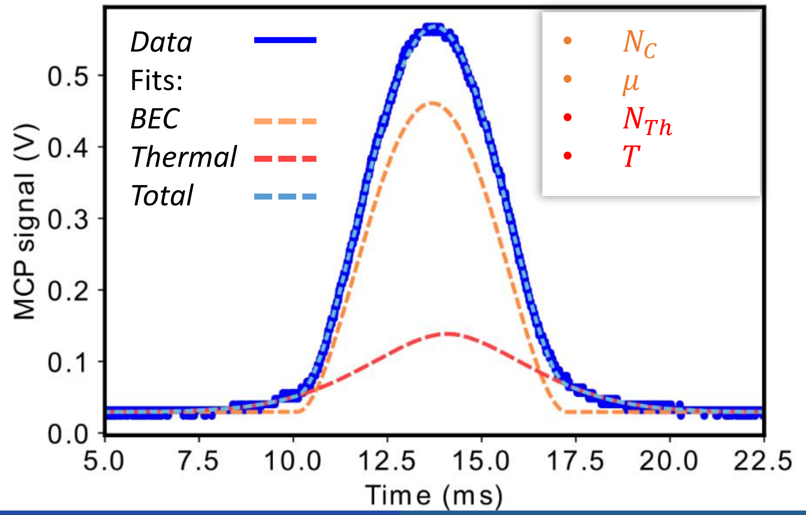
$$\mathrm{He}\,(2^1\mathrm{S}_0) + \mathrm{He}\,(2^3\mathrm{S}_1) \rightarrow \mathrm{He}\,(1^1\mathrm{S}_0) + \mathrm{He}^+ + e^-$$

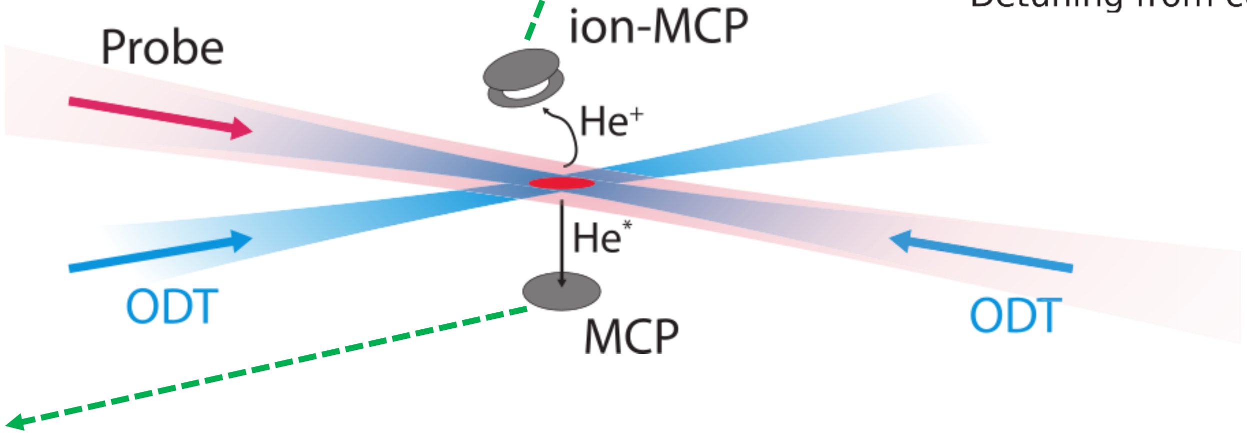
  - **Cold-collision shift:**

$$\langle \Delta\nu \rangle \propto \frac{a_{ts} - a_{tt}}{a_{tt}} \mu$$



single shot TOF:

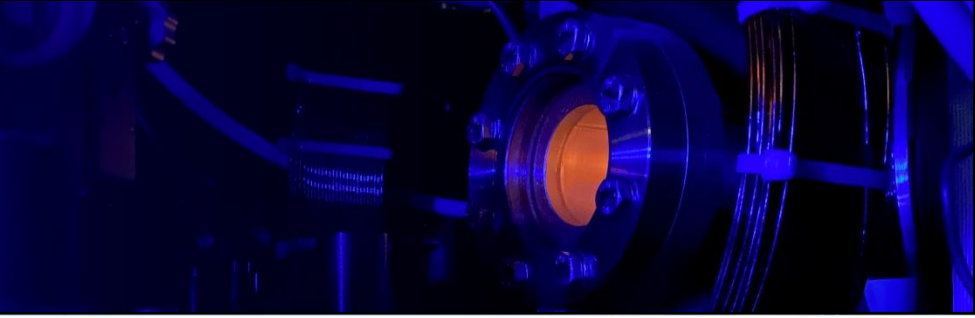




LaserLaB AMSTERDAM

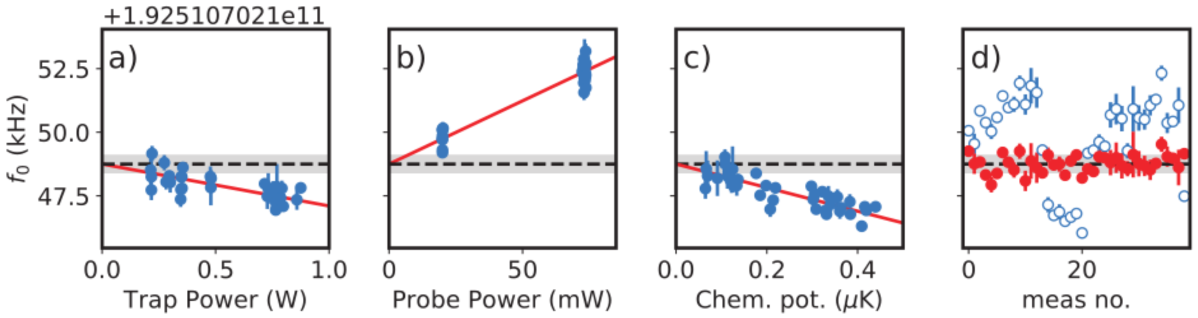
VU

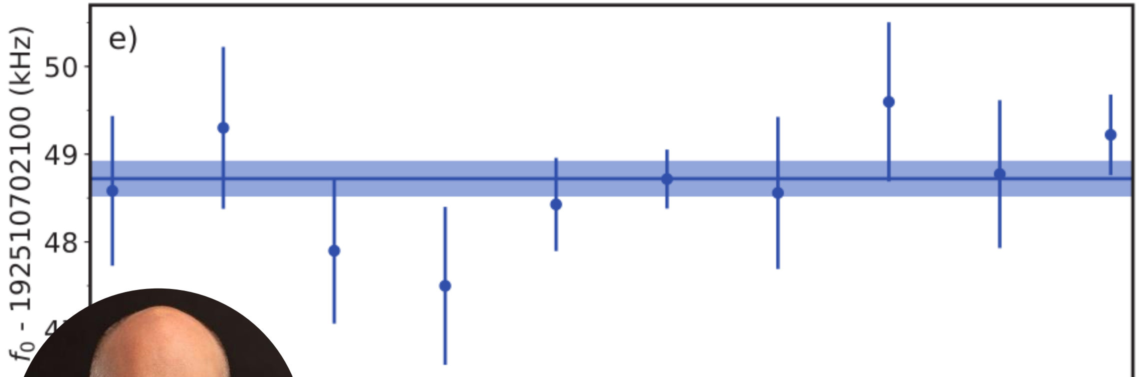
Spectroscopy of a ^{4}He BEC



Nat. Phys. **14**, 1132-1137 (2018)

- Systematics analysis:
  - Spectroscopy laser ac-Stark
  - Dipole trap (residual) shift
    - $\boldsymbol{\lambda_m = 319.81592(15)\ \mathrm{nm}}$
  - Cold-collision shift: $\langle \Delta\nu \rangle \propto \frac{a_{ts} - a_{tt}}{a_{tt}} \mu$
    - $\boldsymbol{a_{ts} = 82.5(5.2)\ a_0}$
  - $2^3S_1 \rightarrow 2^1S_0$ *transition:*
    - $\mathbf{192\ 510\ 702\ 148.72(0.20)\ kHz}$





Most accurate transition in helium (10^{-12})

Three benchmarks for the ^{4}He atom

Bob Rengelink

LaserLaB AMSTERDAM

VU

Working with ^{3}He

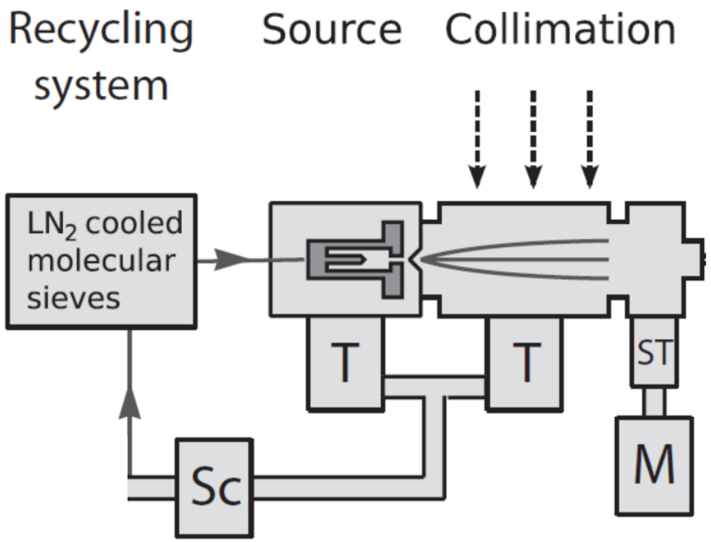
Production of a Degenerate Fermi Gas of $^3He^*$
and investigation of the spectral line shape

LaserLaB AMSTERDAM
VU

Working with ^3He

- Low natural abundance
- Recycling system

	^3He	^4He
Atomic mass	3.016 amu	4.0026 amu
Natural abundance	0.00014 %	99.99986 %
Nuclear spin	$\frac{1}{2}$	0
Cost	\$2000/L [1]	\$0.07/L [2]



*[1] Physics Today **62**, 10, 21 (2009)*
[2] Local party balloon store (2020)

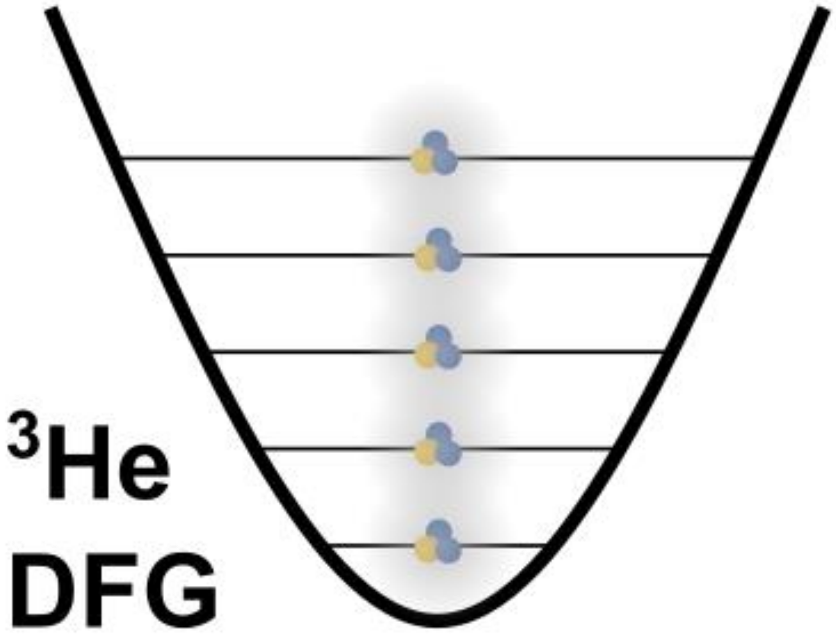
LaserLaB AMSTERDAM

VU

Working with ^{3}He

Pauli principle:
Ultracold Identical Fermions don't collide!

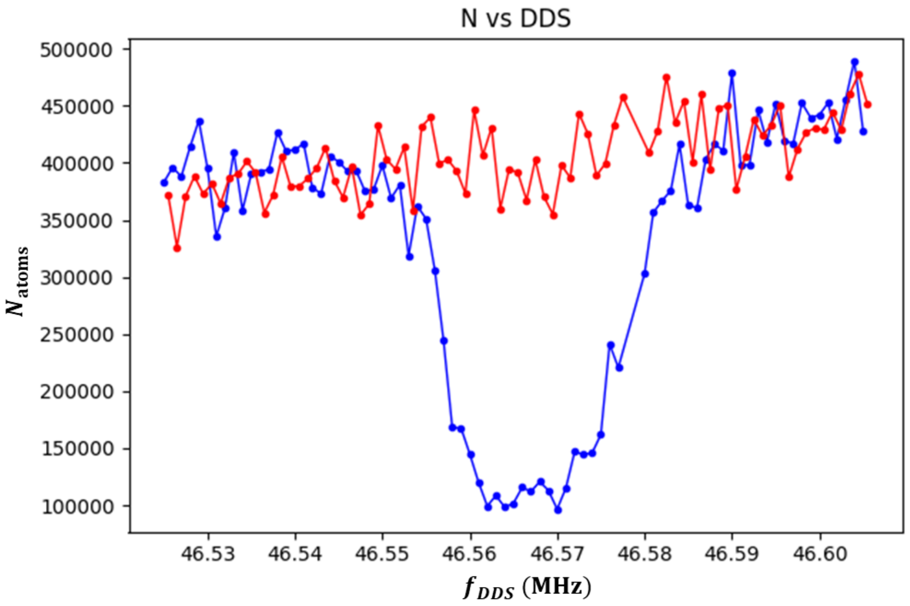
- Sympathetic cooling with ^{4}He
- Fermi-Dirac distribution:
  Doppler broadening
- No Penning ionisation signal:
  Measure trap depletion
- No collisional shift *

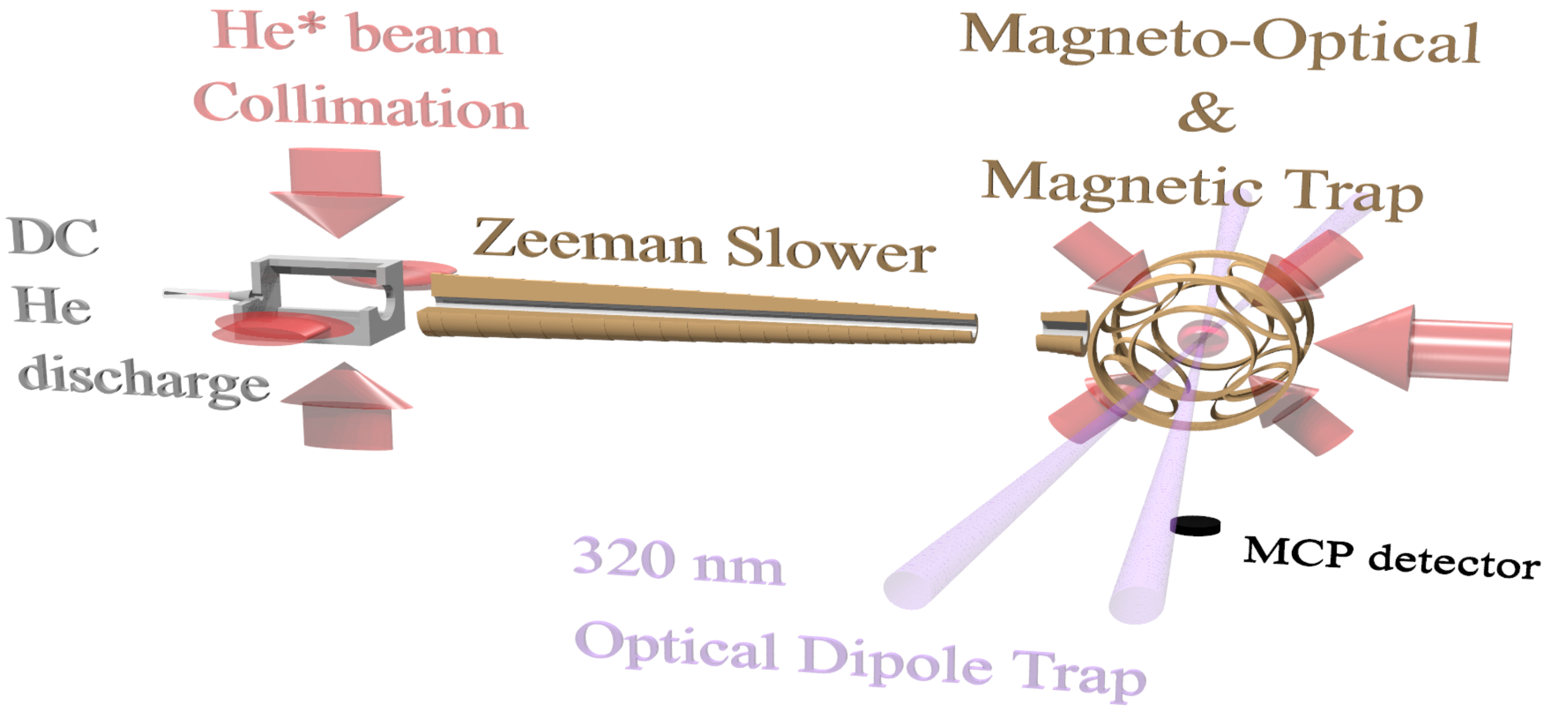


LaserLaB AMSTERDAM
VU

Working with ^{3}He

- Sympathetic cooling with ^{4}He
- Fermi-Dirac distribution:
  Doppler broadening
- No Penning ionisation signal:
  Measure trap depletion
- No collisional shift *

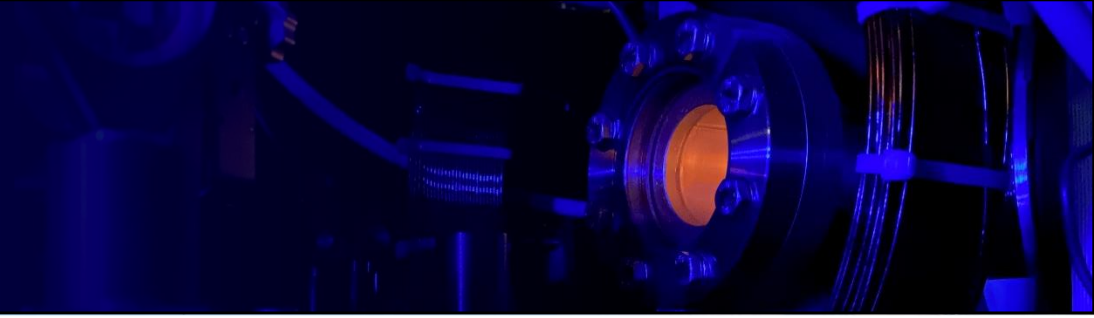




LaserLaB AMSTERDAM

VU

$2^3S_1 \rightarrow 2^1S_0$ spectroscopy



- Fermion line profile: Doppler broadening

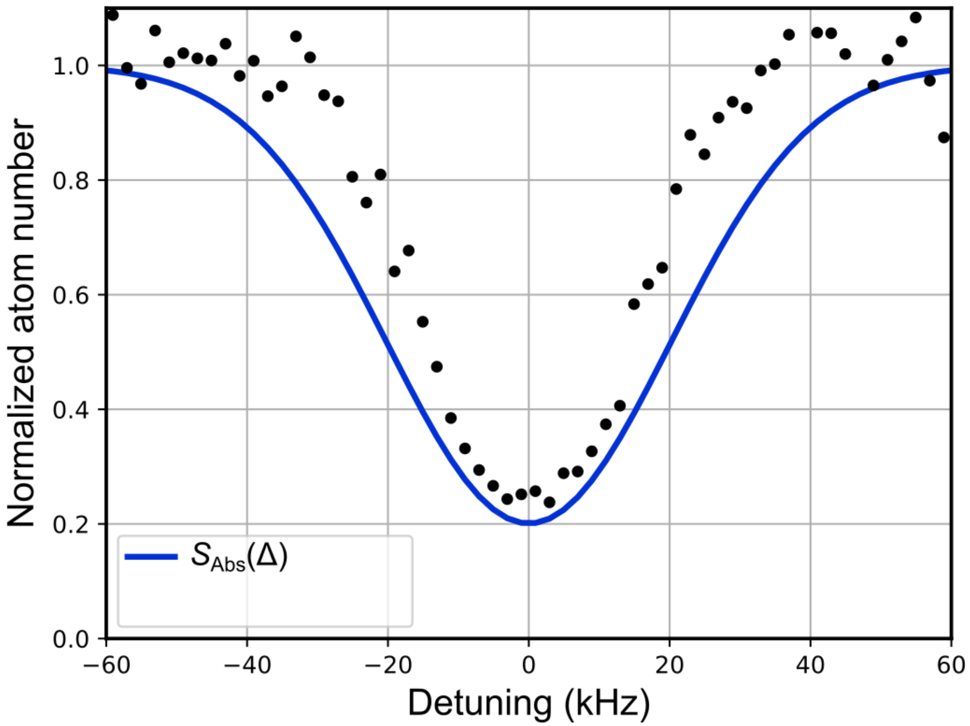
$$S(\Delta) \propto \int \int \rho_g \, \delta(\omega - \omega_0) d^3\vec{r}\, d^3\vec{k}$$

Fermi-Dirac *resonance*

Juzeliūnas & Mašalas, *PRA* **63, 061602** (2001)

- Expect Doppler broadening: $FWHM \leftrightarrow T_F$

- But wait, reduced linewidth!



