Probing Nuclear Sizes with Precision Spectroscopy in Bosonic and Fermionic Helium

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Ascona, 07-07-2023

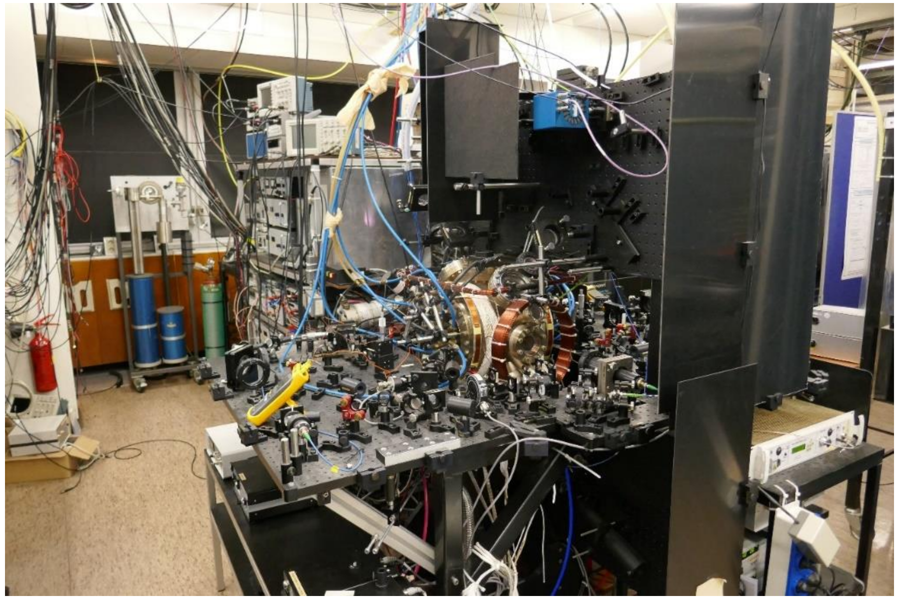
Precision measurements for fundamental physics

Fundamental Physics

Tabletop Experiments

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

He, He^+, H_2, HD, HT, HD^+, H_2^+, …



Simple, calculable, systems

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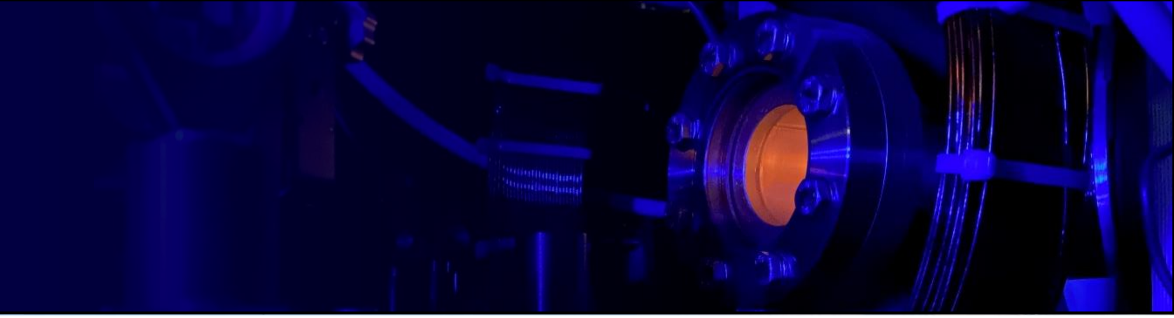
Precision measurements For fundamental physics

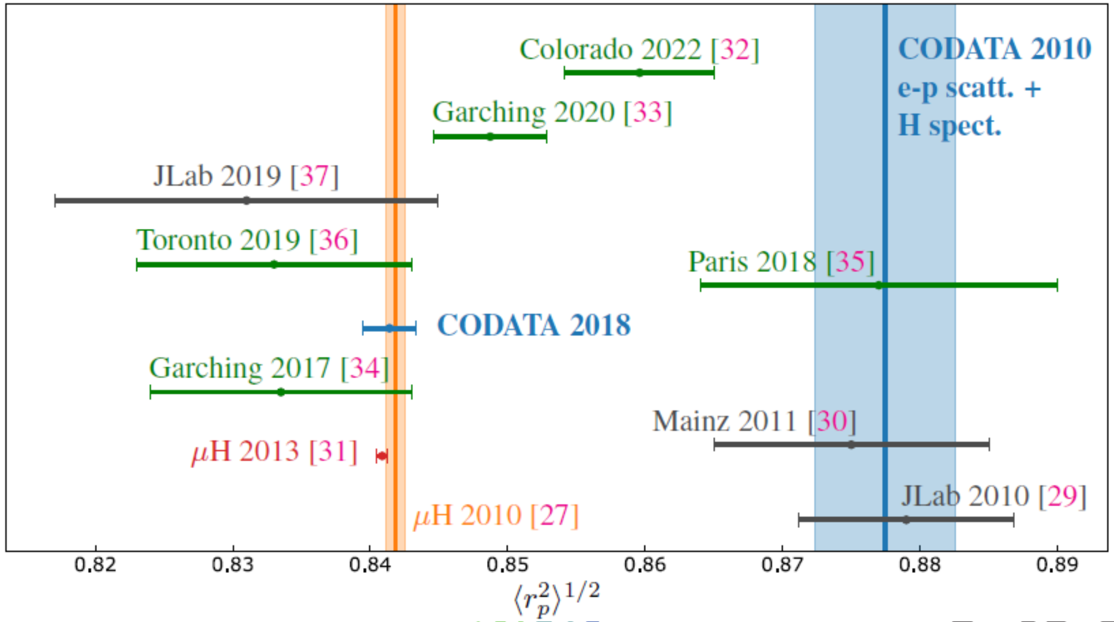


Simple, calculable, systems

$^{1}_{1}H$
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'