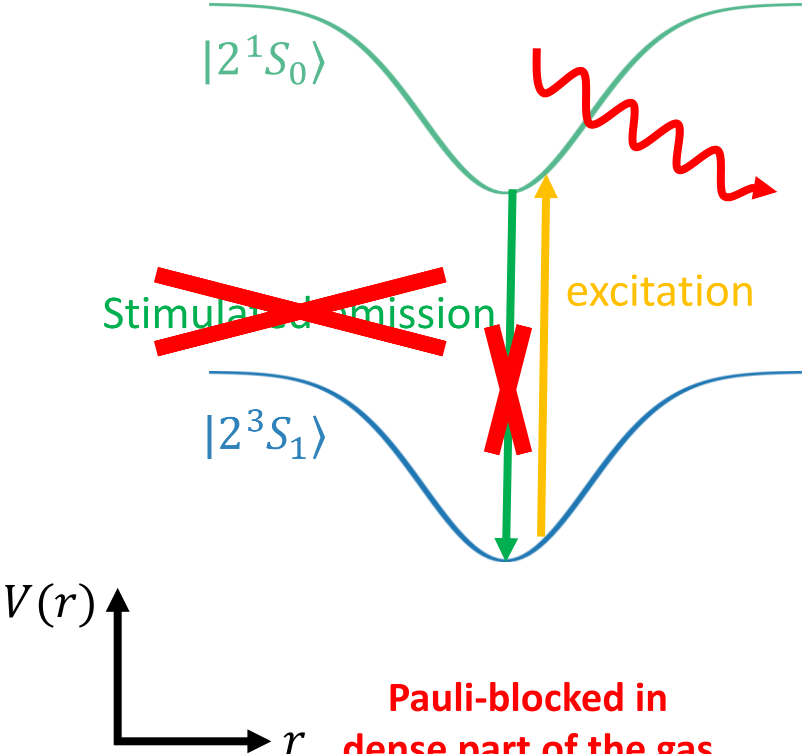
LaserLaB AMSTERDAM
VU

Understanding the spectral lineshape

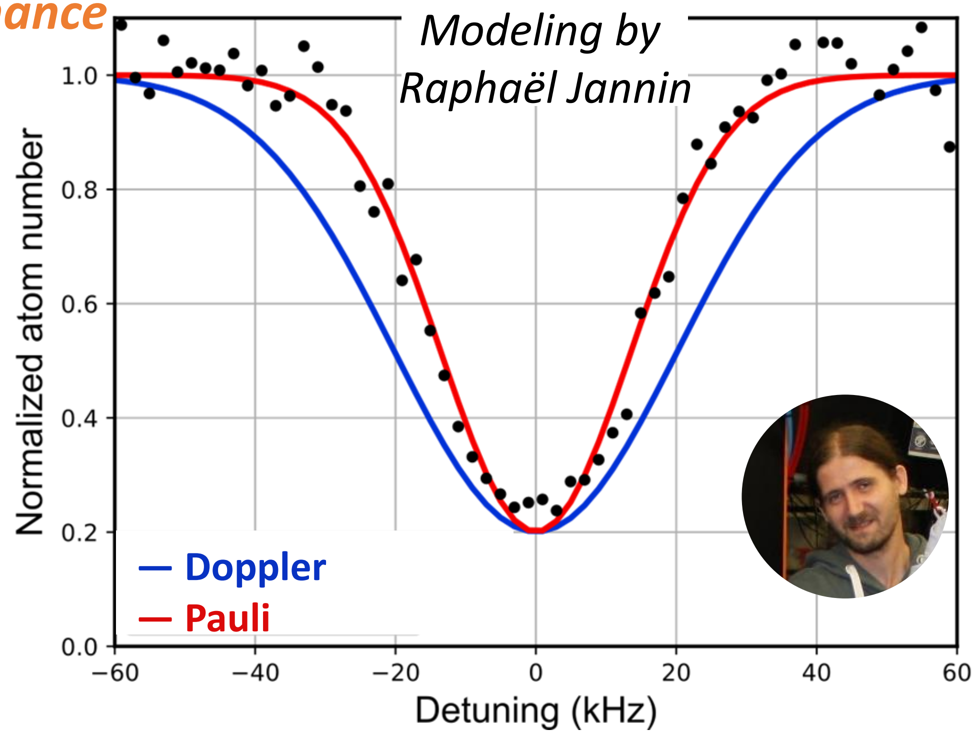
$$S(\Delta) \propto \int\int \left[\rho_g - \rho_g(1-\rho_g)\right]\delta(\omega-\omega_0)\, d^3\vec{r}\, d^3\vec{k}$$

Excitation ***Blockade*** ***Resonance***

Decay $2^1S_0 \rightarrow 1^1S_0$:
$\boldsymbol{\tau = 20}$ **ms**



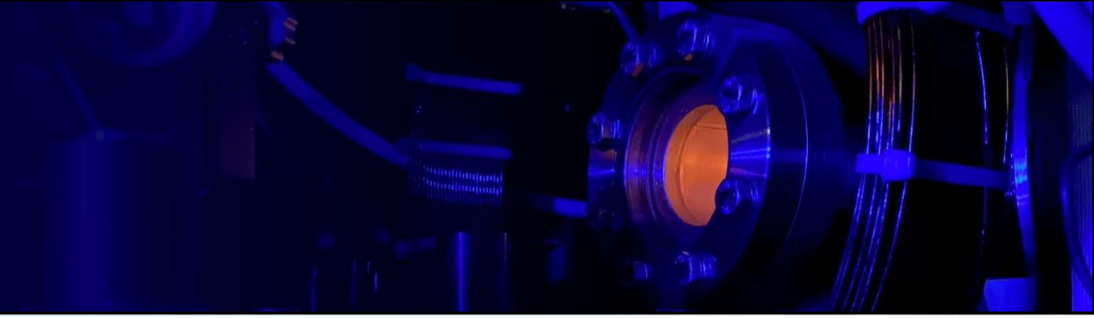
Pauli-blocked in dense part of the gas

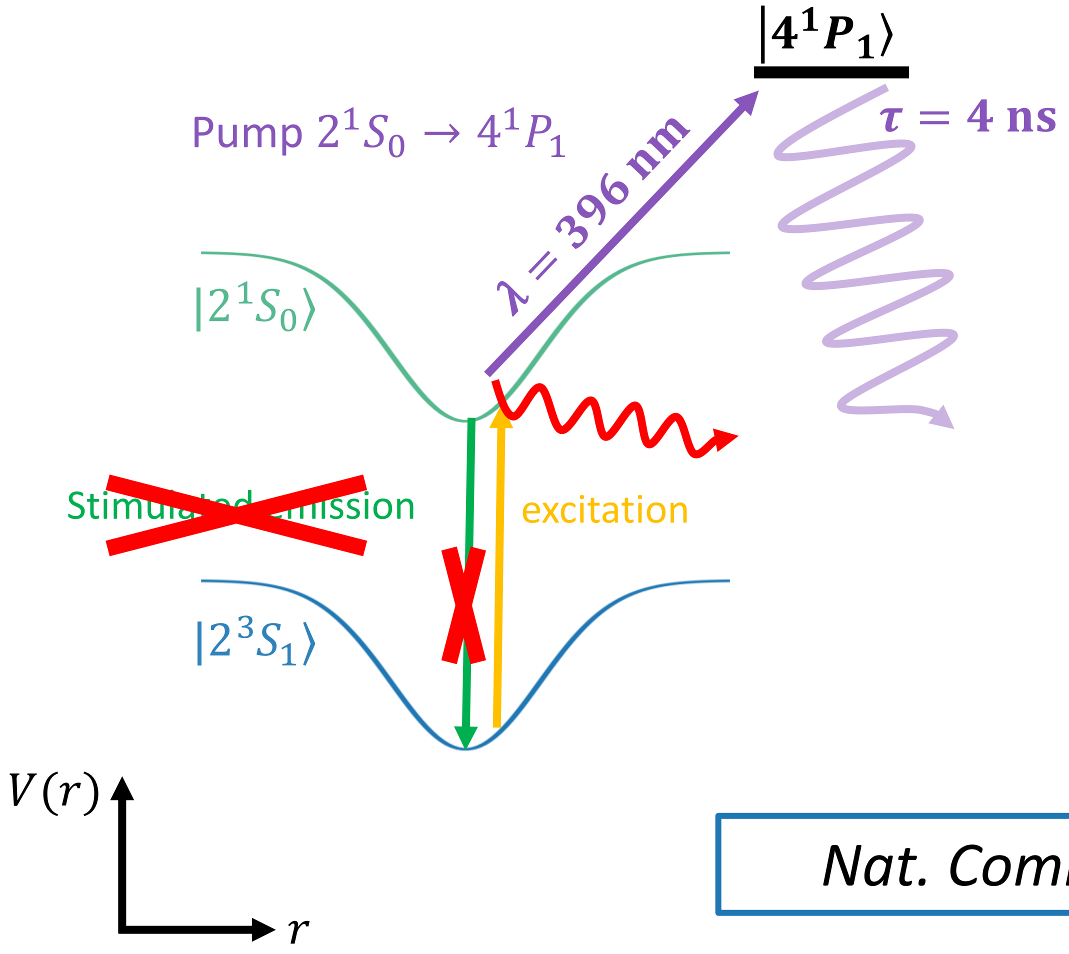


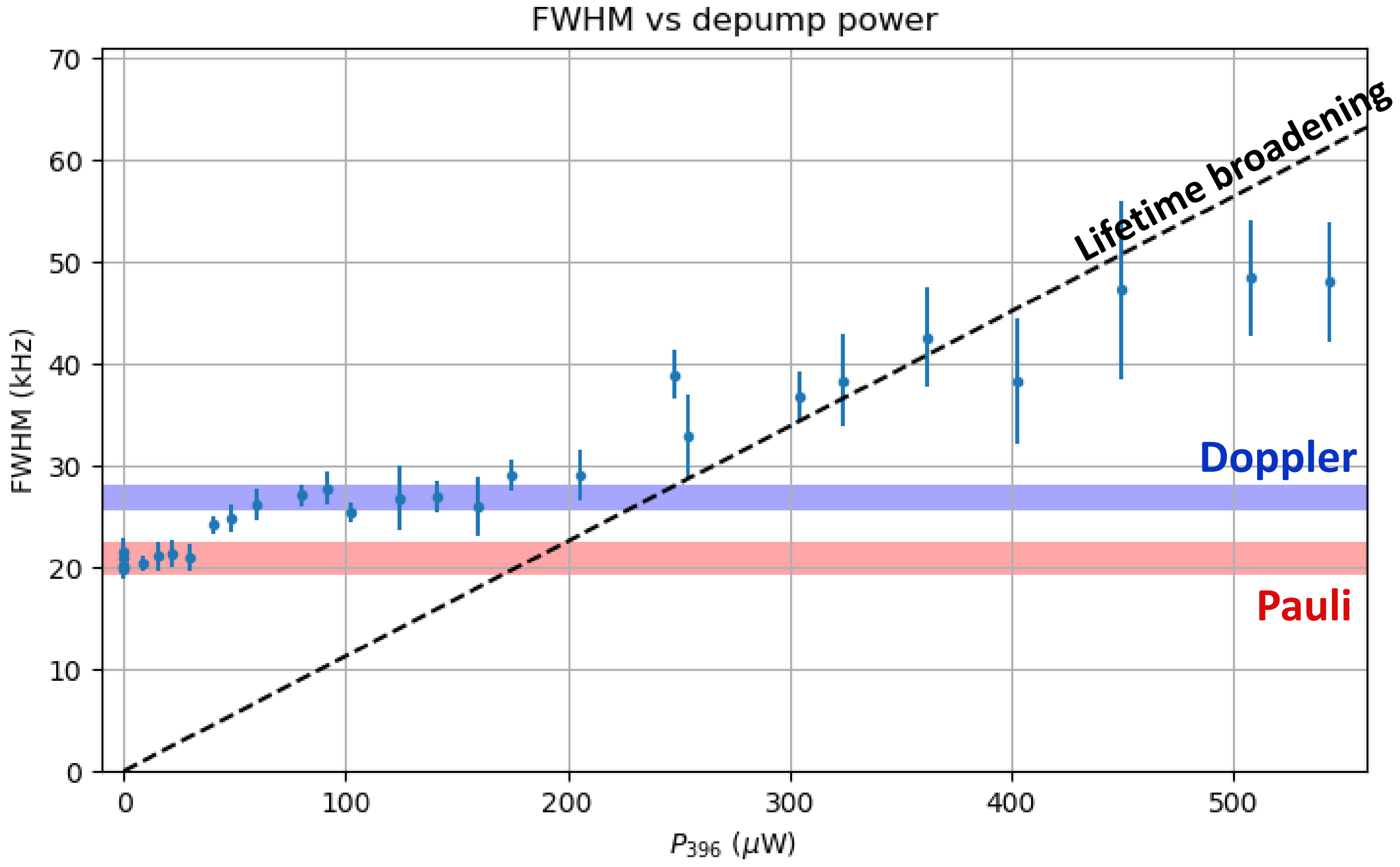
LaserLaB AMSTERDAM

VU

Testing the lineshape model



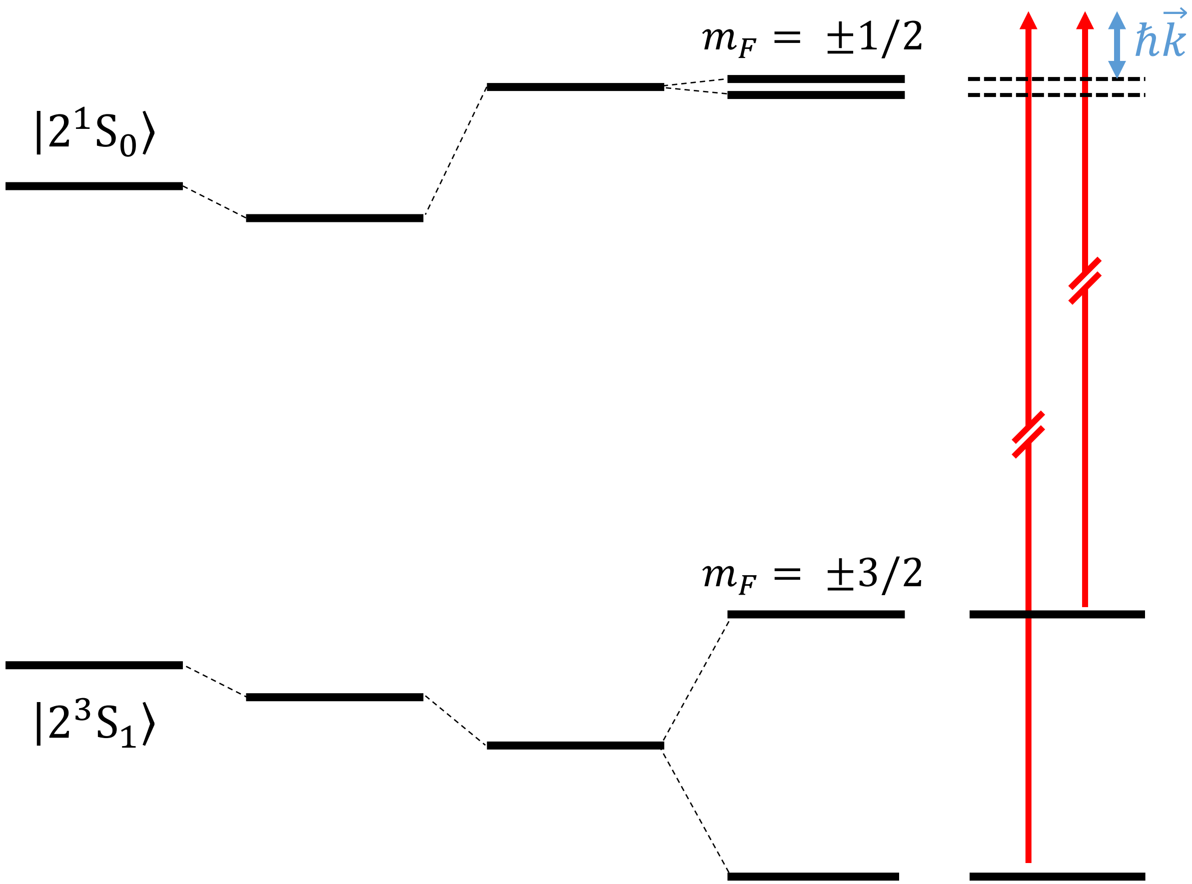




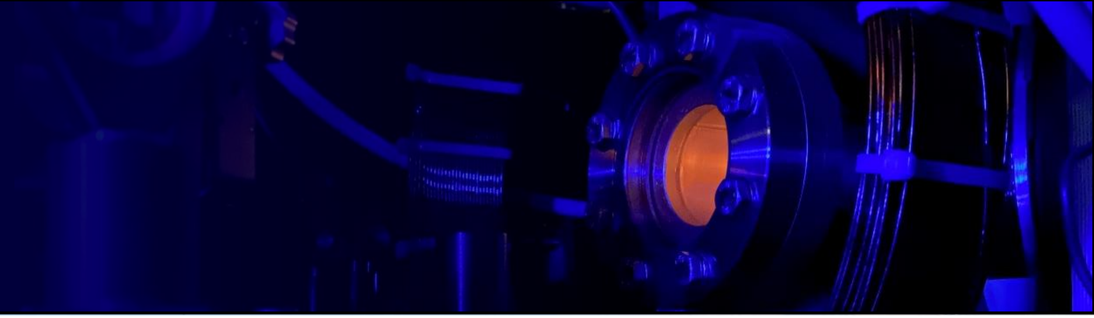
Nat. Comm. **13,** 6479 (2022)

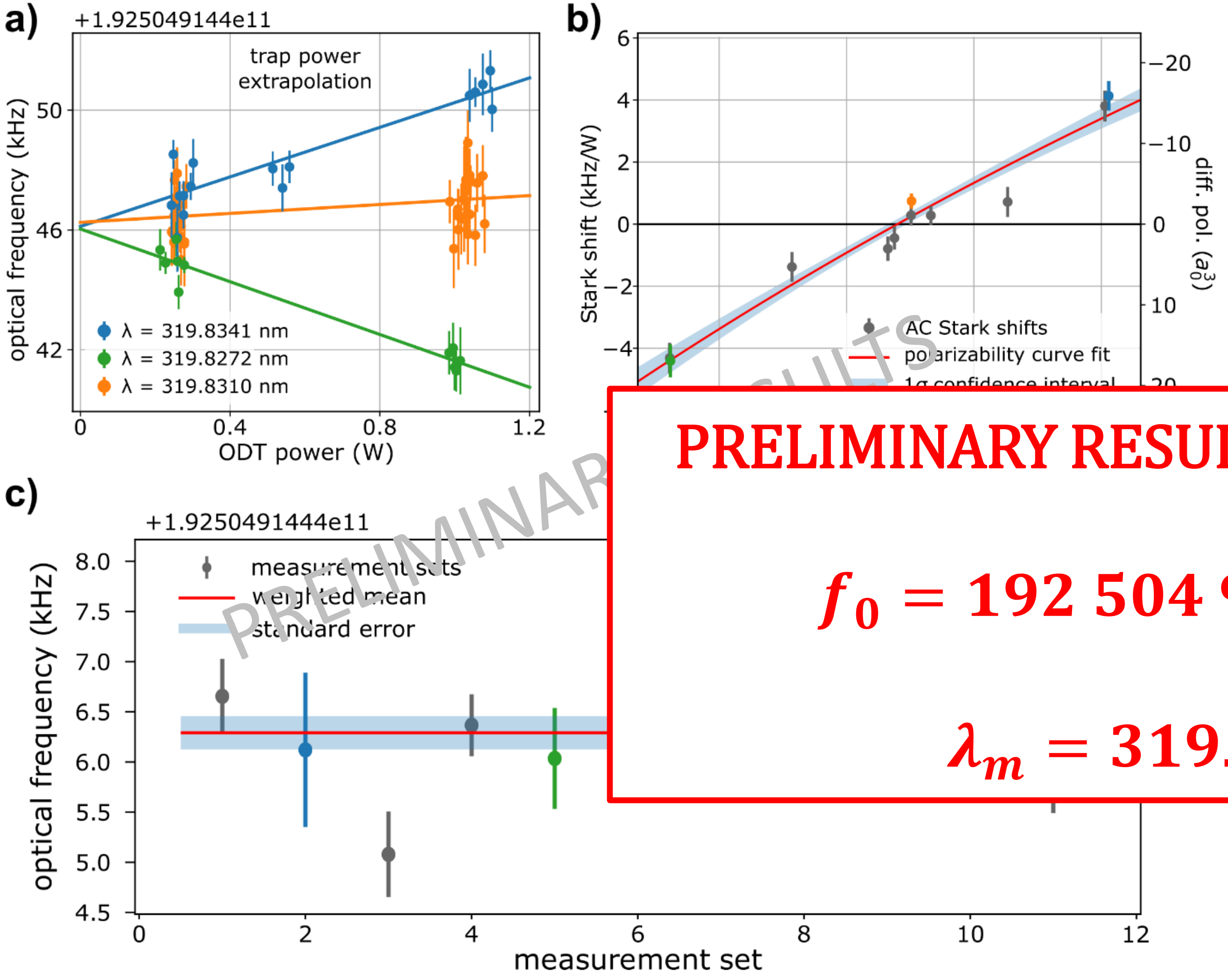
Precision spectroscopy

- Measure *unperturbed* $2^3S_1 \rightarrow 2^1S_0$ energy difference
- Systematic effects:
  - Dipole trap Stark shift
  - Spectroscopy laser Stark shift
  - Zeeman shift
  - photon recoil
  - Lineshape Model ✓