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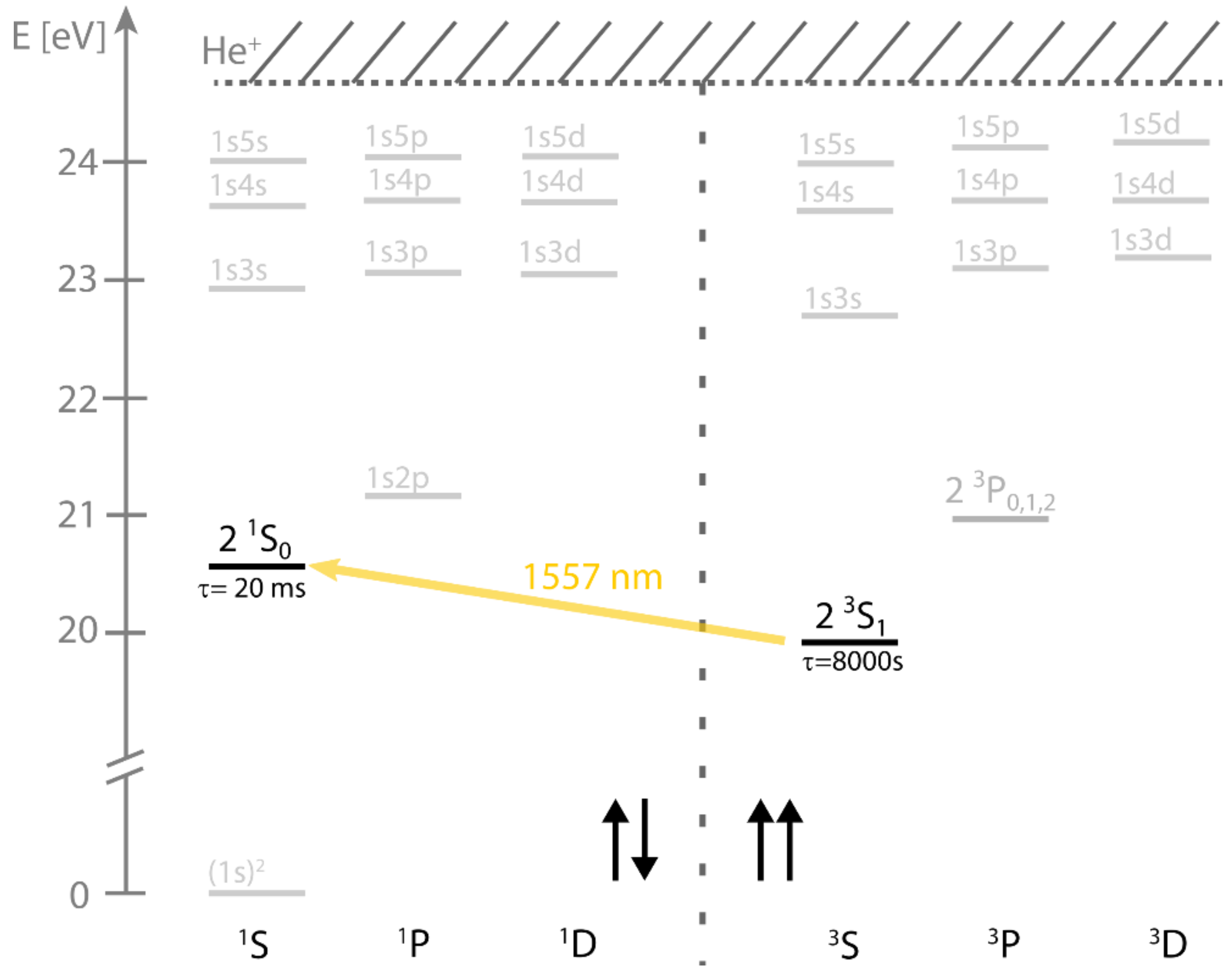
[1] Matveev et al. *Phys. Rev. Lett.* 110, no. 23 (June 2013): 230801.

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.*)

$^{4}_{2}\mathrm{He}$

Helium

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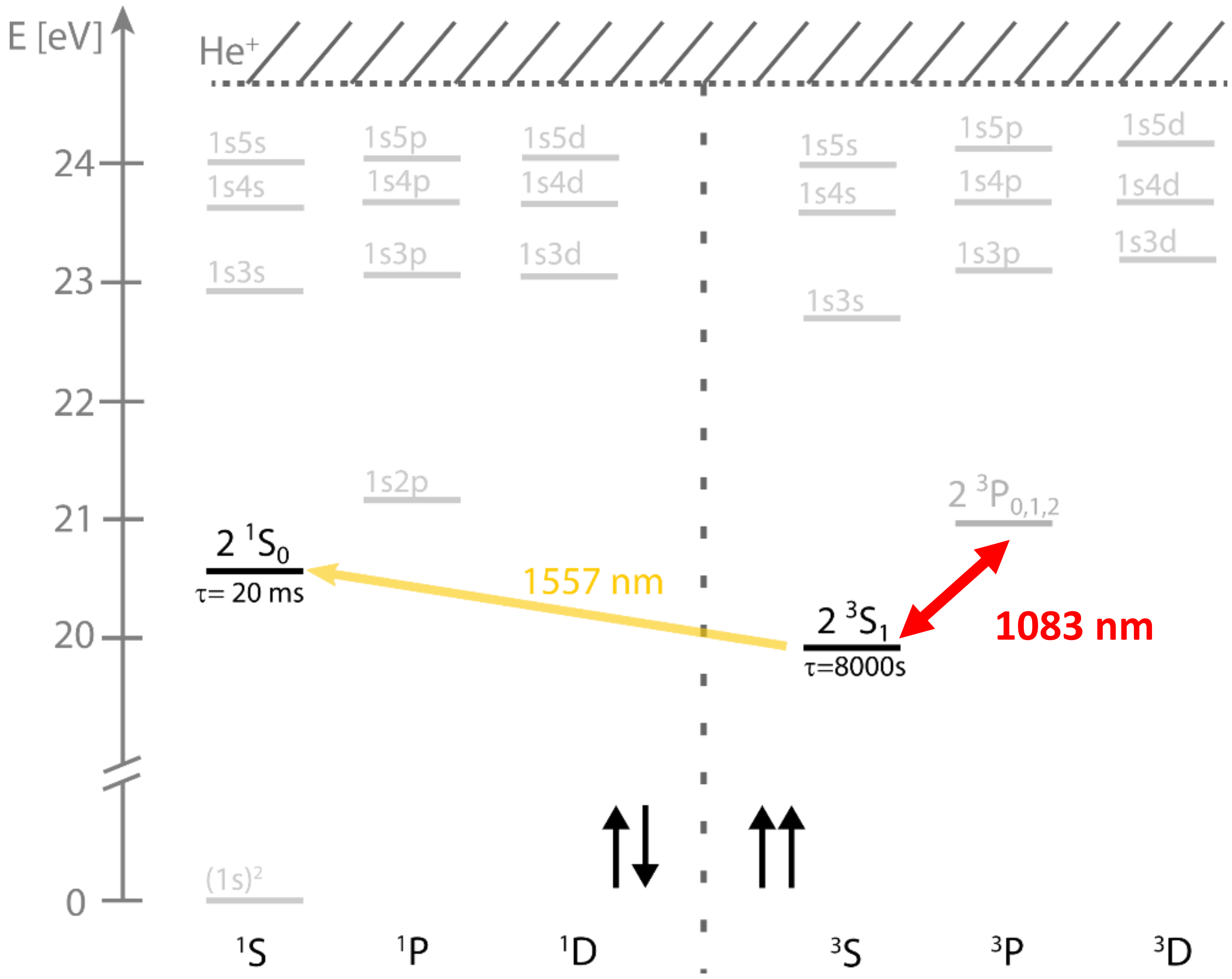
Precision measurements
For fundamental physics



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

$^4_2$He
Helium

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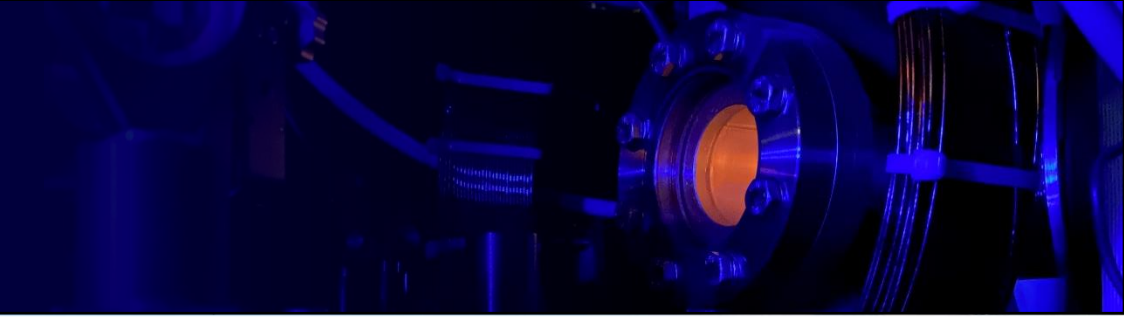
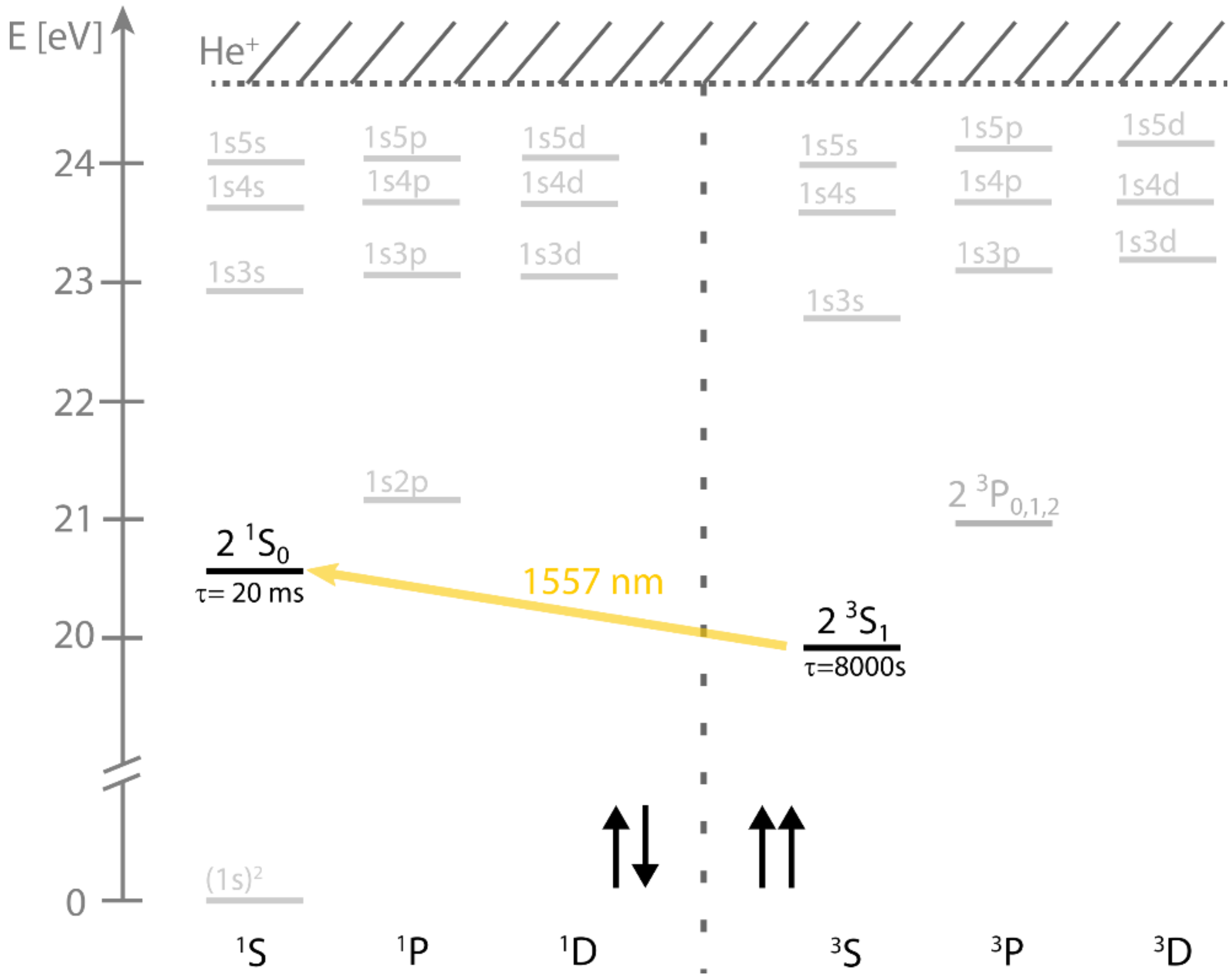
Precision measurements For fundamental physics





^4_2He Helium

- Next atom, He
- Two electrons:
  - Singlet/Triplet structure
- BUT: complicated QED theory from electron-electron terms
- SOLUTION: ^3He-^4He isotope shift
  - Most difficult terms drop out
  - Nuclear sizes: $\delta r^2 = r_3^2 - r_4^2$

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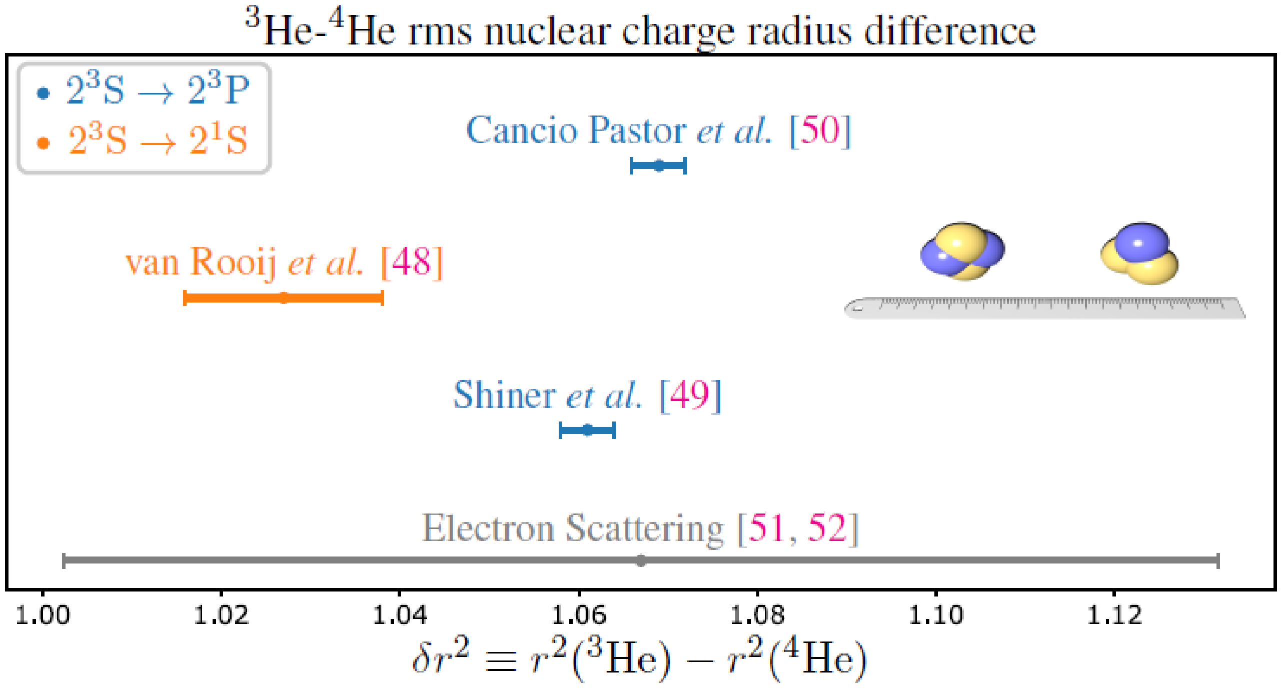
The helium atom