Precision spectroscopy

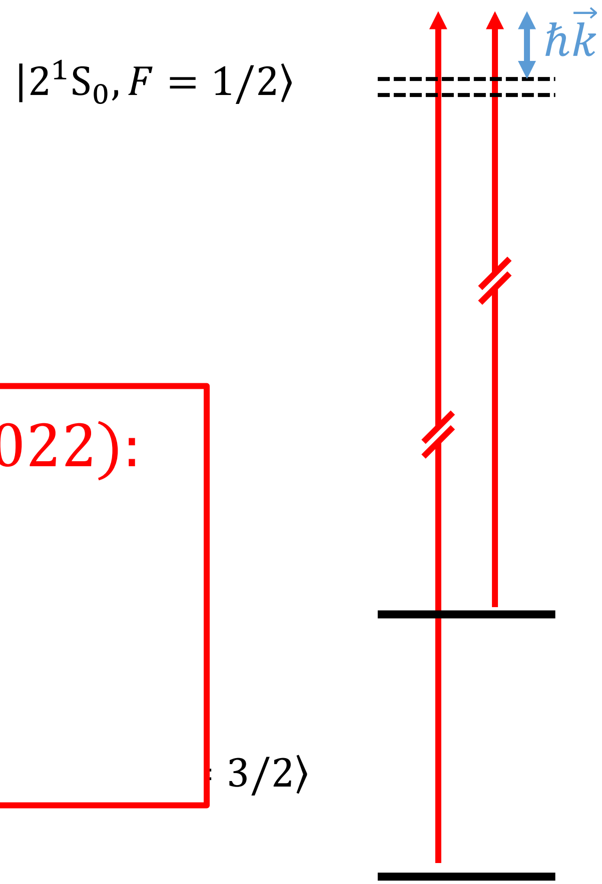




PRELIMINARY RESULT ^{3}He $2^3S_1 \rightarrow 2^1S_0$ (2022):

$$\boldsymbol{f_0 = 192\,504\,914\,418.96(17)\ \mathrm{kHz}}$$

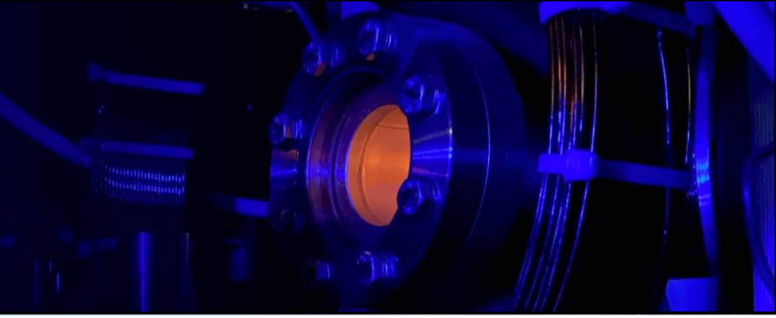
$$\boldsymbol{\lambda_m = 319.830\,80(15)\ \mathrm{nm}}$$