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

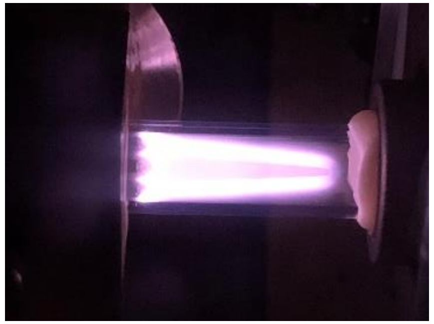
- Approach:
  - Measure ^{3}He-^{4}He isotope shift
  - Extract differential charge radii $r_3^2 - r_4^2$ using QED theory
  - Compare with other measurements:

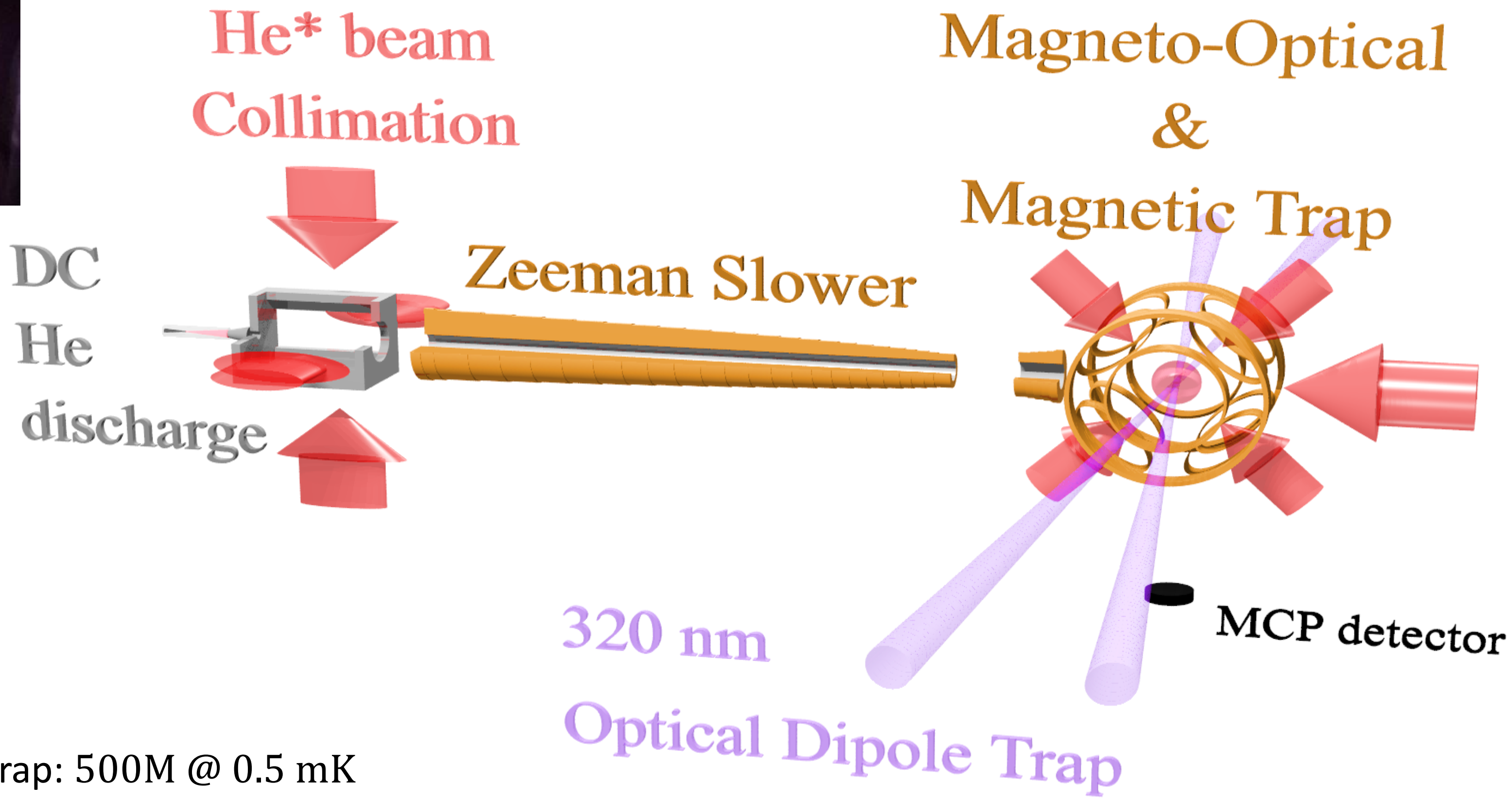
    Spectroscopic, scattering, $\mu\mathrm{He}^+$

    Consistency check

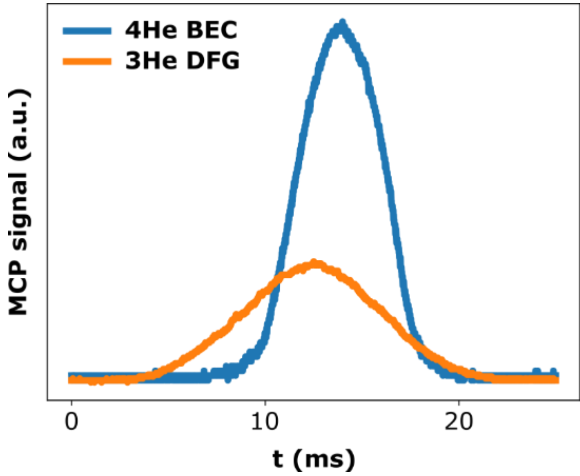


Quantum degenerate He*





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)