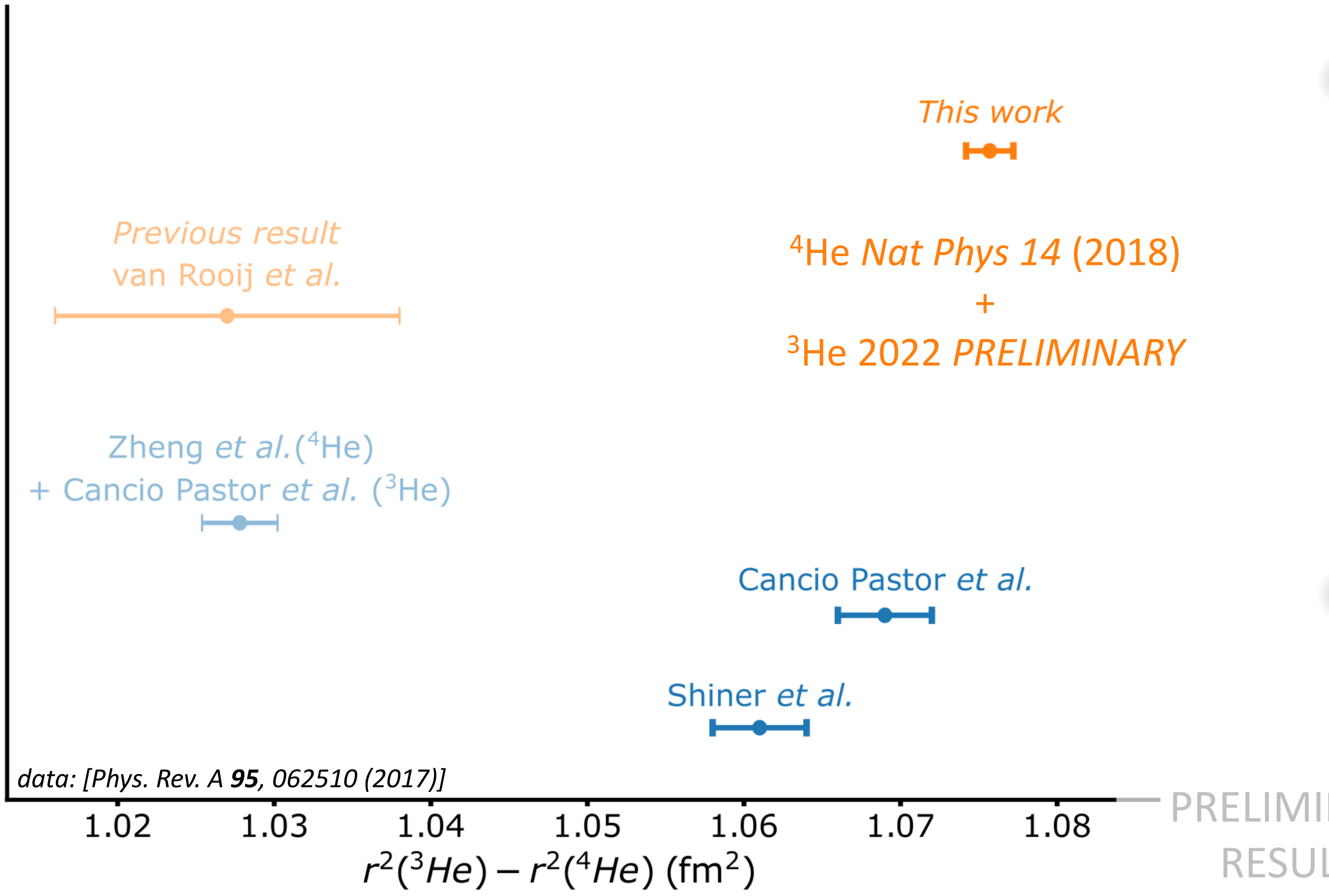


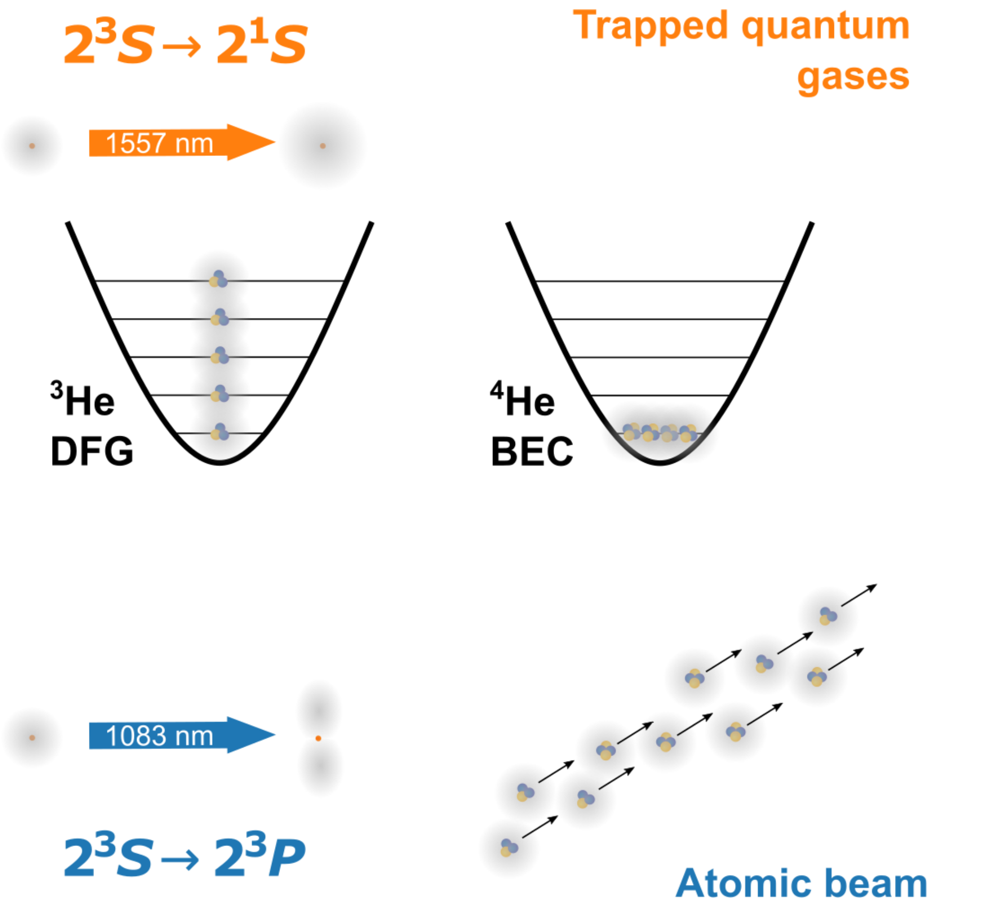
LaserLaB AMSTERDAM

VU

Nuclear Charge Radius Difference





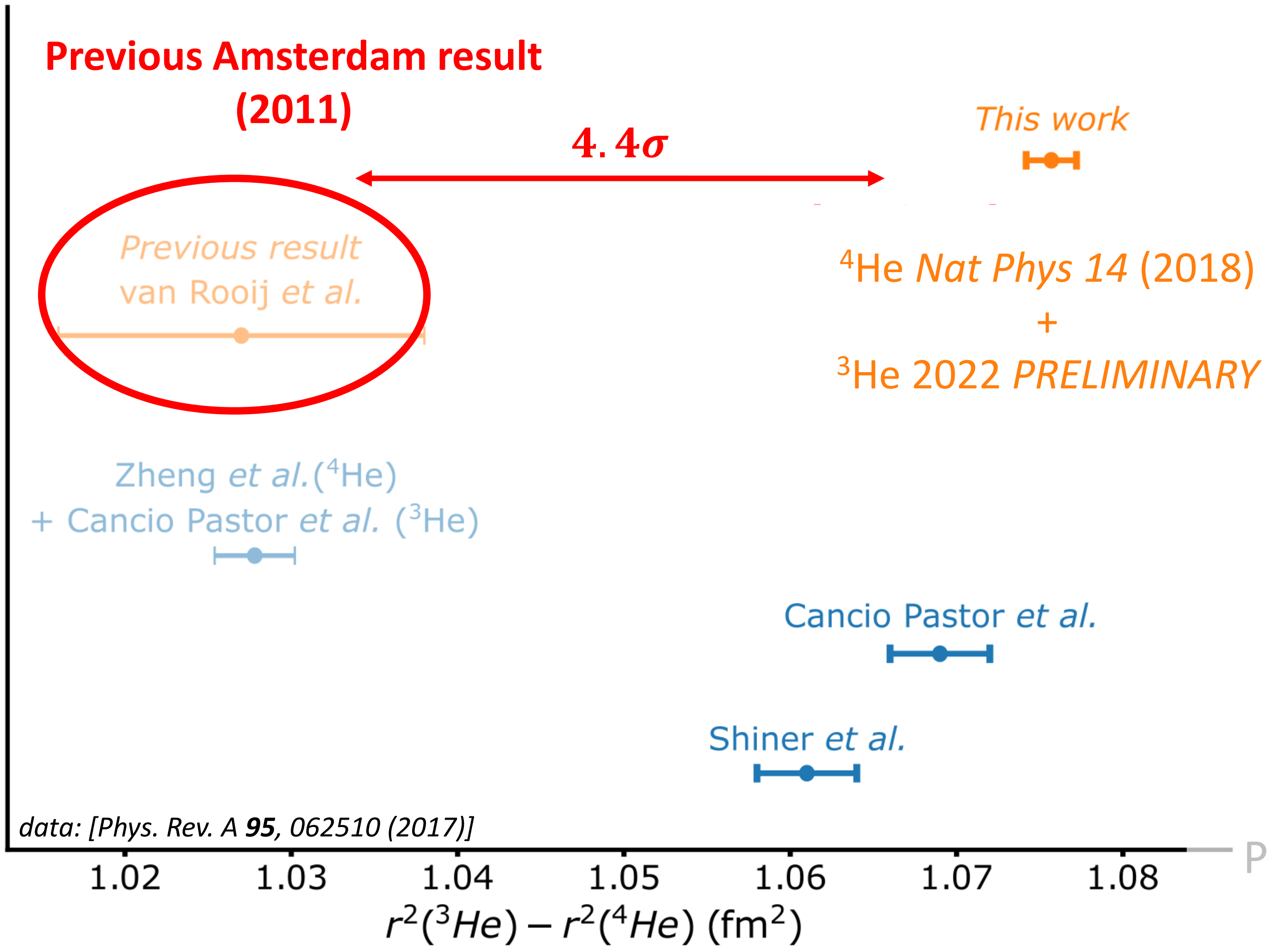


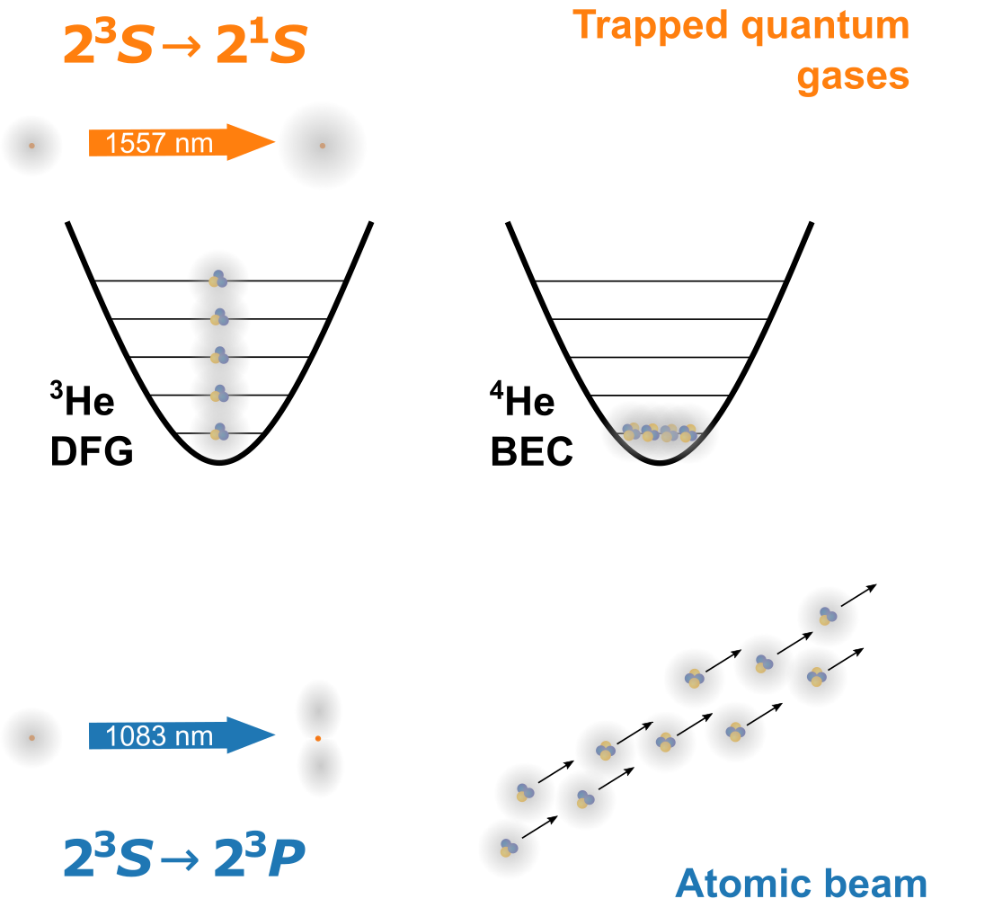
PRELIMINARY RESULTS

LaserLaB AMSTERDAM

VU

Nuclear Charge Radius Difference



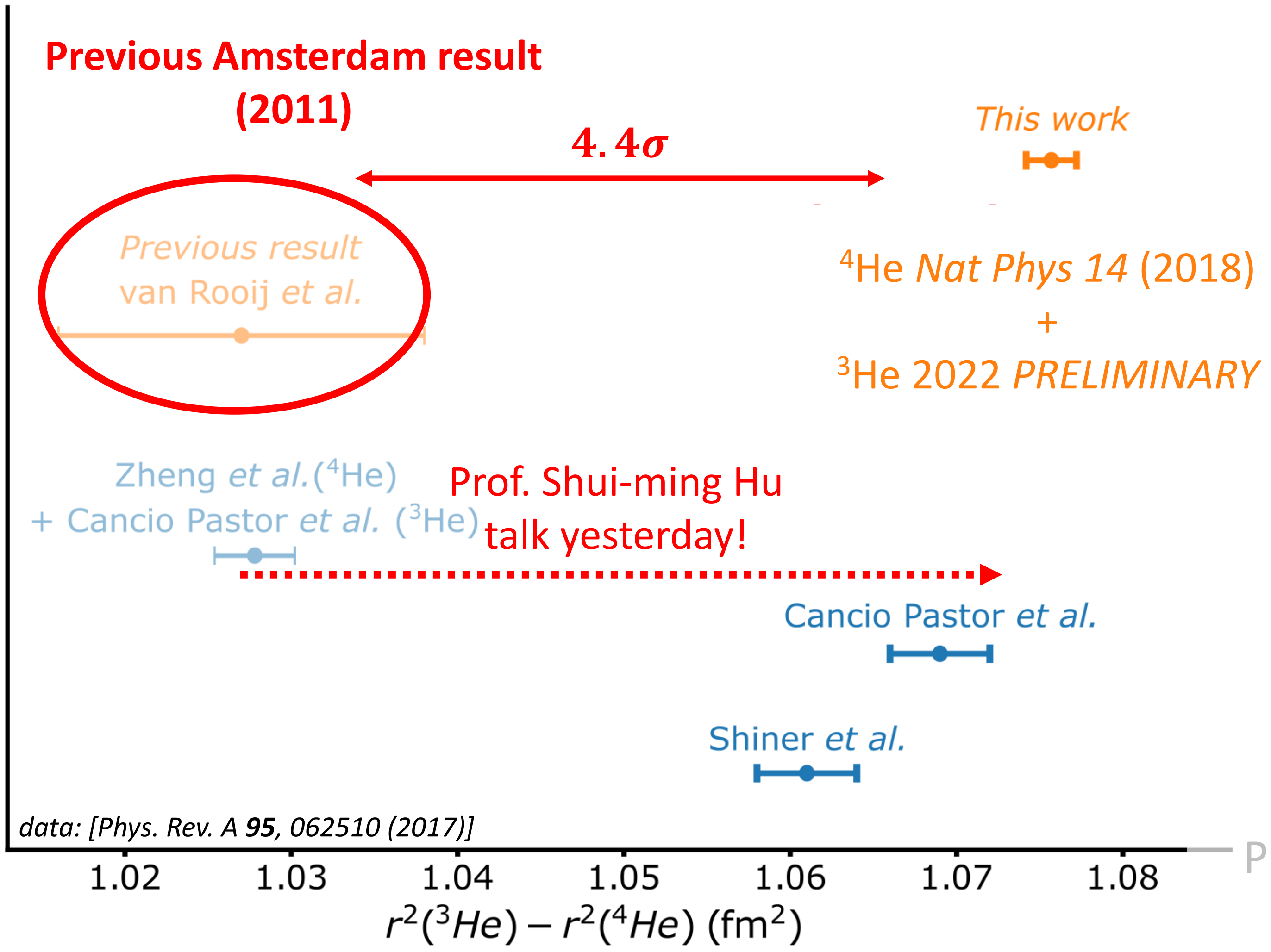


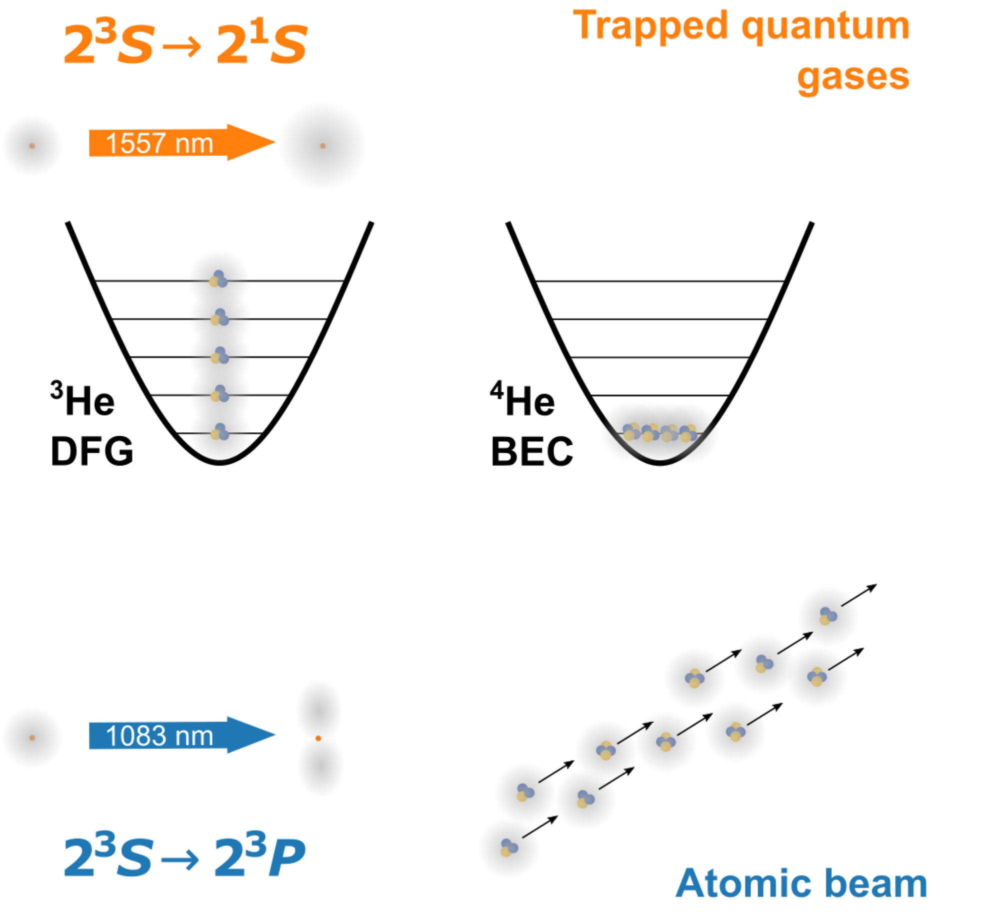
PRELIMINARY RESULTS

LaserLaB AMSTERDAM

VU

Nuclear Charge Radius Difference



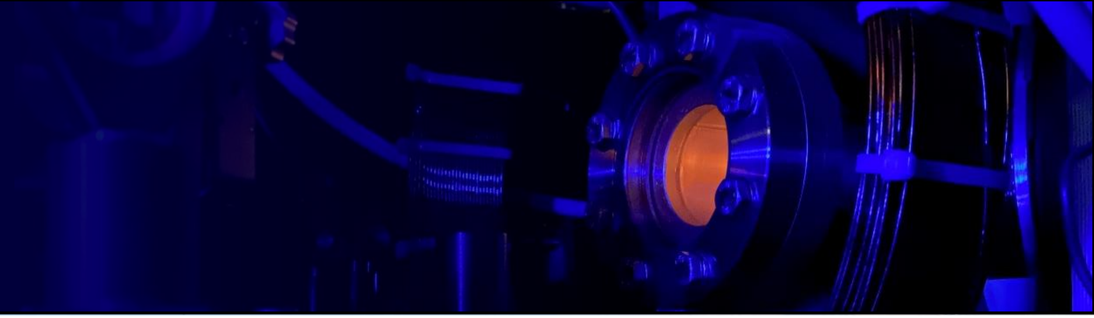


PRELIMINARY RESULTS

LaserLaB AMSTERDAM

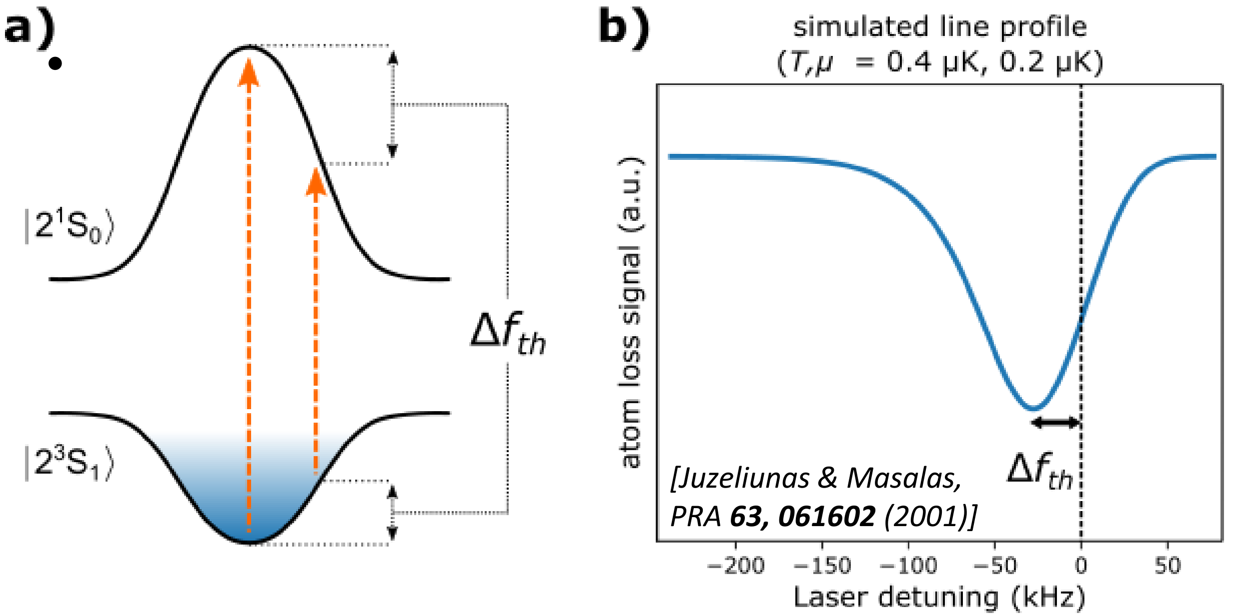
VU

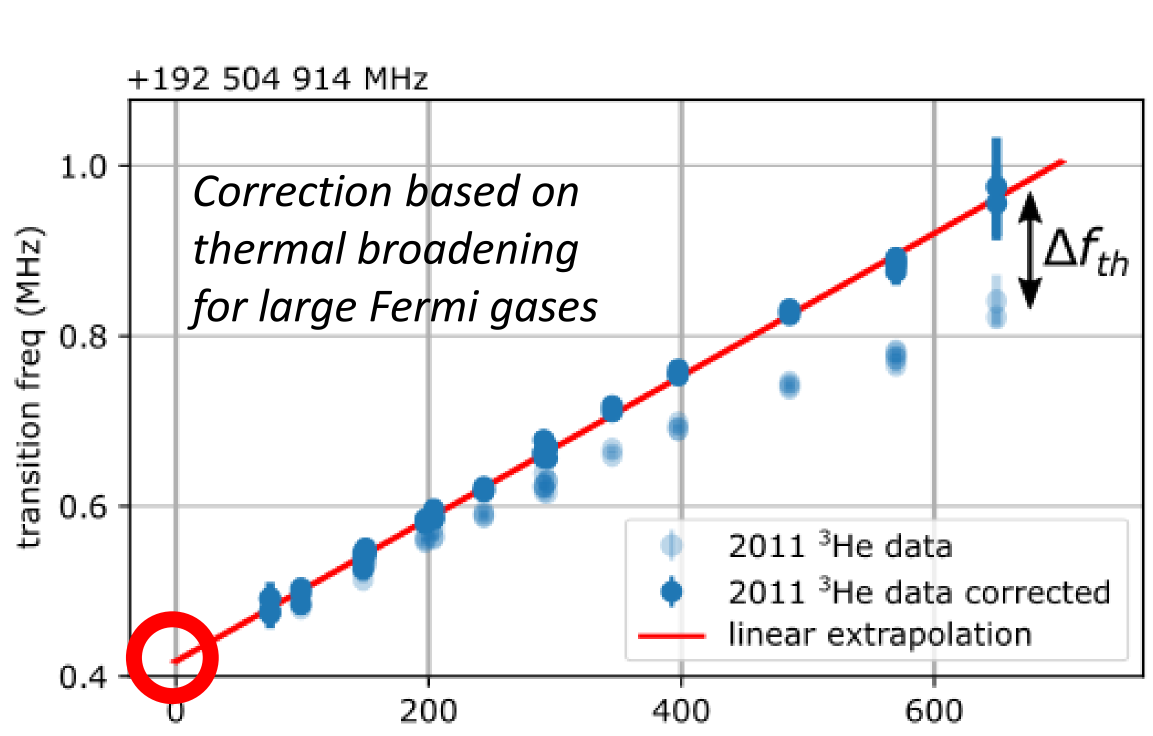
7 kHz (4.4 σ) deviation?



Previous Result: non-magic wavelength

- Fermi-Dirac: AC Stark shift asymmetry
- Not resolved within laser bandwidth
- **New setup:**
  - magic wavelength: *no AC Stark from trap*
  - improved laser lock: *resolve quantum effects*





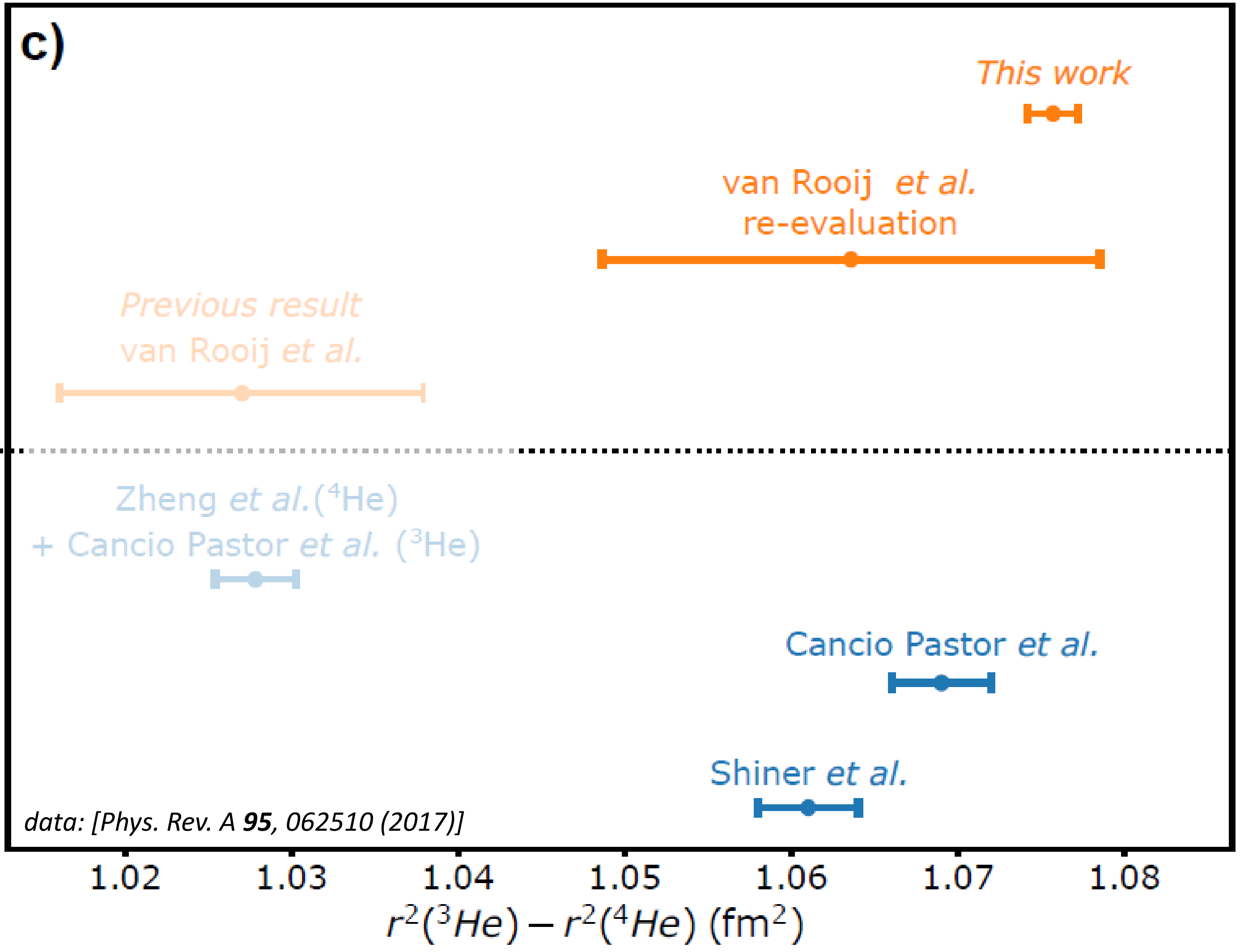
192 504 914 417.2(2.0) kHz

PRELIMINARY RESULTS

LaserLaB AMSTERDAM

VU

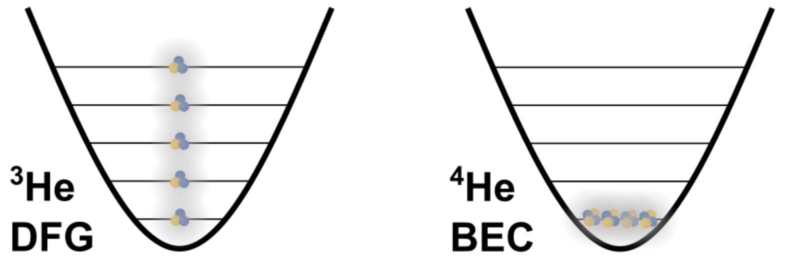
Nuclear Charge Radius Difference



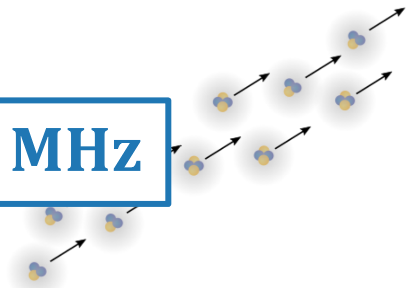
$2^3S \rightarrow 2^1S$

Trapped quantum gases

$$\sigma_{exp} > \Gamma = 8\ \mathrm{Hz}$$



$$\sigma_{exp} \ll \Gamma = 1.6\ \mathrm{MHz}$$



$2^3S \rightarrow 2^3P$

Atomic beam

PRELIMINARY RESULTS

LaserLaB AMSTERDAM

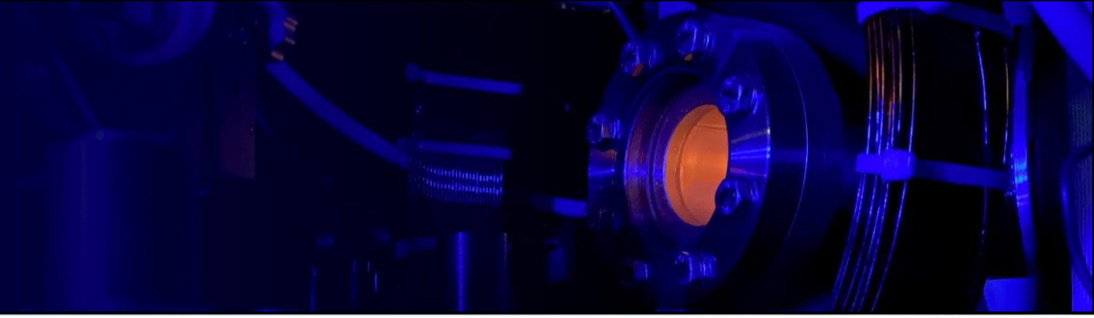
VU

Electrons vs. Muons

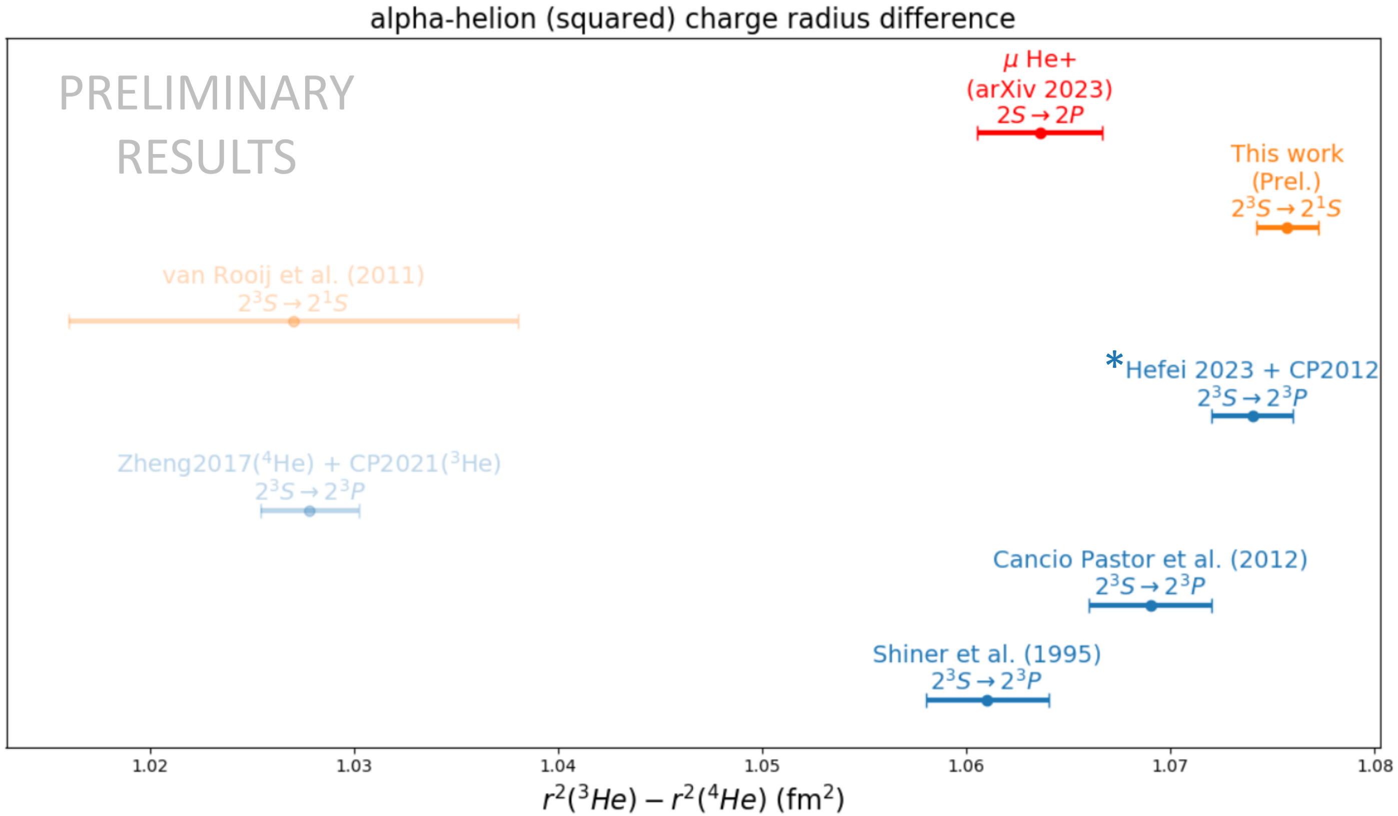
- He nuclear charge radii from $\mu\mathrm{He}^{+}$ spectroscopy
  - ^{4}He: $1.67824(83)$ fm *[Krauth et al. Nature* ***589****, p. 527–531 (2021)]*
  - **Fresh off the press:** ^{3}He $1.97007(94)$ fm https://arxiv.org/abs/2305.11679

LaserLaB AMSTERDAM VU

Electrons vs. Muons



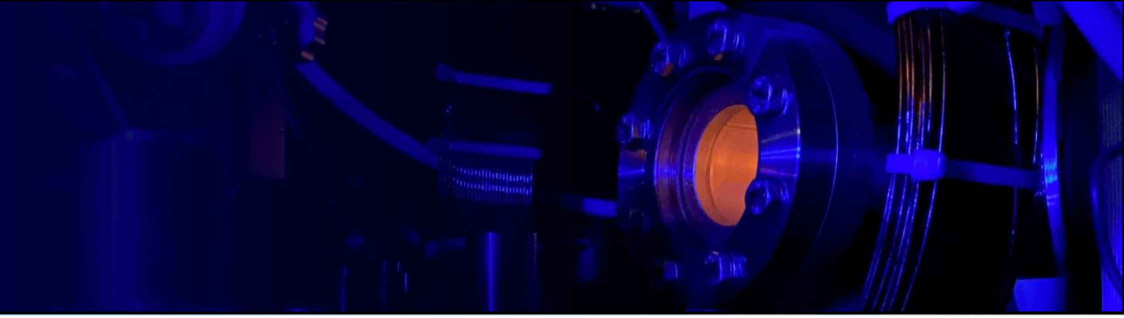
- He nuclear charge radii from $\mu\mathrm{He}^+$ spectroscopy
  - ^{4}He: $1.67824(83)$ fm *[Krauth et al. Nature* ***589****, p. 527–531 (2021)]*
  - **Fresh off the press:** ^{3}He $1.97007(94)$ fm https://arxiv.org/abs/2305.11679