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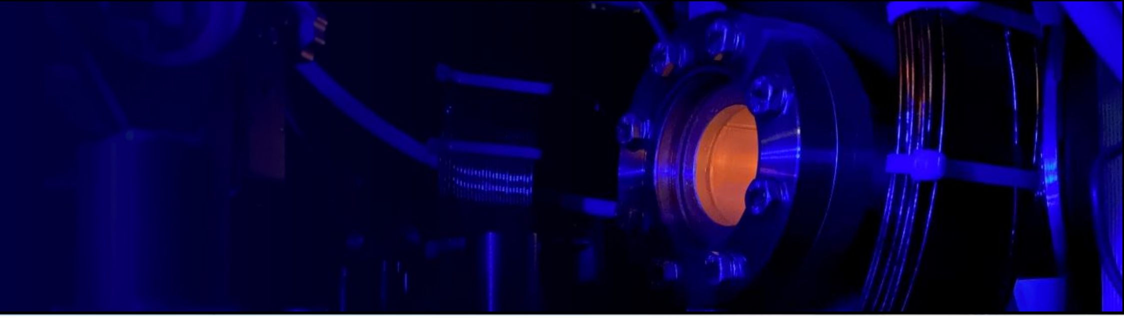
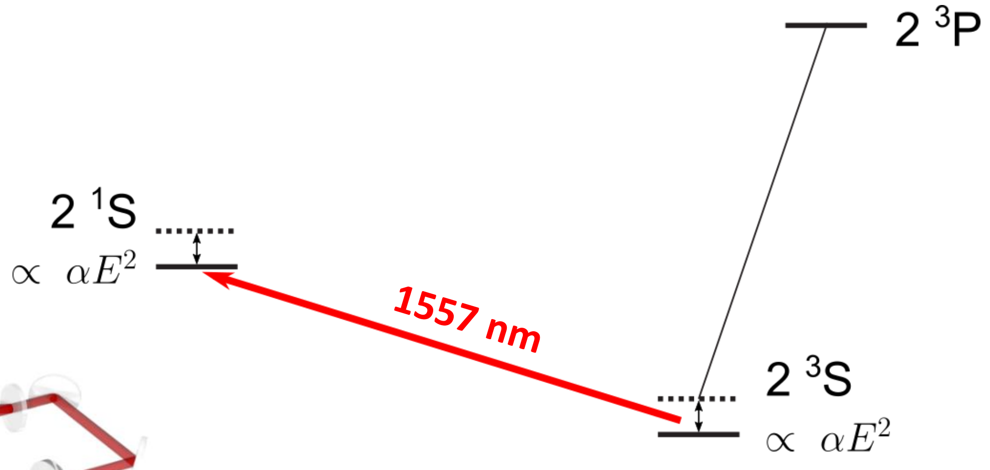
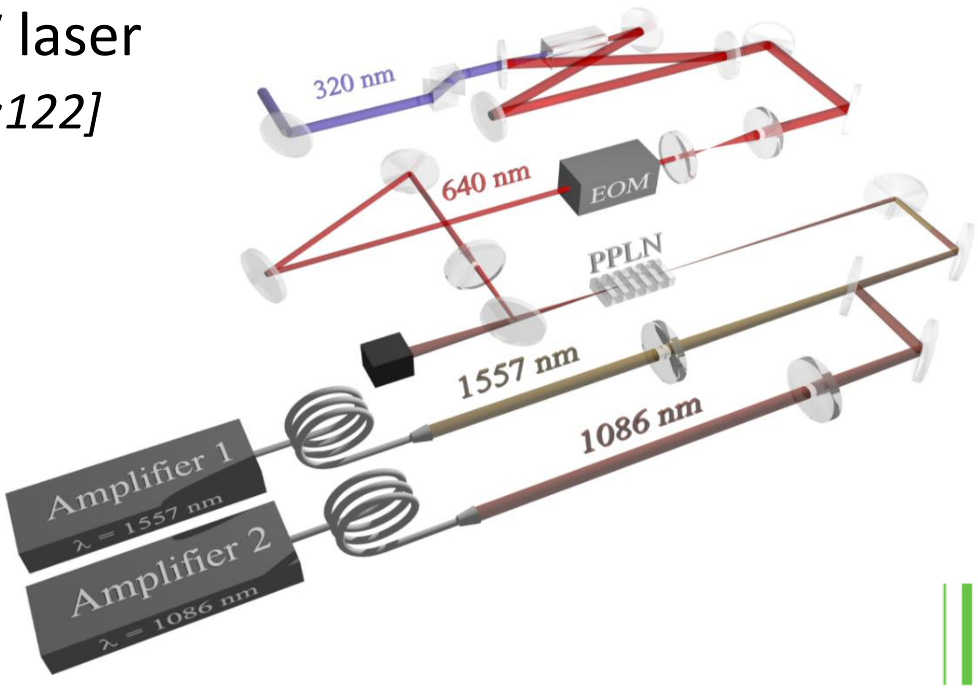
Precision Spectroscopy



- **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]





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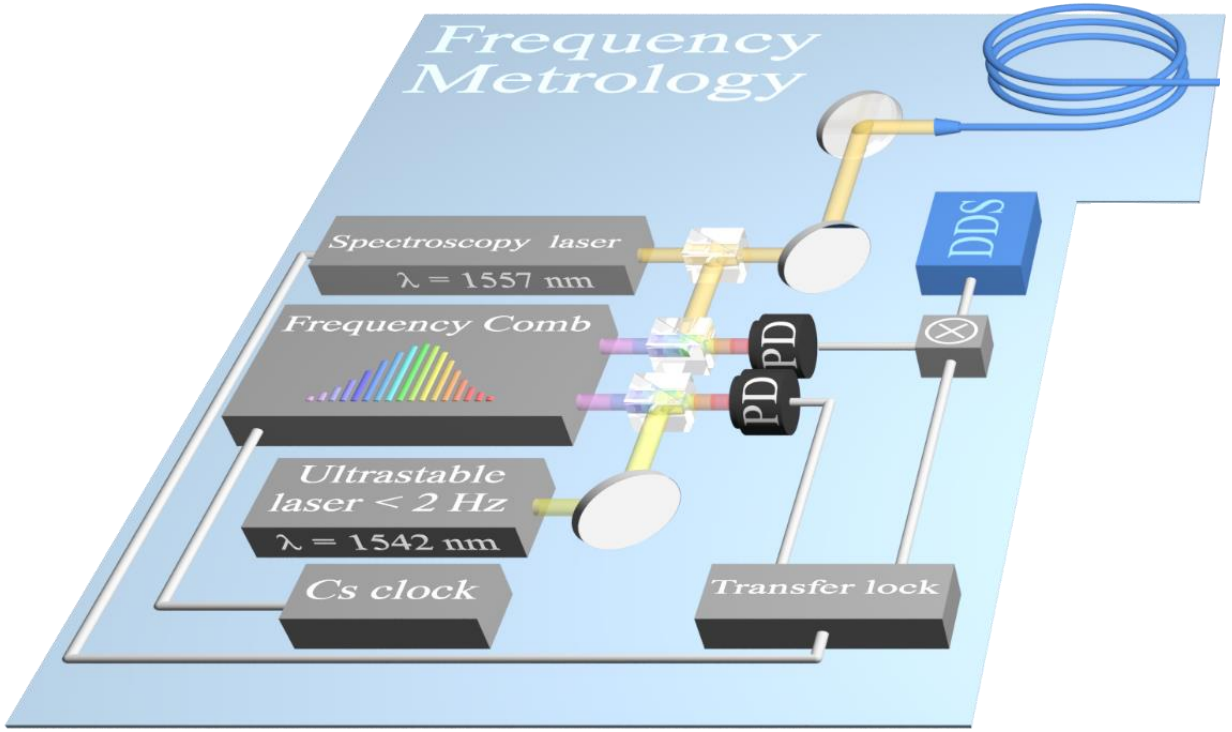
Precision spectroscopy

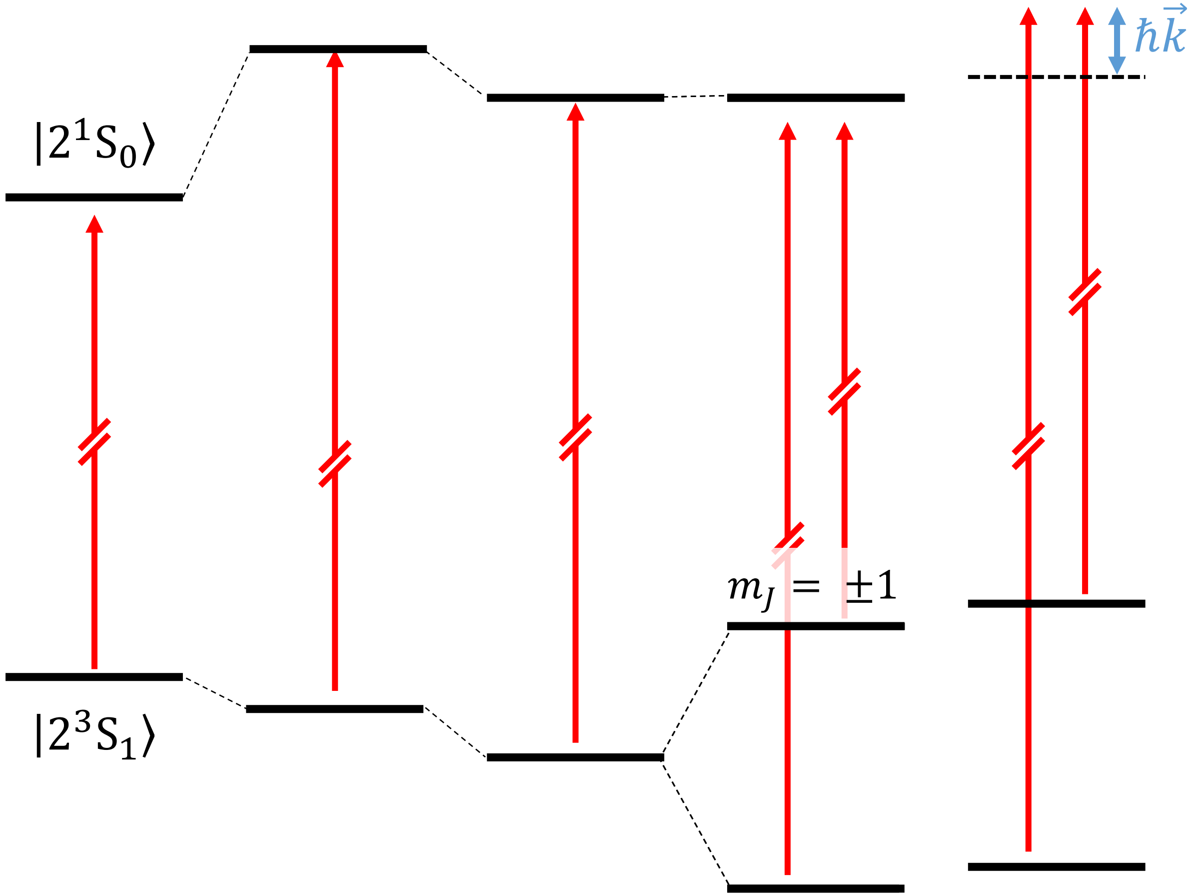
Two ingredients for precision spectroscopy:

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



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**



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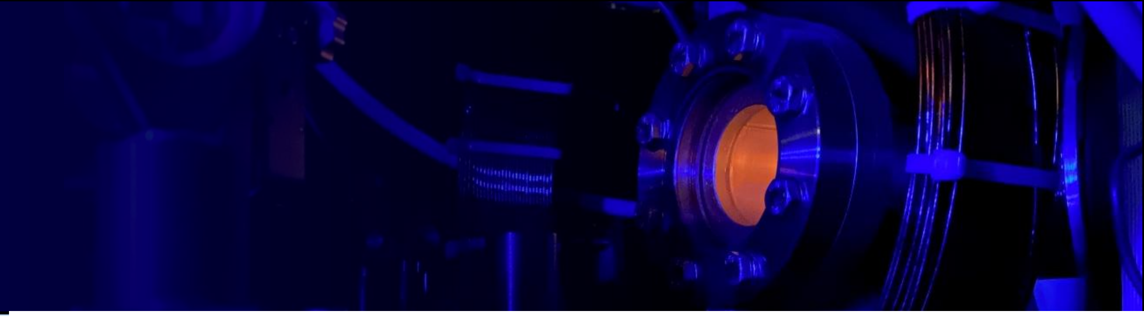
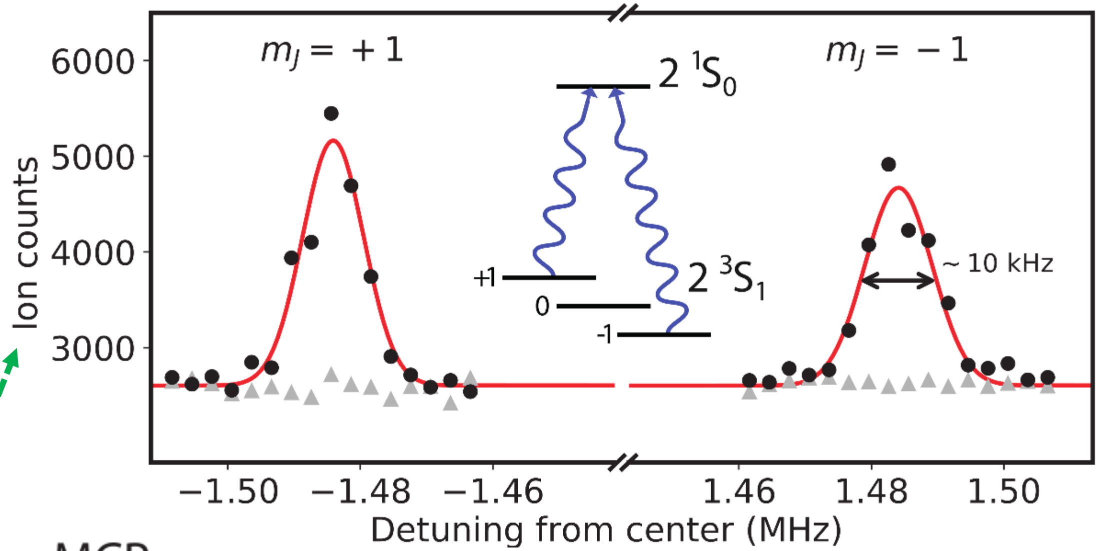
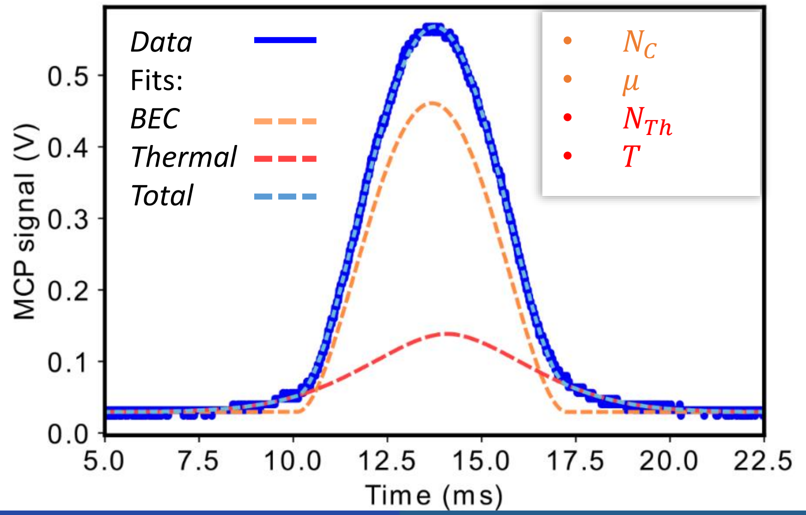
Spectroscopy of a ^{4}He BEC