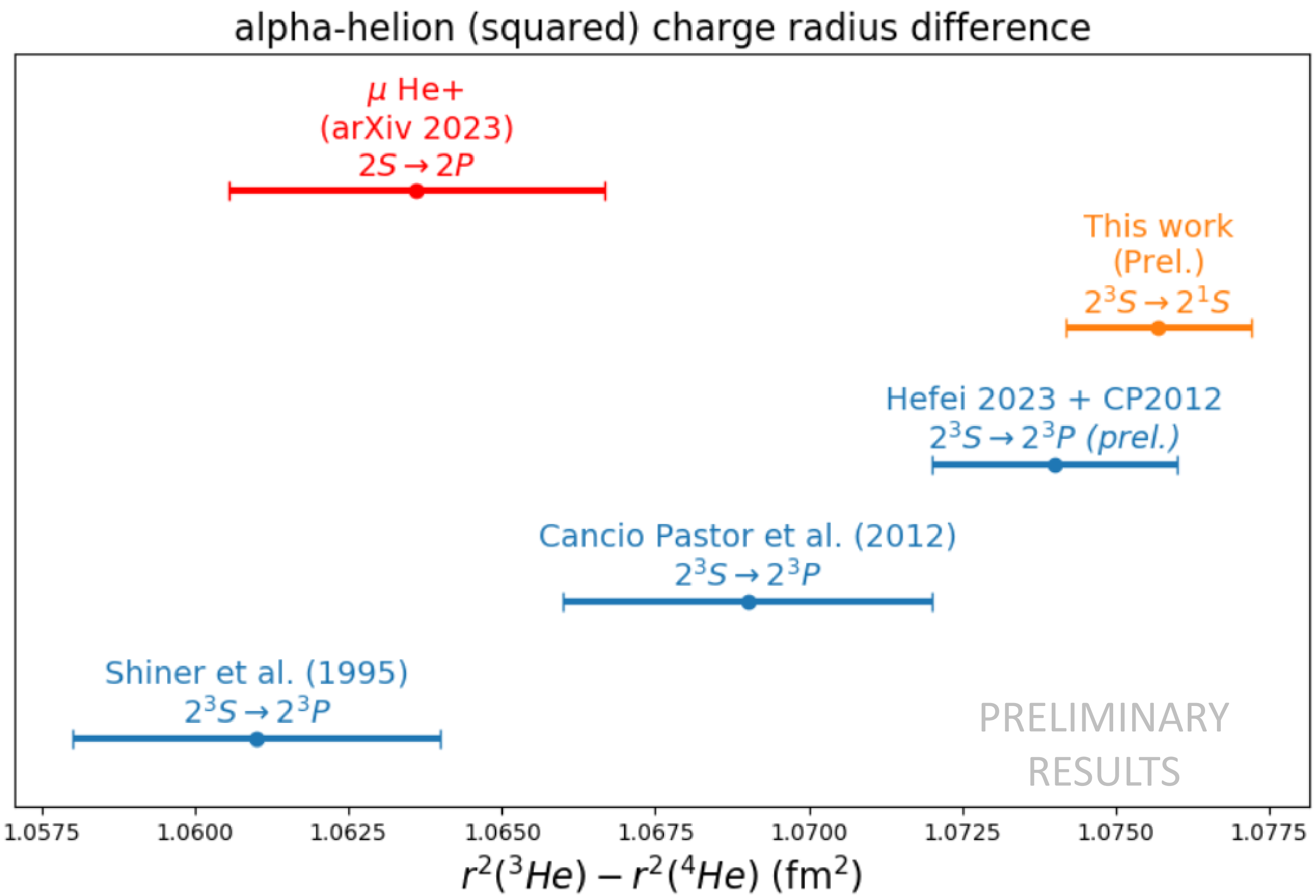


**Also fresh:*
Preliminary Hefei 2023

LaserLaB AMSTERDAM VU

Electrons vs. Muons



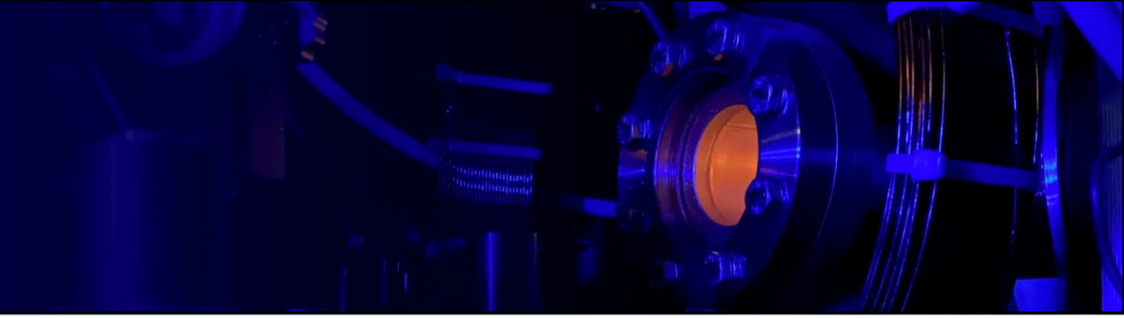


- 3.6σ from μHe^{+}
- $2\sigma - 4\sigma$ from $2^3S \rightarrow 2^3P$
- Hefei ^3He?
- 1.9 kHz shift for 1σ agreement with muonic
- Discrepancies:
  - *New physics? Well………………*
  - Very different systematics
  - Theory: triplet vs. singlet
  - Muonic: higher-order QED

LaserLaB AMSTERDAM

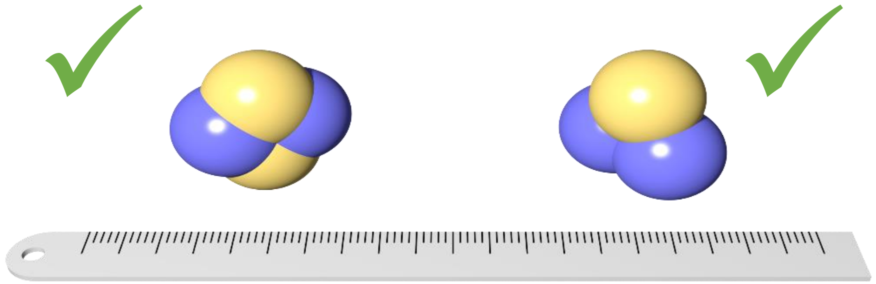
VU

In conclusion



- Fundamental physics with ultracold helium:
  - Precision spectroscopy: narrow transition
  - Nuclear charge radii → most accurate $r_3^2 - r_4^2$
  - QED benchmark
  - Comparison with other works, exciting times:

    Other spectroscopy, *scattering*, ***muonic systems***



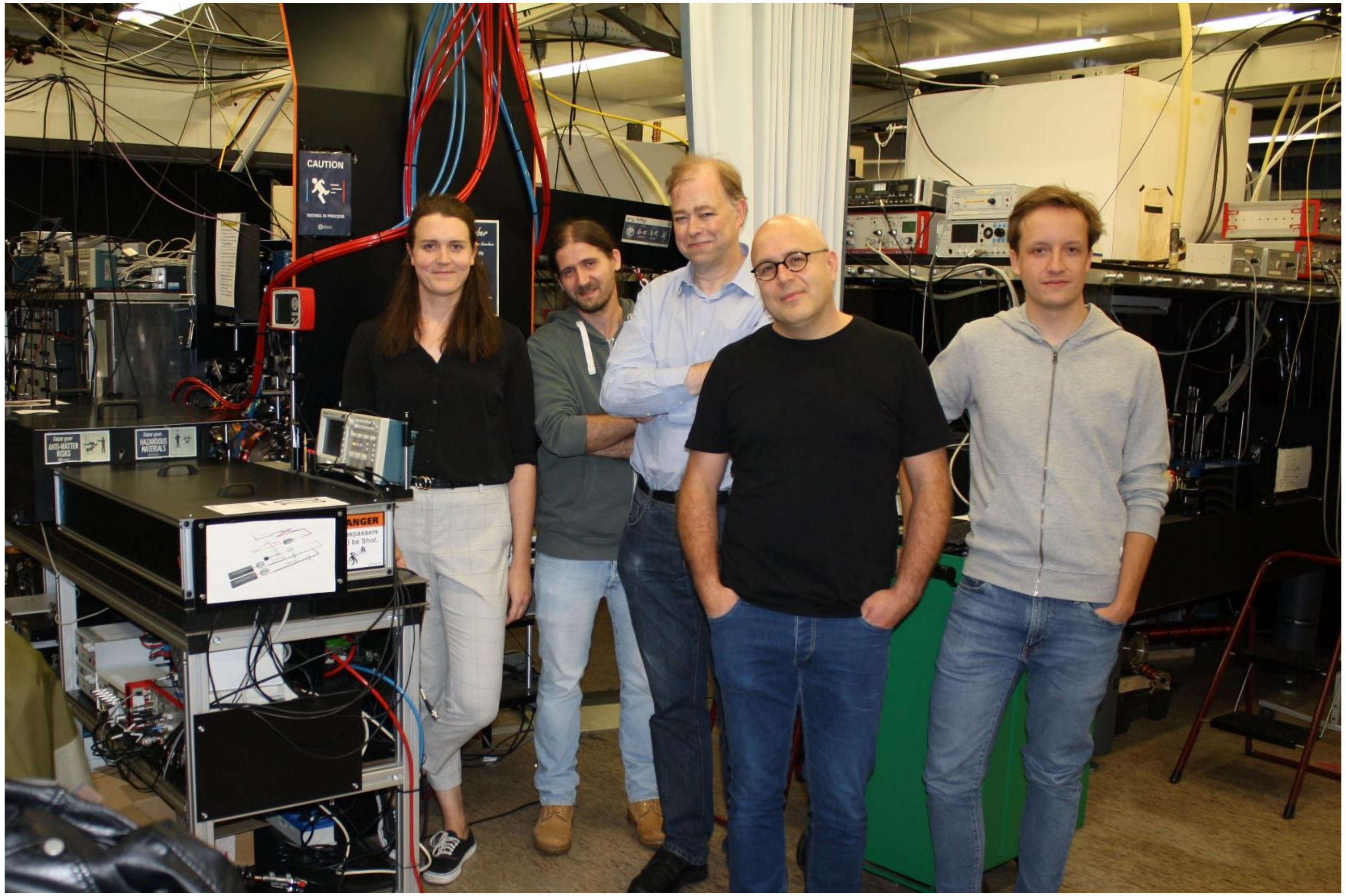
- More than just the transition frequency:
  - magic wavelengths: benchmarks for QED
  - ^{4}He BEC: insight into collisions, mean-field shift, scattering length a_{ts}
  - ^{3}He Fermi gas: Observation of unexpected Pauli Blockade effects

- Higher precision? $\Gamma = 8\ \mathrm{Hz}$ (experimentally challenging)
- Other measurements in helium?

LaserLaB AMSTERDAM

VU

Thanks for your attention!



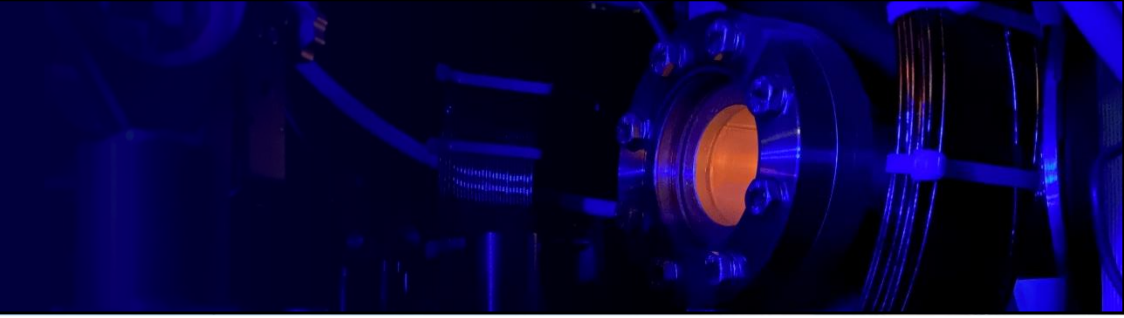
He* team:
- Raphael Jannin
- Kees Steinebach
- Yuri van der Werf
- Rick Bethlem
- Kjeld Eikema
- Bob Rengelink

Technical support:
- Rob Kortekaas
- Lex van der Gracht

Funding & facilities:

Wim Vassen:
† *11-2-2019*

Thanks for your attention!



Questions?

Email: y.vander.werf@vu.nl

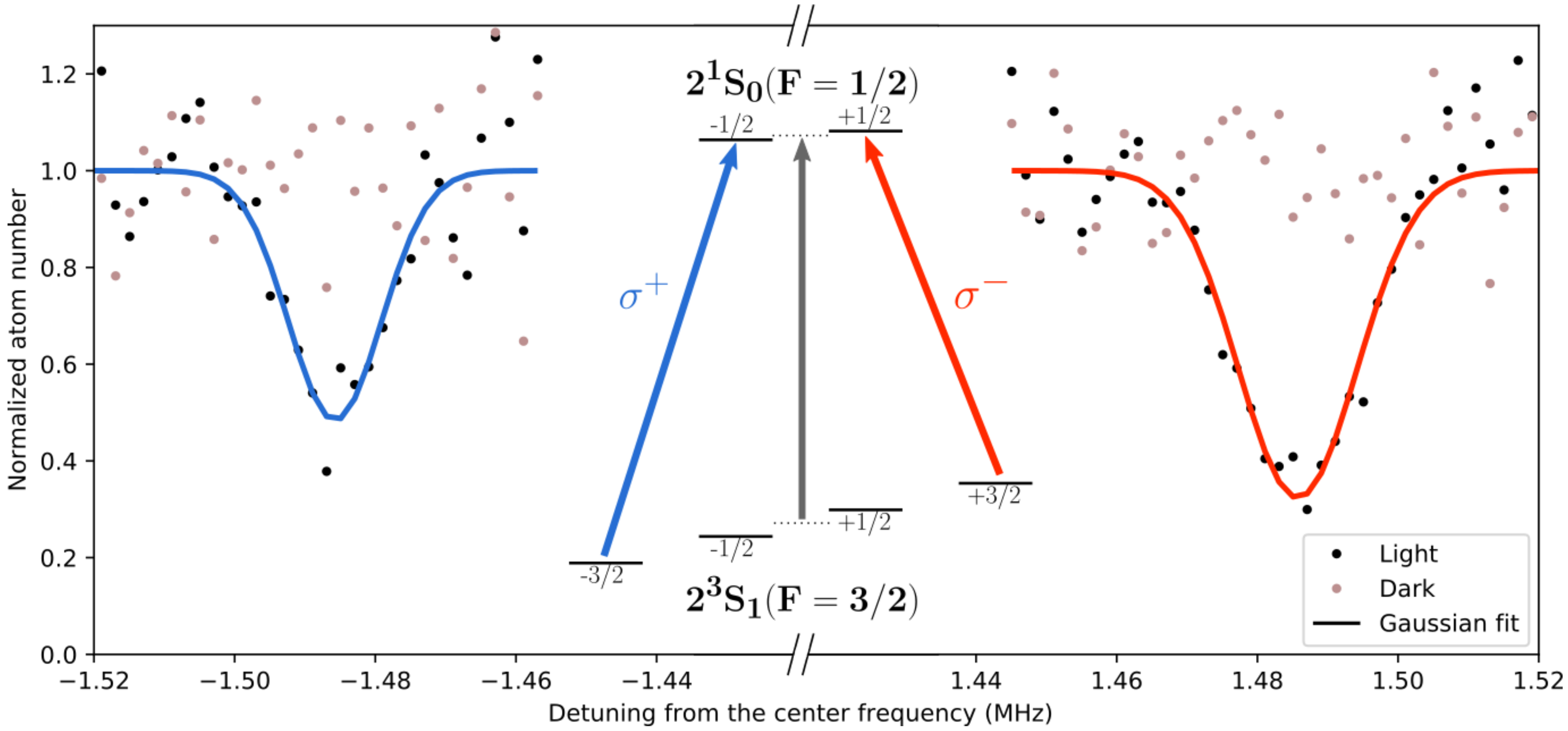
NWO

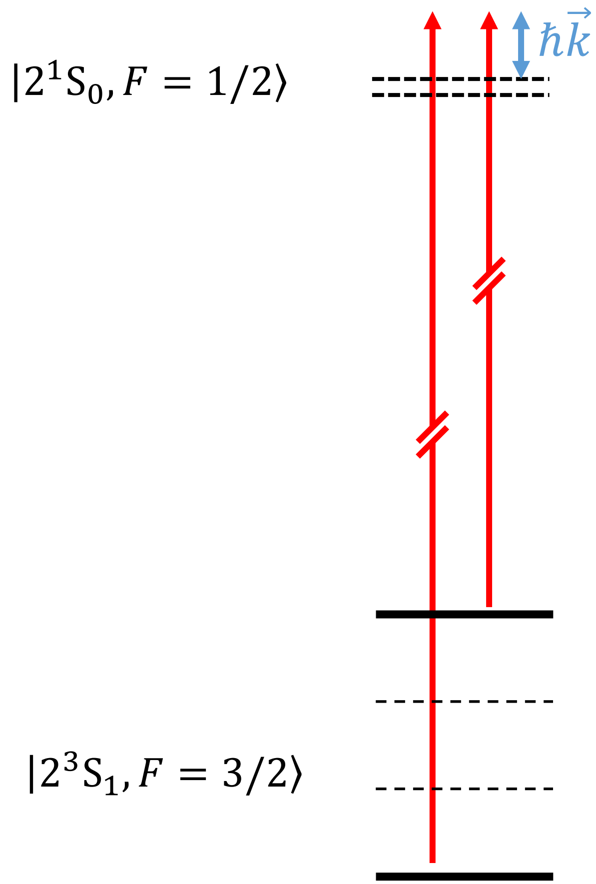
LaserLaB AMSTERDAM

VU

Precision spectroscopy

- Systematics analysis: **Zeeman shift**



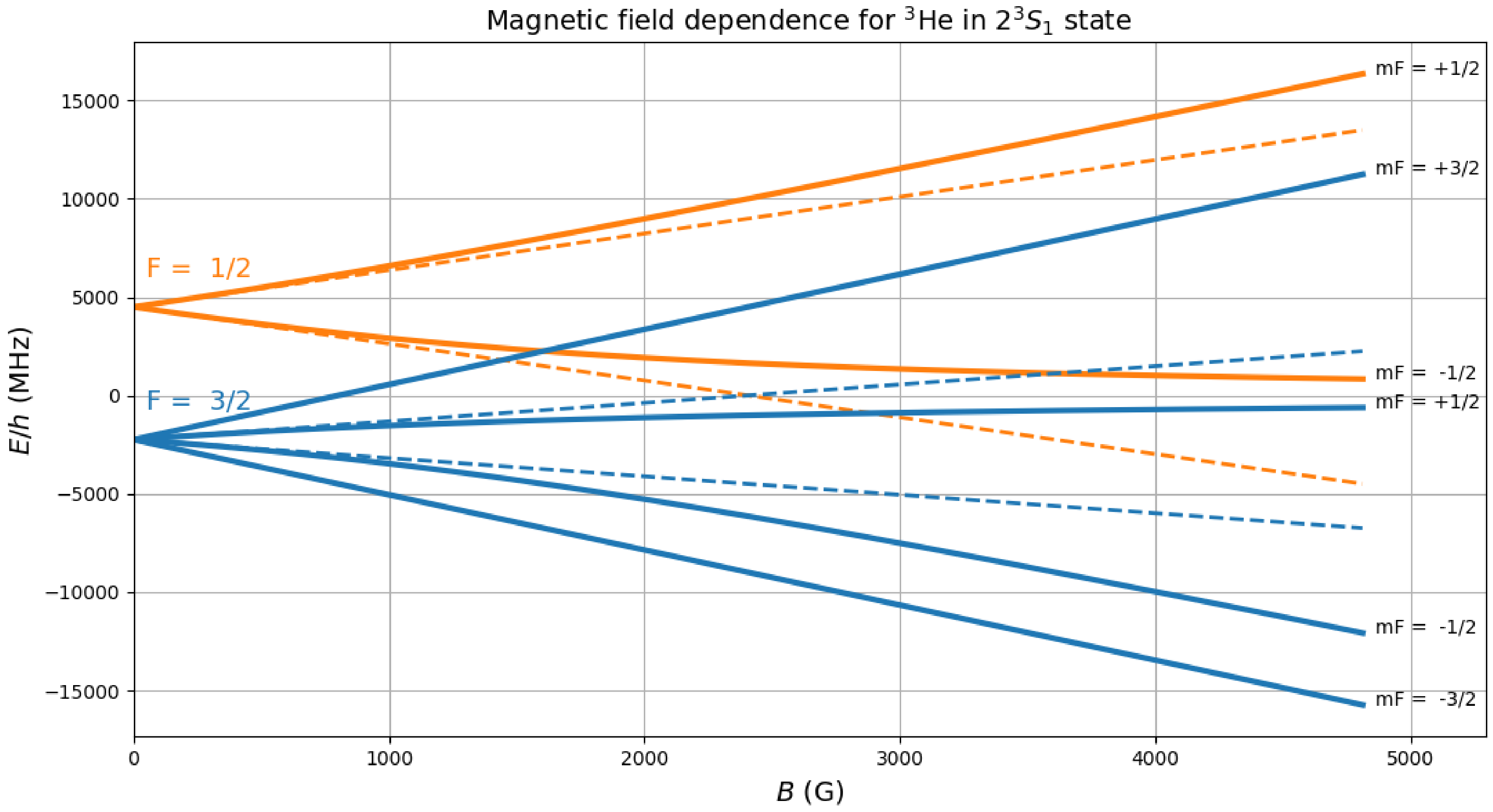


LaserLaB AMSTERDAM

VU

Systematic analysis

- 2nd order Zeeman shift:



Using the Breit-Rabi formula with $J \leftrightarrow I$

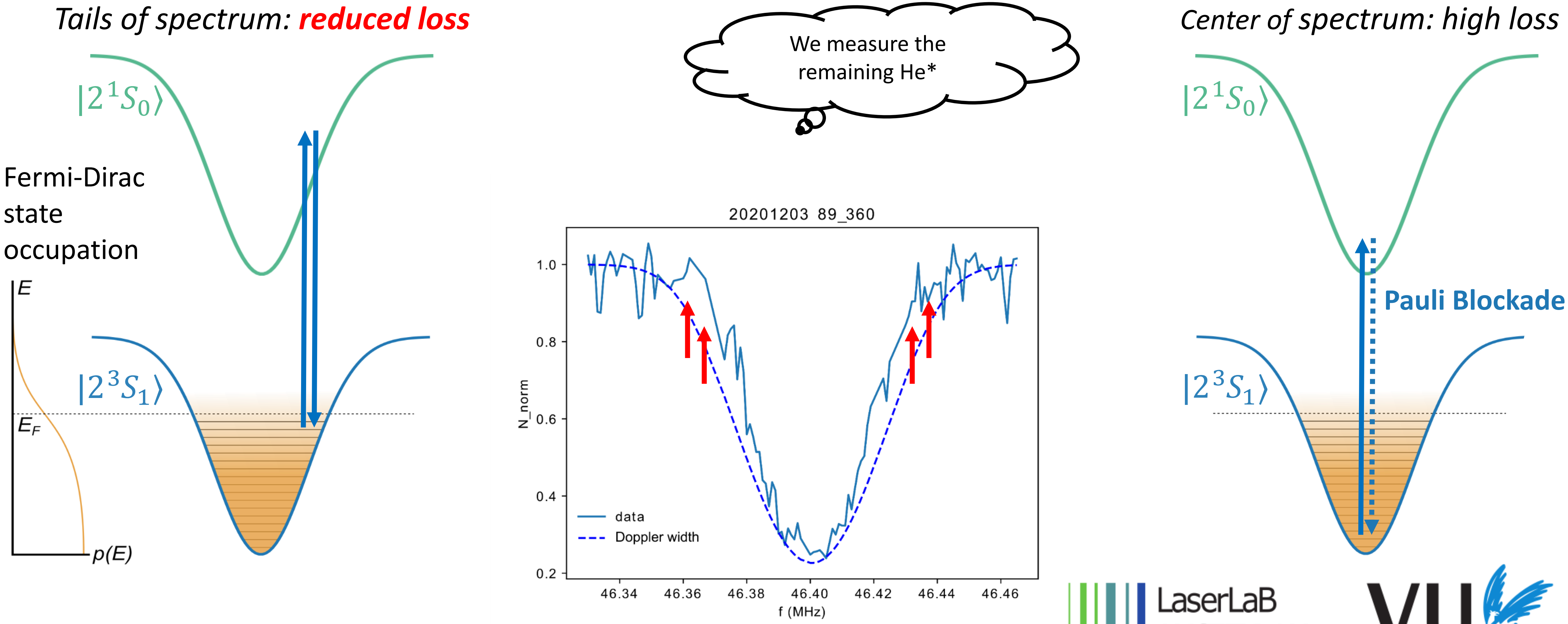
No coupling to $F = 1/2$ from spin-stretched $m_F = \pm 3/2$

2nd order Zeeman from coupling to 2^3P_J, same as ^{4}He: $< 4\ \mathrm{mHz/G^2}$

LaserLaB AMSTERDAM

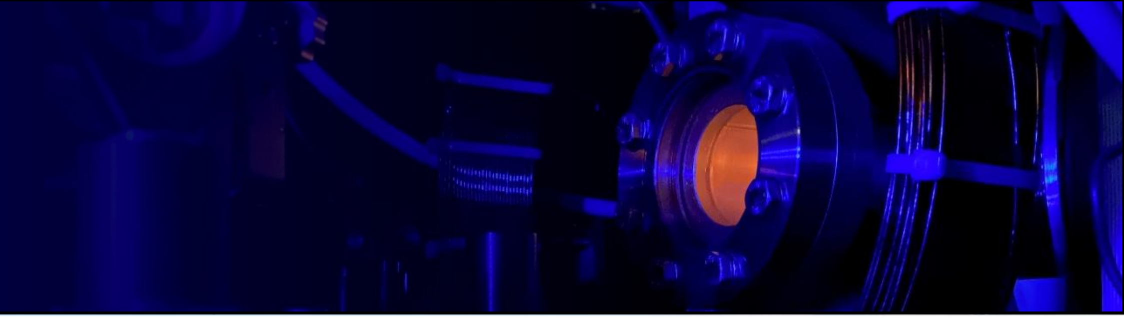
VU

Reduced linewidth



LaserLaB AMSTERDAM
VU

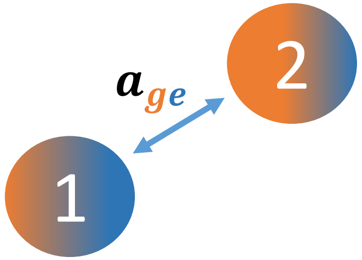
Systematic analysis



- Cold collision shift?

  IDENTICAL cold* fermions don't collide

$$|g_1\rangle \rightarrow \alpha_1 |\boldsymbol{g_1}\rangle + \beta_1 |\boldsymbol{e_1}\rangle$$
$$|g_2\rangle \rightarrow \alpha_2 |\boldsymbol{g_2}\rangle + \beta_2 |\boldsymbol{e_2}\rangle$$



$$|S\rangle = \frac{(\alpha_1\beta_2 - \alpha_2\beta_1)}{\sqrt{2}} \cdot (\,|ge\rangle - |eg\rangle)$$

$$\langle S|S\rangle \equiv G_{ge}^{(2)}$$

$$\Delta_{mfs} = \frac{\hbar a_{ge}}{m} \rho_g(r) \cdot G_{ge}^{(2)} < 2\pi \times 1\ \mathrm{Hz}$$

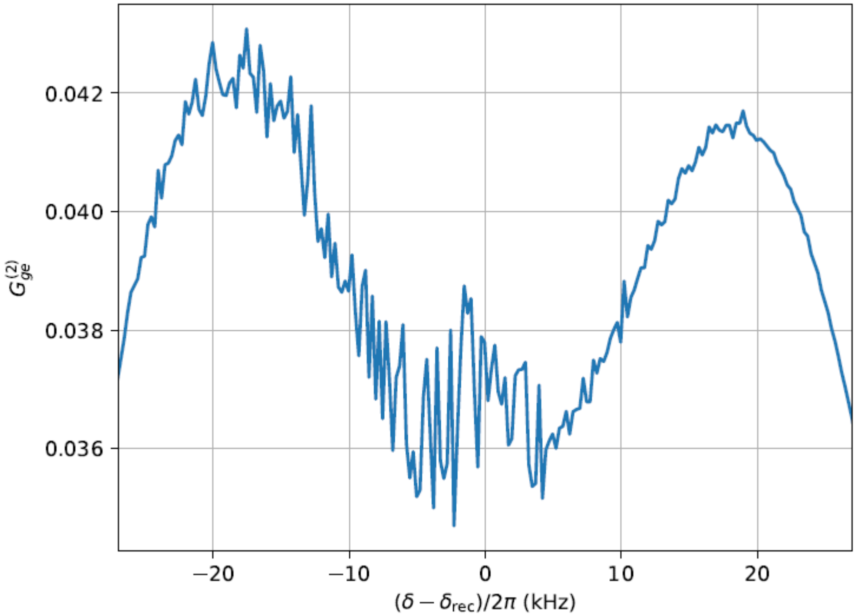


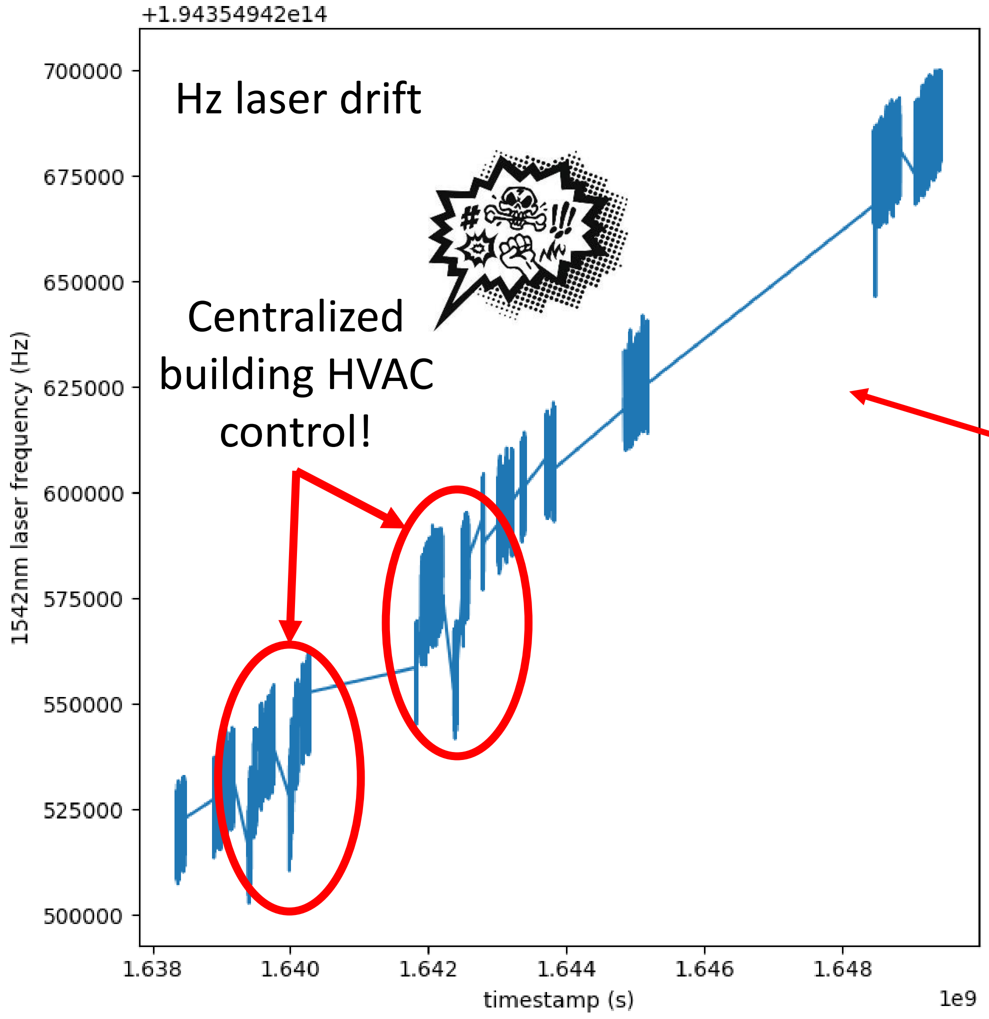
Figure 2: Time-averaged correlation as a function of the detuning of the spectroscopy laser.

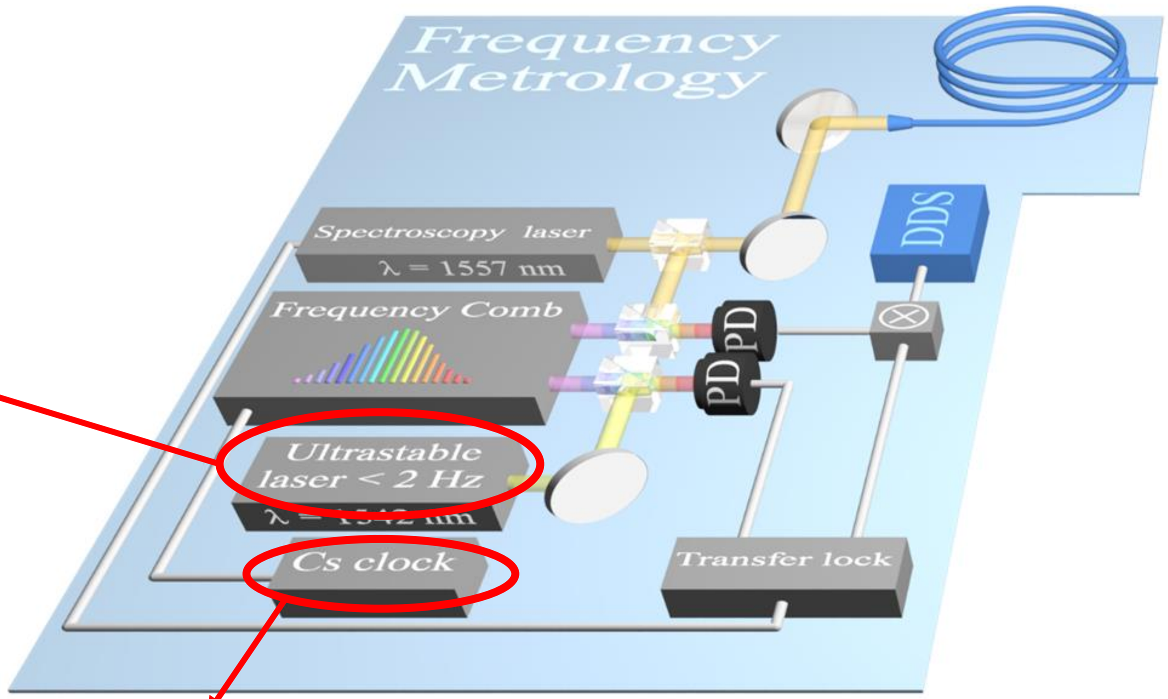
*p-wave frozen out $T < 500$ mK

LaserLaB AMSTERDAM

VU

Frequency metrology



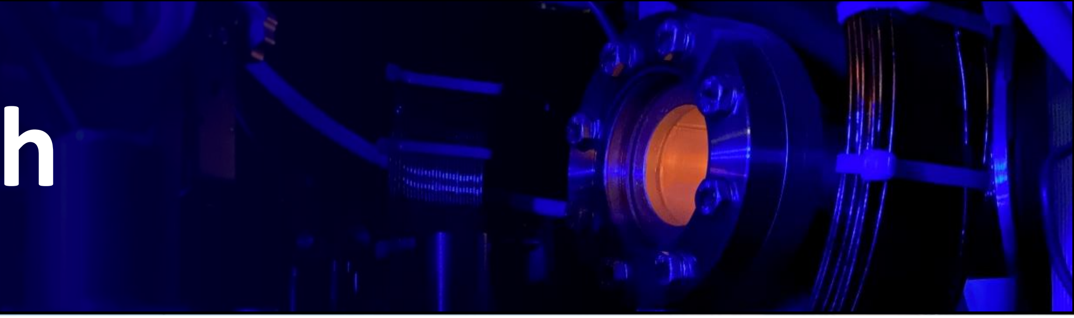


Correction to the *real* SI second:
local Cs clock deviation from GPS
$\Delta f = 55$ Hz

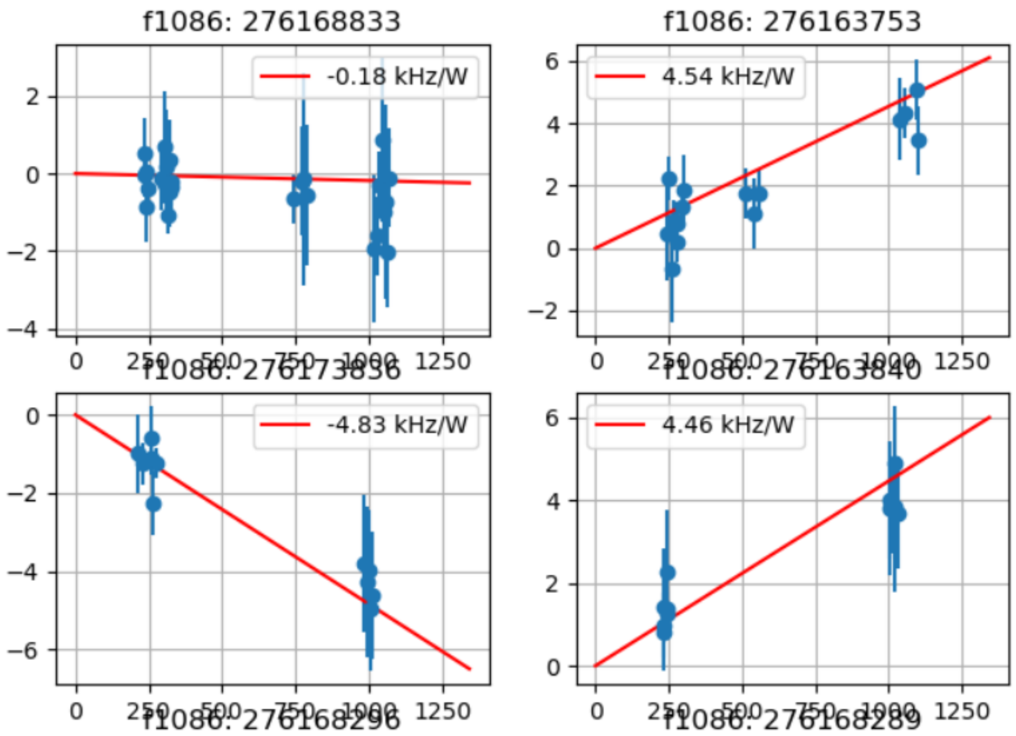
LaserLaB AMSTERDAM

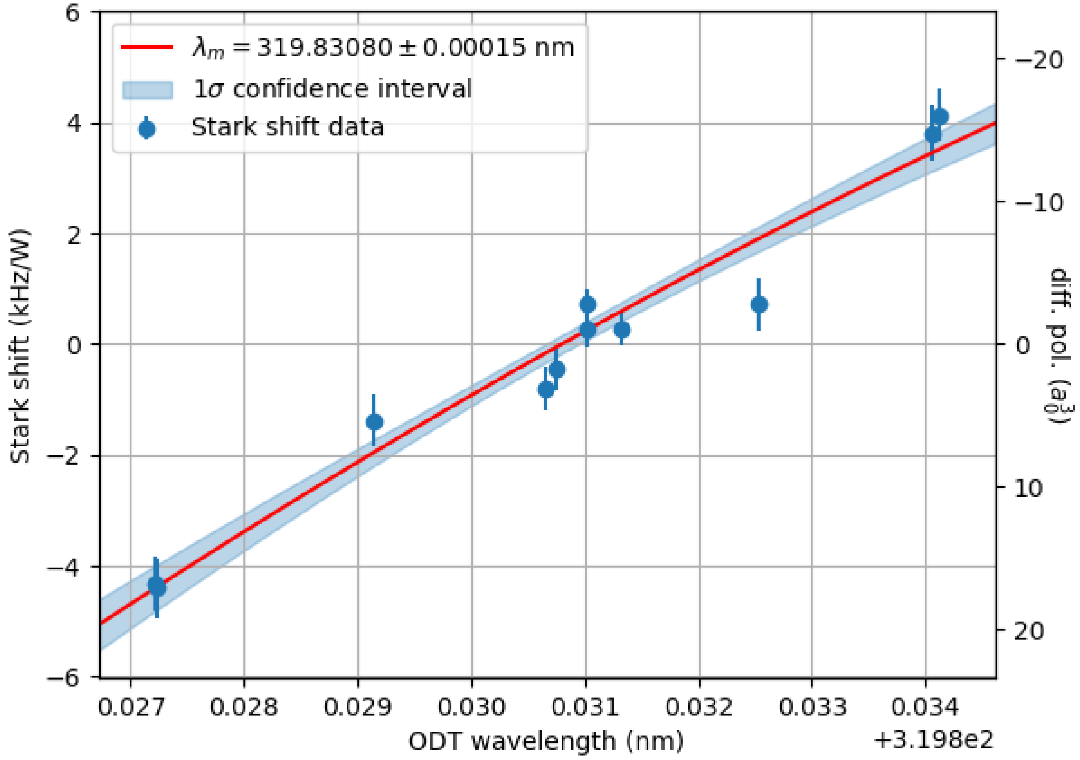
VU

Finding the magic wavelength



- Measurements at different wavelengths
- Measure strength of the a.c. Stark shift

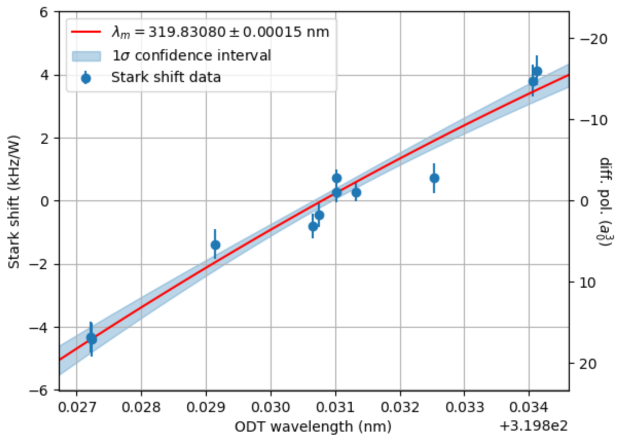




LaserLaB AMSTERDAM

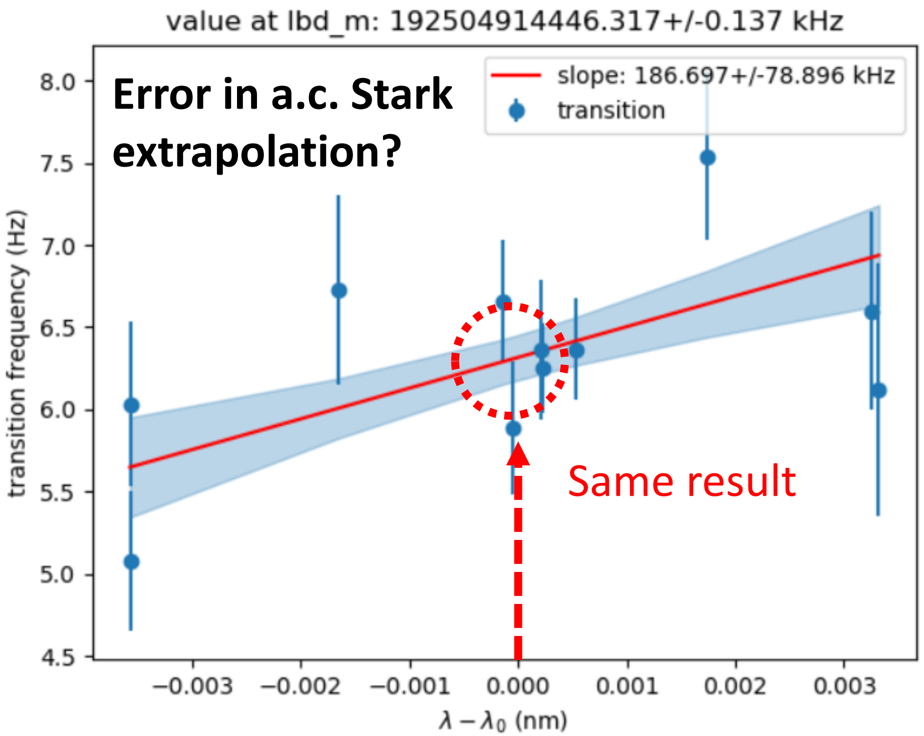
VU

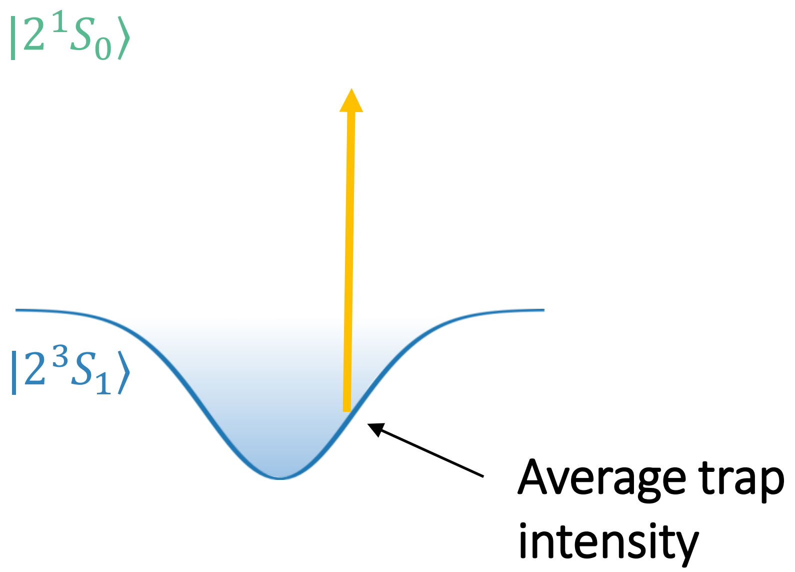
Thermodynamic shift: @320nm



$\langle I_{320} \rangle = \Delta f_{Stark}/\alpha \approx 5.5 \times 10^7\ \mathrm{Wm^{-2}}$ *

$I_{peak} \approx 10^8\ \mathrm{Wm^{-2}}$



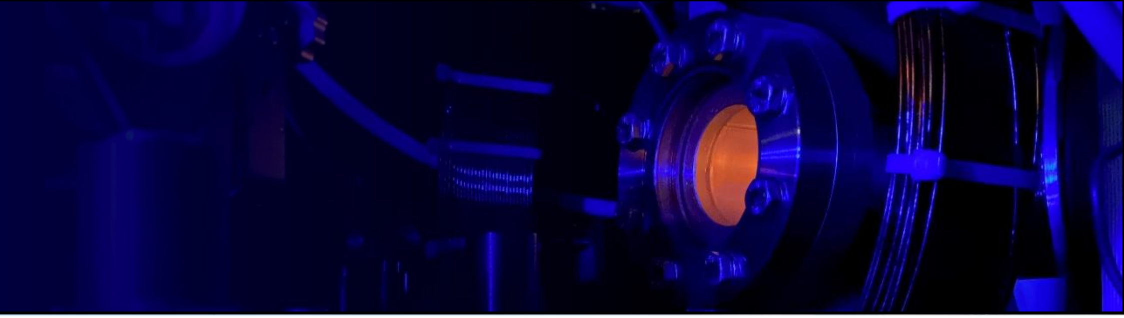


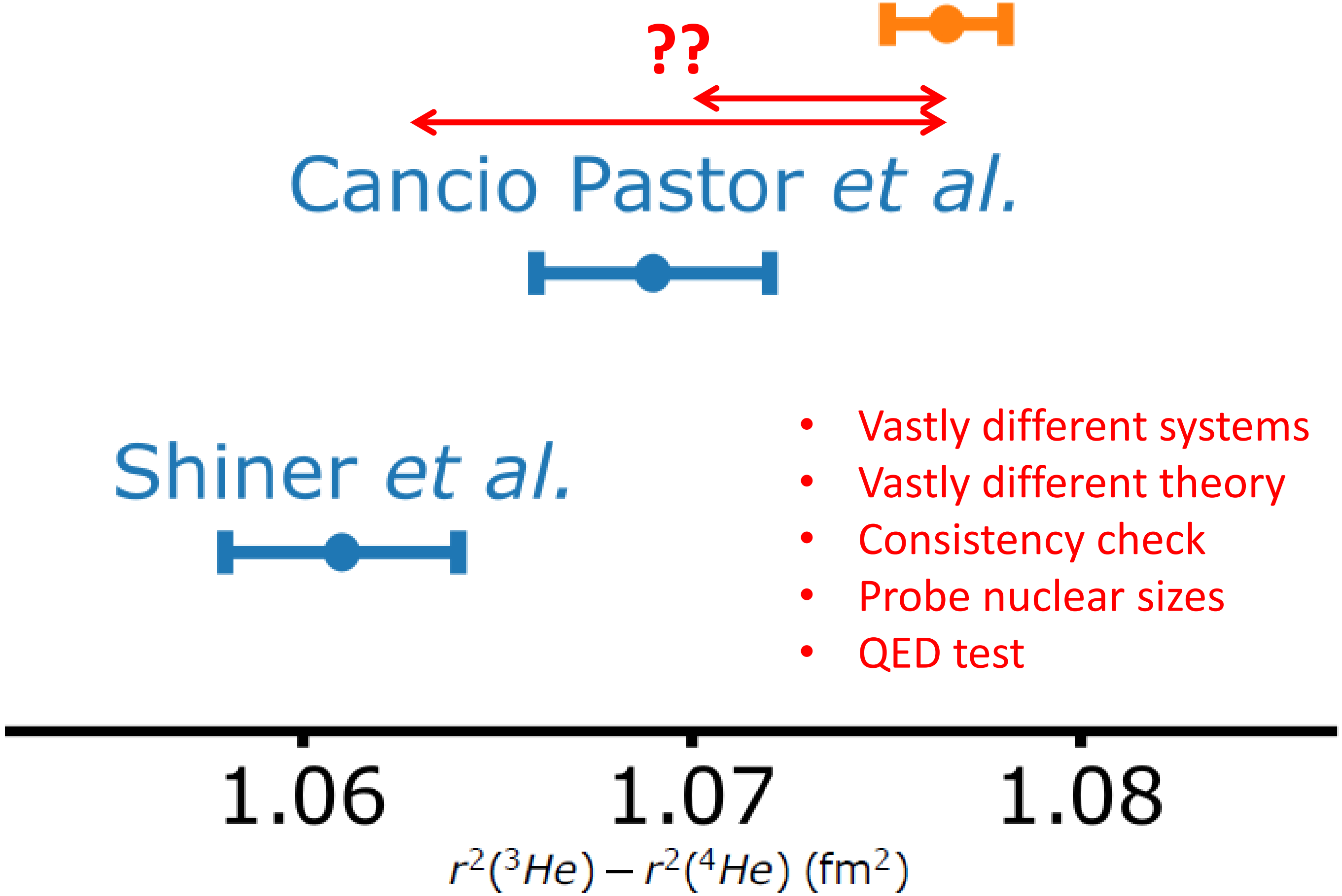
LaserLaB AMSTERDAM

VU

* @ 1W UV power

Electrons vs Muons?



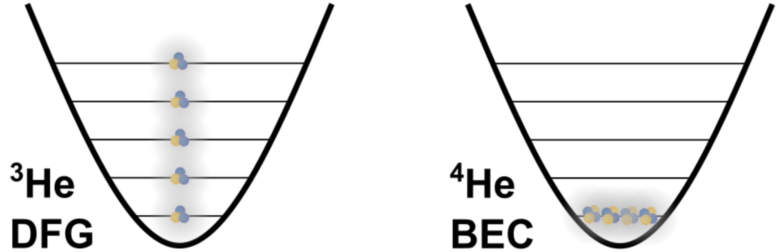


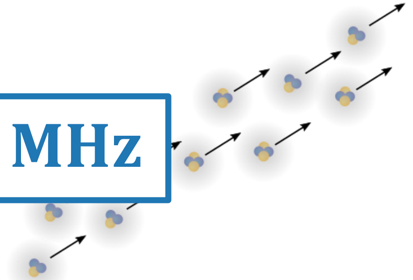
- Vastly different systems
- Vastly different theory
- Consistency check
- Probe nuclear sizes
- QED test

$2^3S \rightarrow 2^1S$

Trapped quantum gases

$$\sigma_{exp} > \Gamma = 8 \text{ Hz}$$





$$\sigma_{exp} \ll \Gamma = 1.6 \text{ MHz}$$

$2^3S \rightarrow 2^3P$

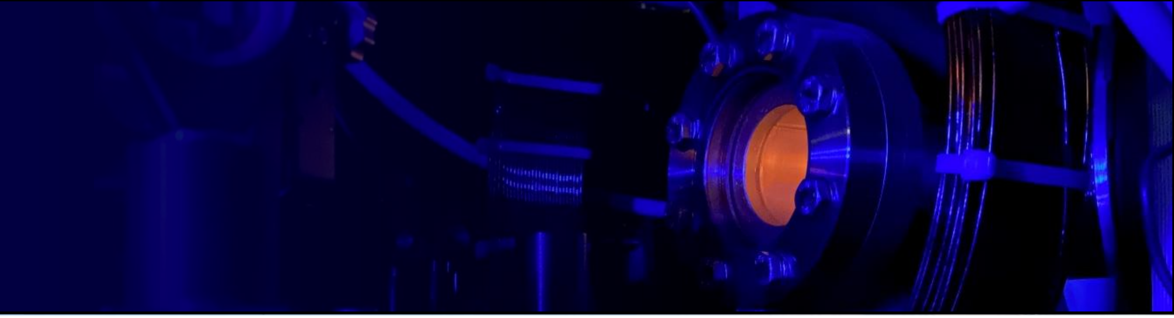
Atomic beam

PRELIMINARY RESULTS

LaserLaB AMSTERDAM

VU

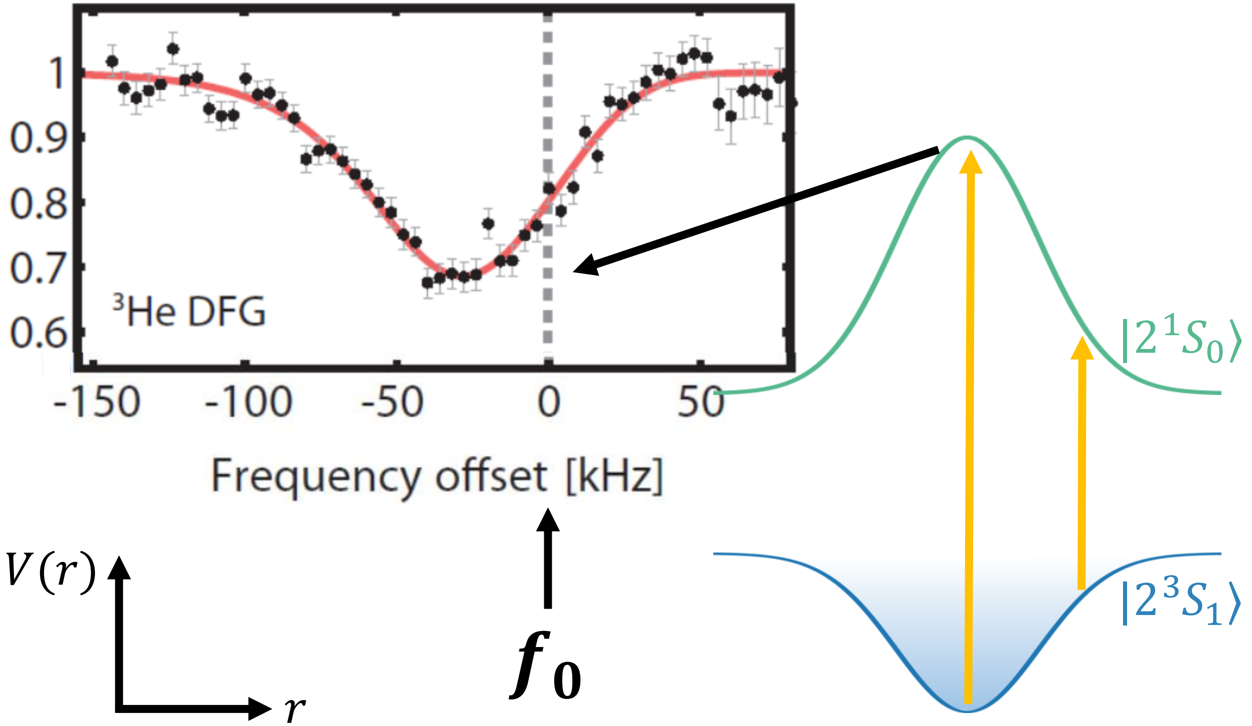
4.4 σ deviation?



2011 result:

1557 nm dipole trap + direct frequency comb lock

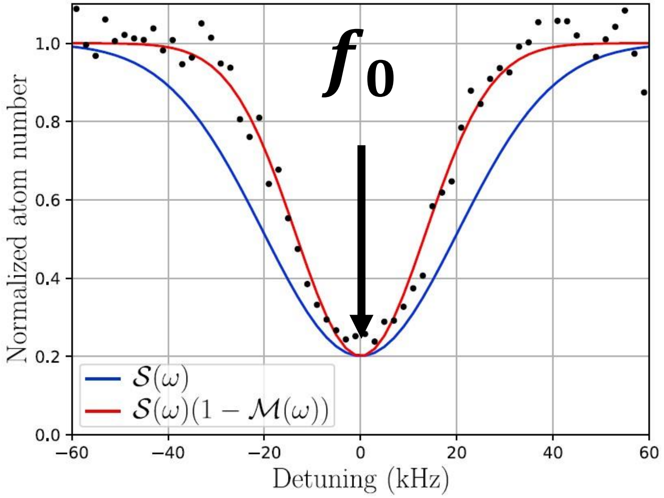
- Fermi-Dirac: AC Stark shift asymmetry
- Not resolved within laser bandwidth
- Verified now with new spectroscopy laser

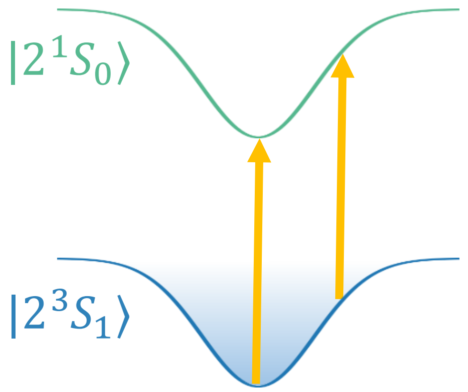


2022 result:

magic wavelength trap + ultrastable reference laser

- Fermi-Dirac: Doppler + Pauli blocking
- No trap AC Stark → Fully symmetric
- Quantum effects resolved *(2018: ^{4}He meanfield)*