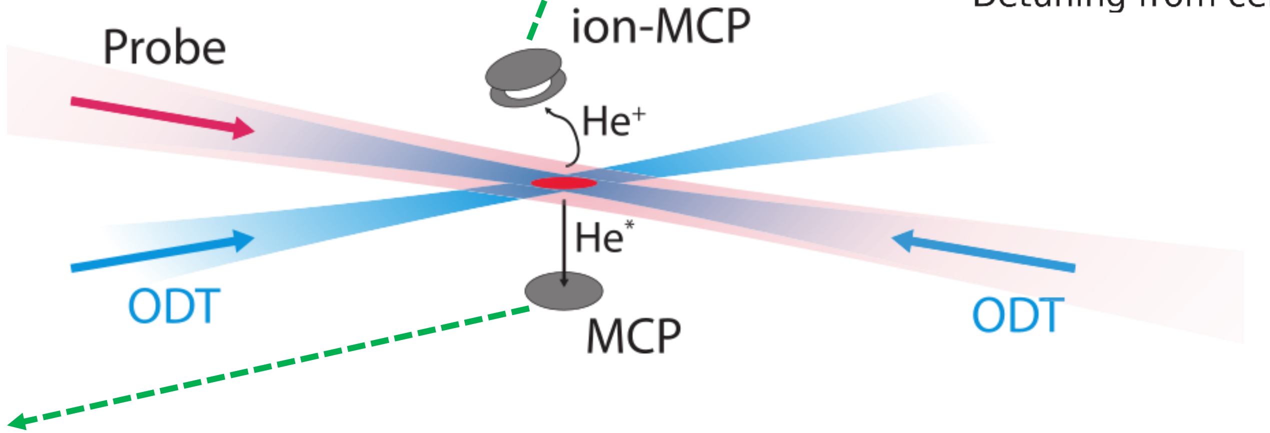


- Dominated by collisions:
  - Penning ionization signal
    $$\mathrm{He}\,(2^1\mathrm{S}_0) + \mathrm{He}\,(2^3\mathrm{S}_1) \rightarrow \mathrm{He}\,(1^1\mathrm{S}_0) + \mathrm{He}^+ + e^-$$
  - **Cold-collision shift:**
    $$\langle \Delta\nu \rangle \propto \frac{a_{ts} - a_{tt}}{a_{tt}}\,\mu$$



single shot TOF:





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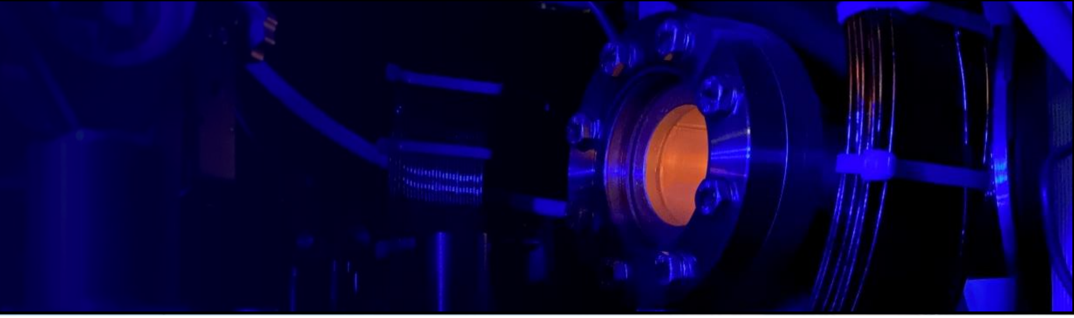
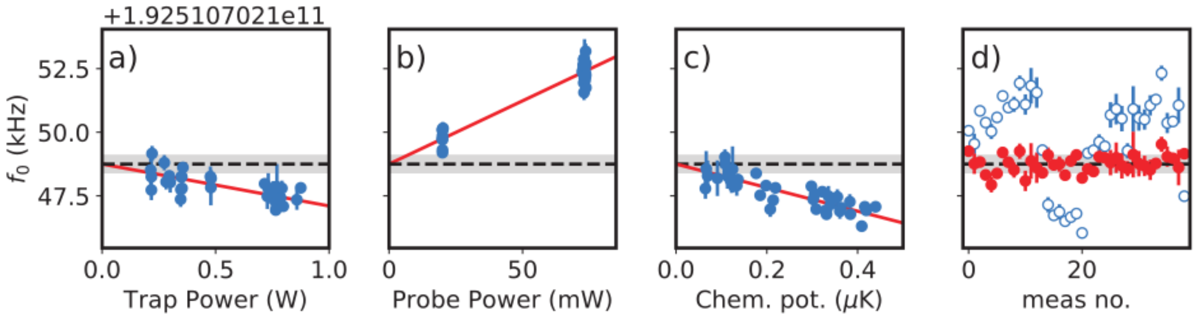
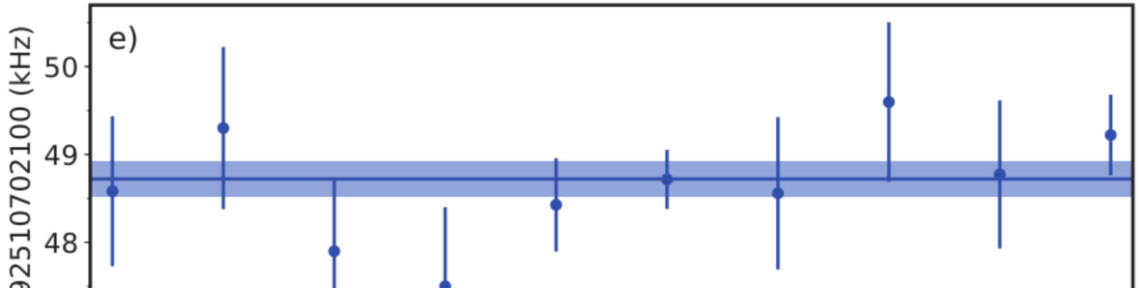
Spectroscopy of a ^{4}He BEC



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

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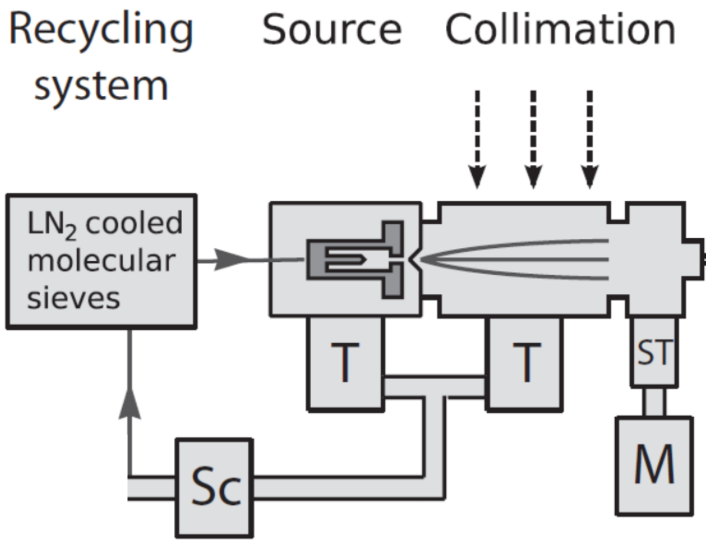
Working with ^{3}He

Production of a Degenerate Fermi Gas of ^{3}He*
and investigation of the $2^3S_1 \rightarrow 2^1S_0$ spectra

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)