PRELIMINARY RESULTS

LaserLaB AMSTERDAM

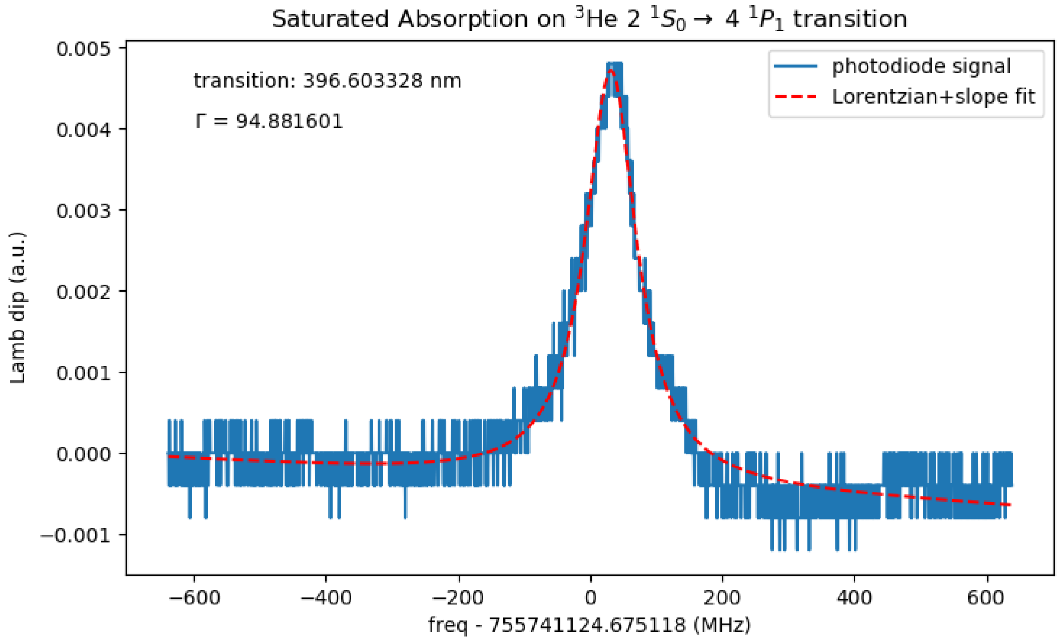
VU

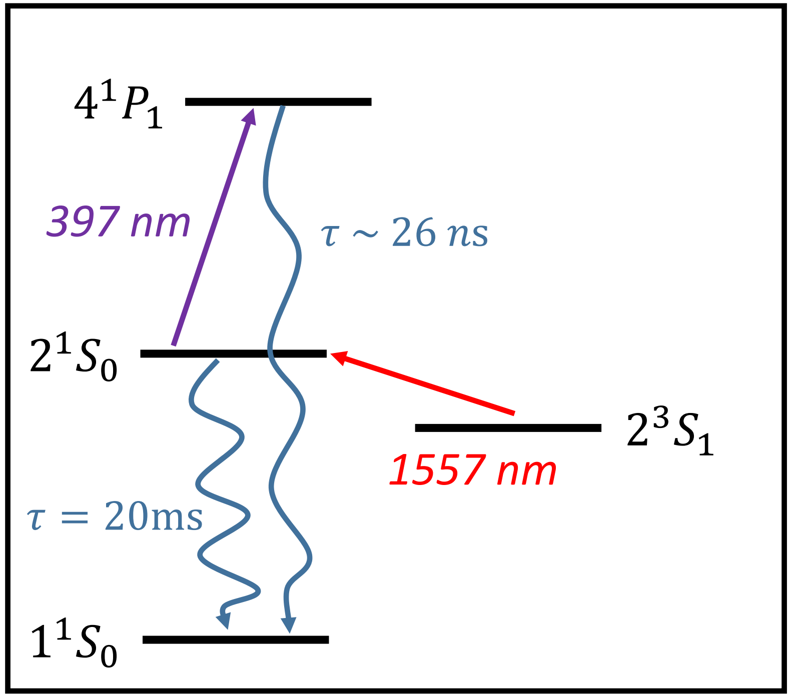
Testing the model

- Enhanced ground state decay through 4^1P_1 state

  Eliminate the stimulated emission channel

  Lift Pauli Blockade effect





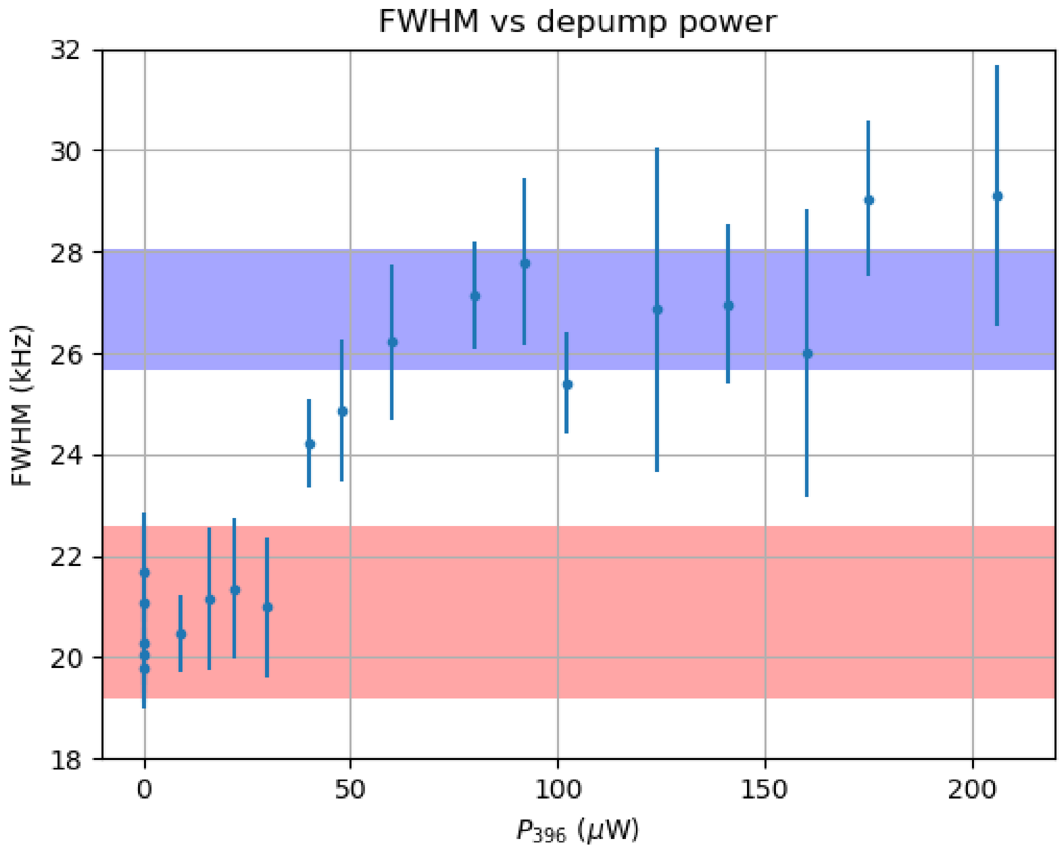
PRELIMINARY RESULT

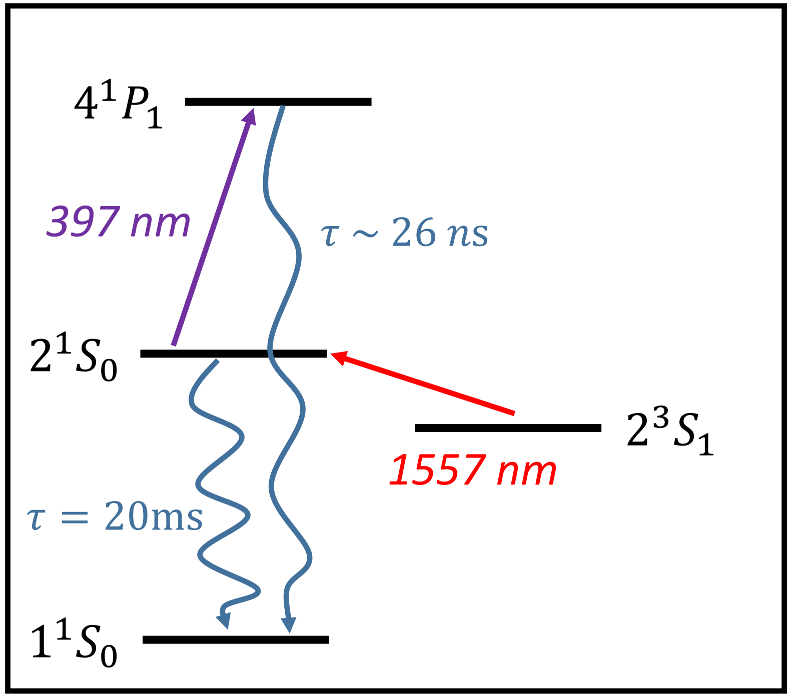
LaserLaB AMSTERDAM

VU

Testing the model

- Enhanced ground state decay through 4^1P_1 state





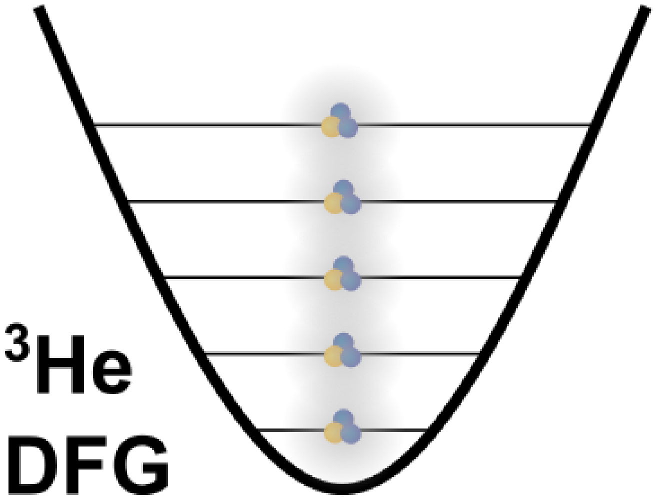
$T \approx 95$ nK
T/T_F 0.35 ~ 0.55

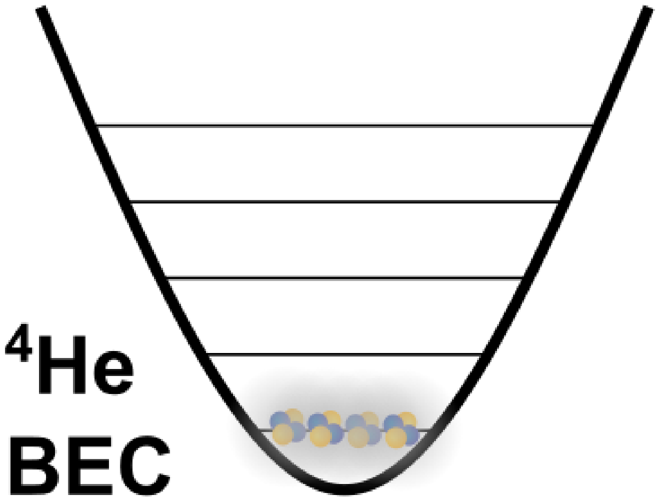
PRELIMINARY RESULT

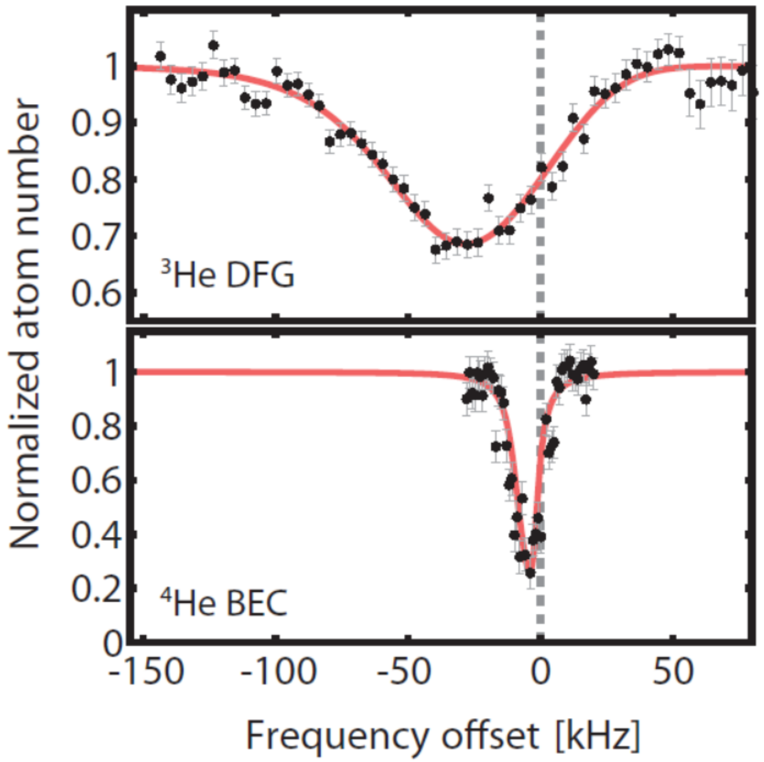
LaserLaB AMSTERDAM VU

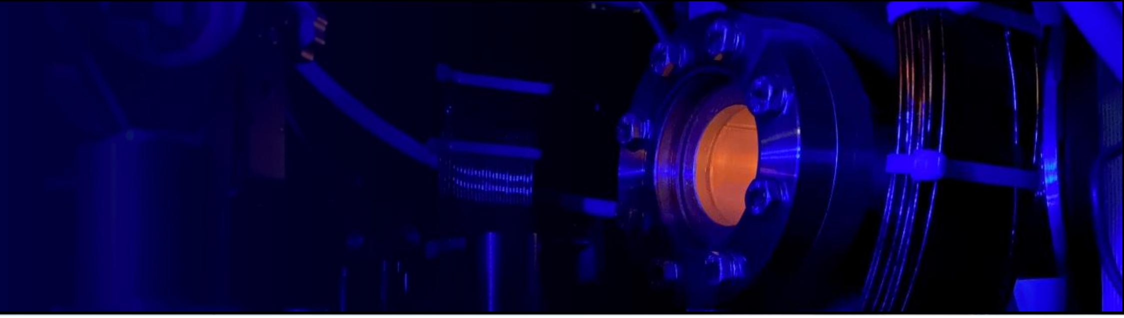
Understanding the spectral lineshape

- Trapped fermionic ^{3}He: Fermi-Dirac distribution
  - Distribution over motional states in the trap
  - Laser absorption Doppler broadened ($T_F \sim 1\ \mu K$)





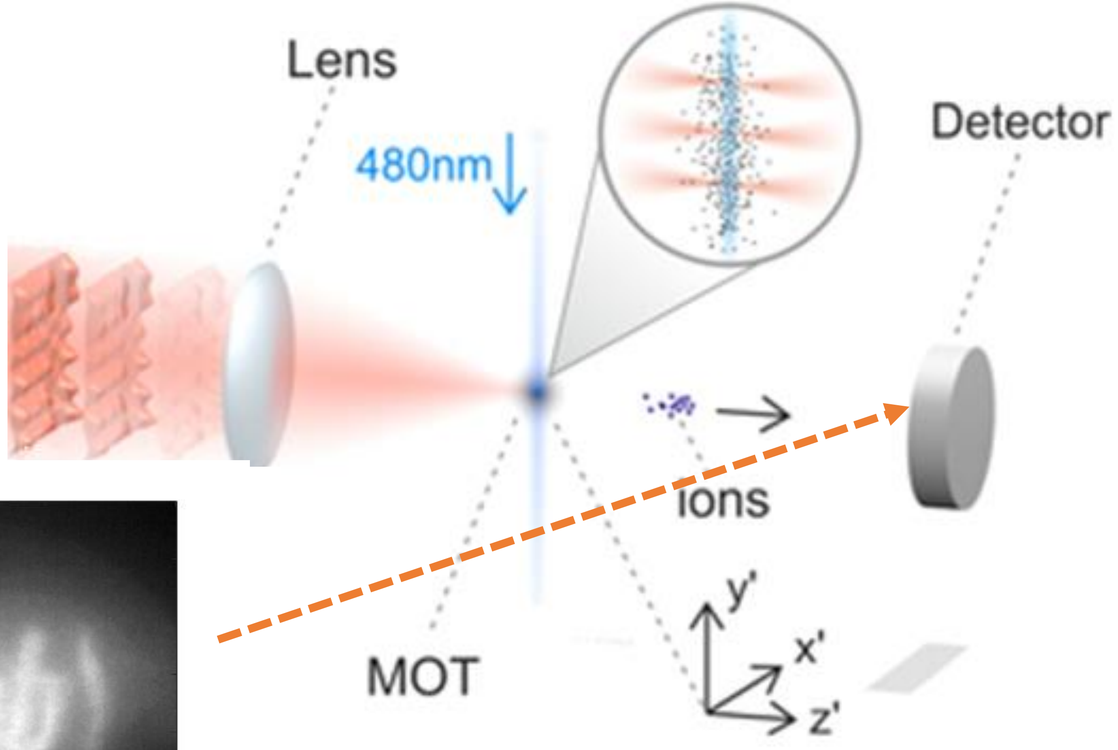


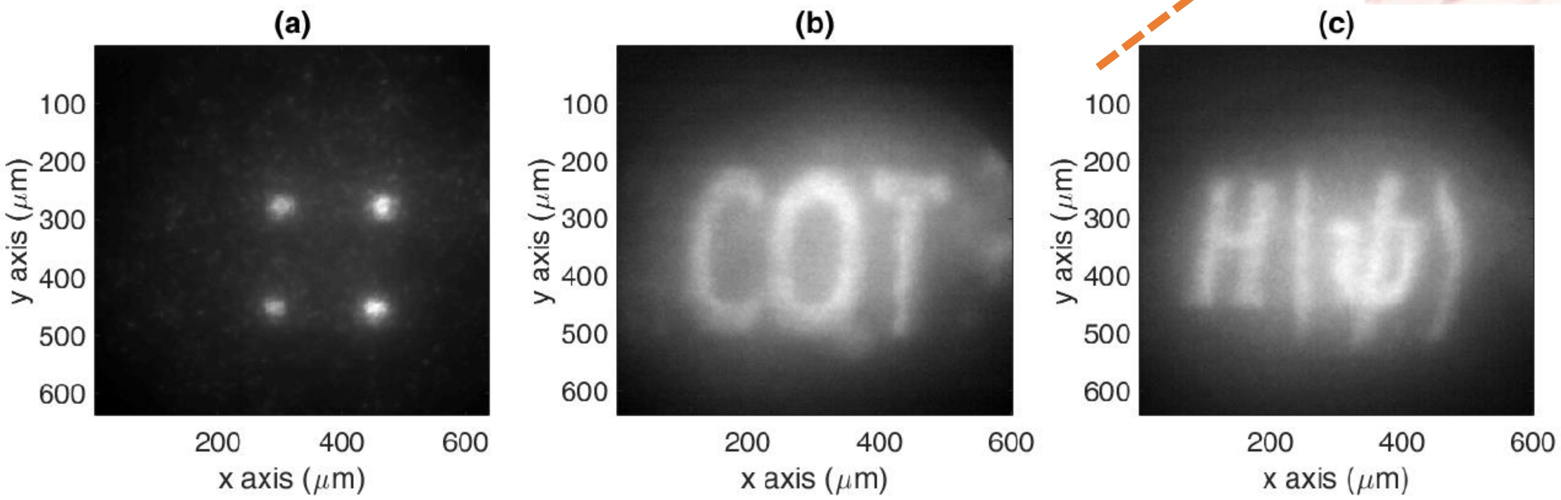


Before PhD

- Master thesis work at Eindhoven University of Technology

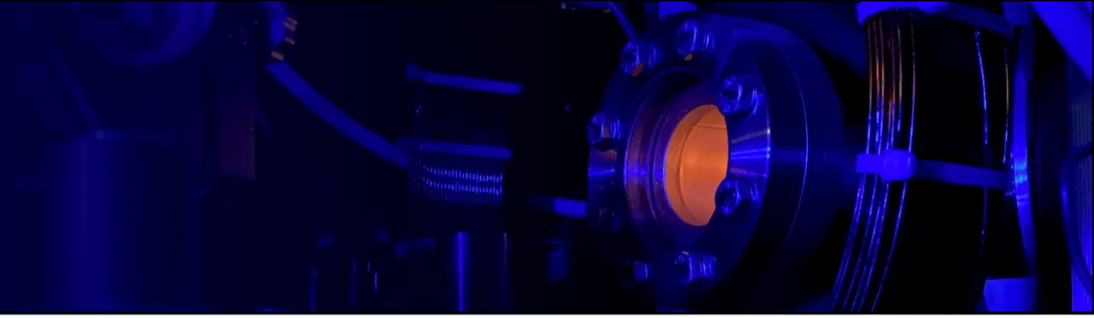
- ^{85}Rb MOT
- Rydberg excitation (780 + 480)
- SLM: shaped excitation volume



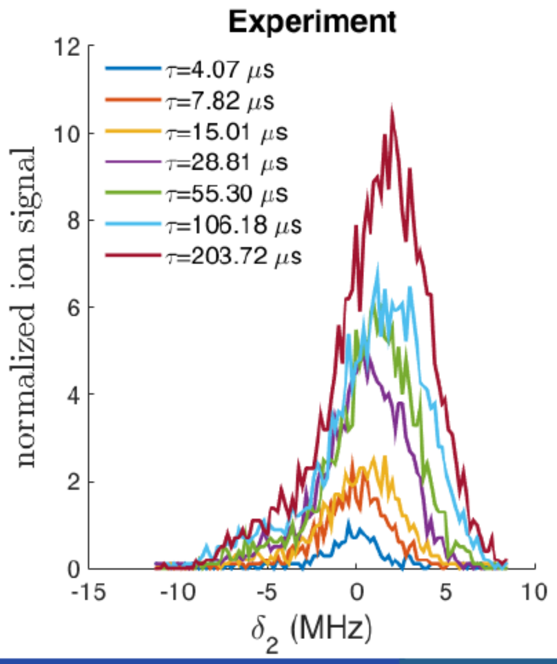


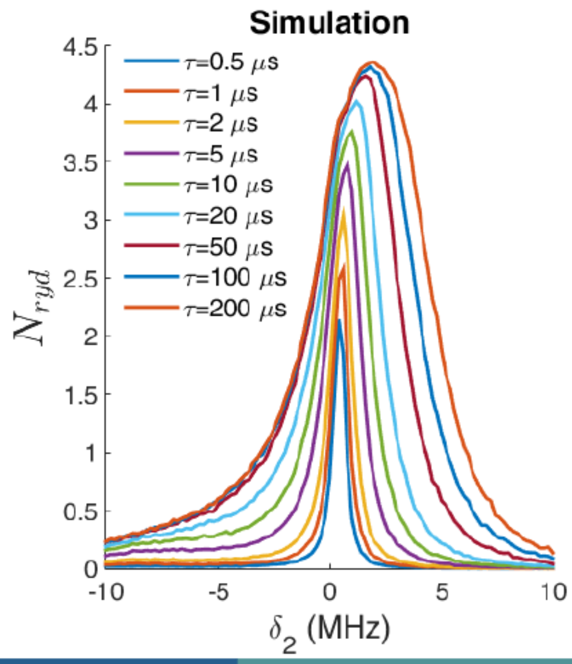
EINDHOVEN UNIVERSITY OF TECHNOLOGY

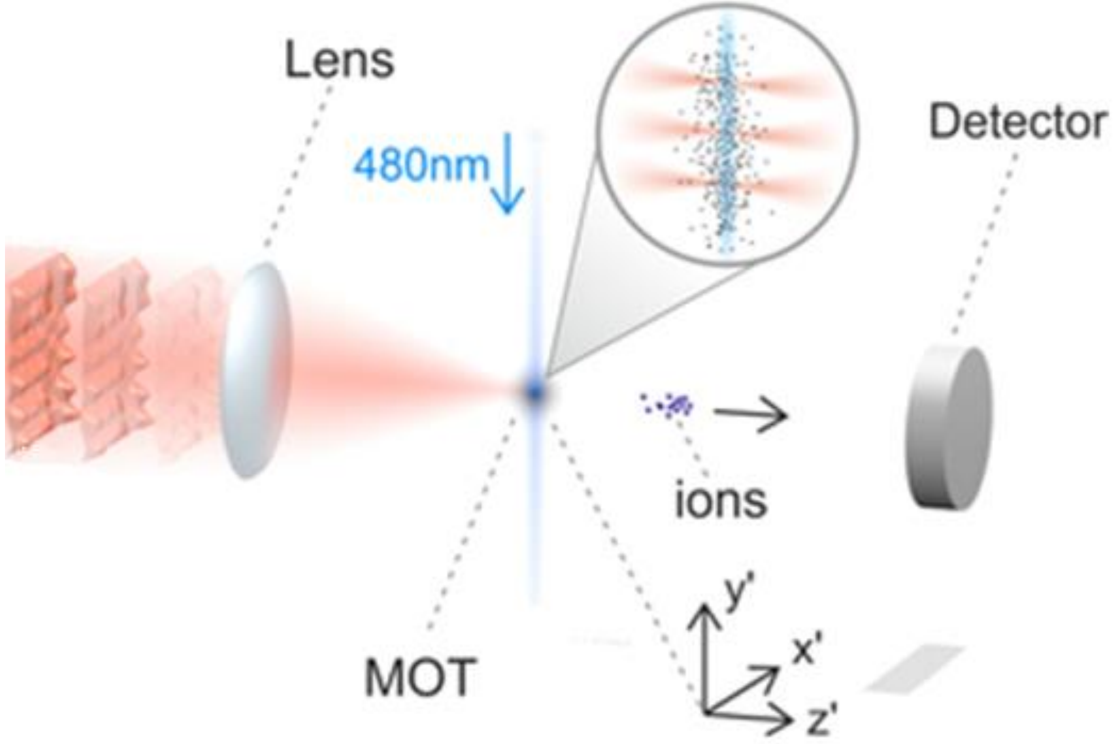
Before PhD



- Rydberg spectra:
  - Lineshape mediated by interactions
  - Rydberg facilitation
  - Spatial resolution obscured by ion repulsion







EINDHOVEN UNIVERSITY OF TECHNOLOGY