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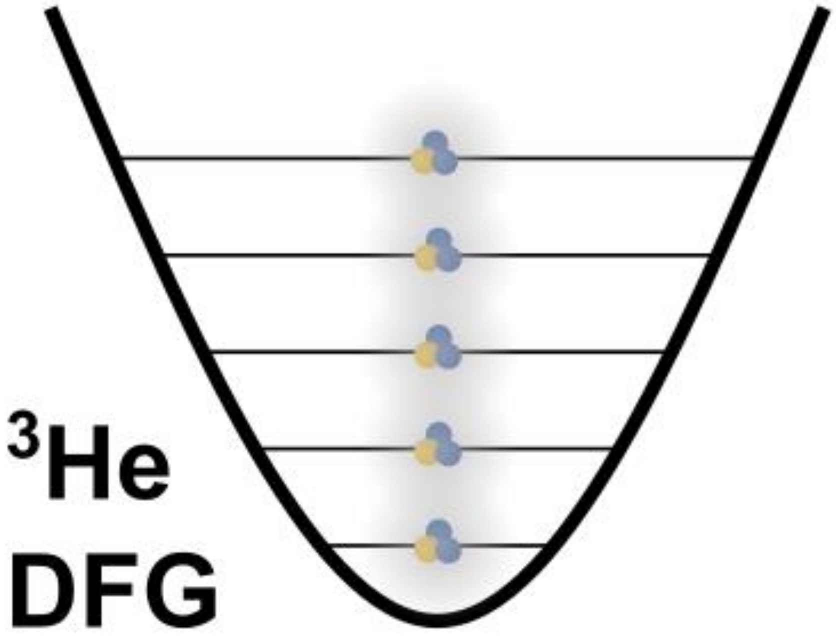
Working with ^{3}He

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 *



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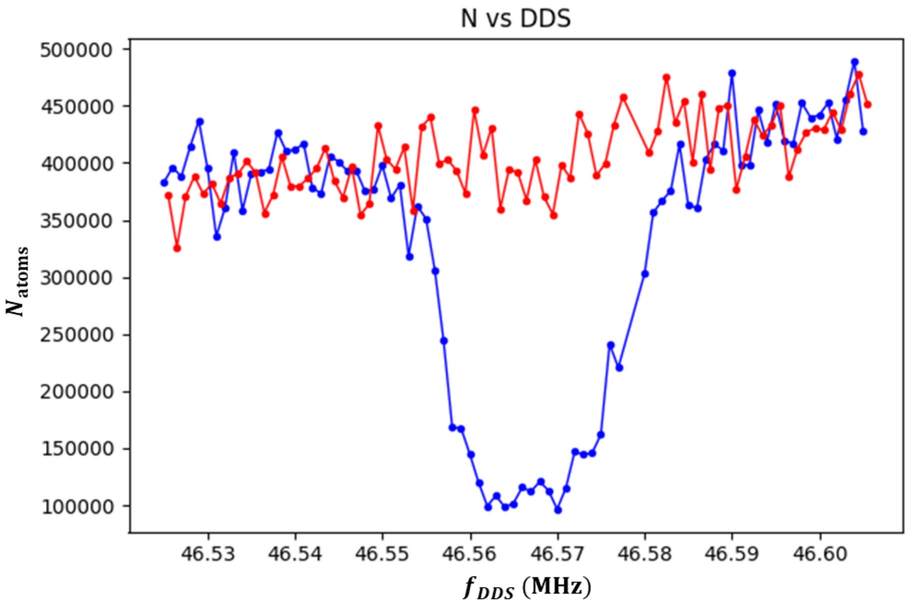

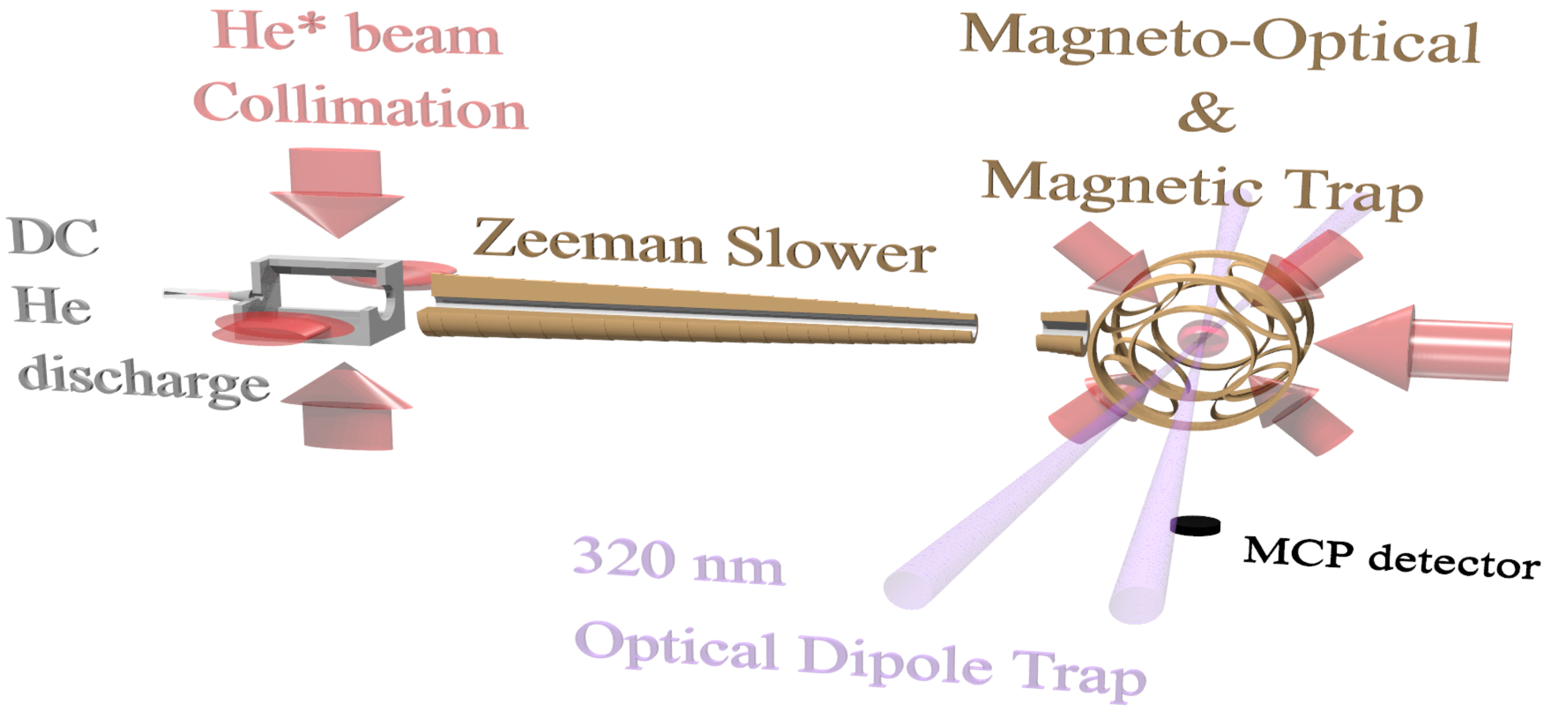

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$2^3S_1 \rightarrow 2^1S_0$ spectroscopy

- Fermion line profile: Doppler broadening

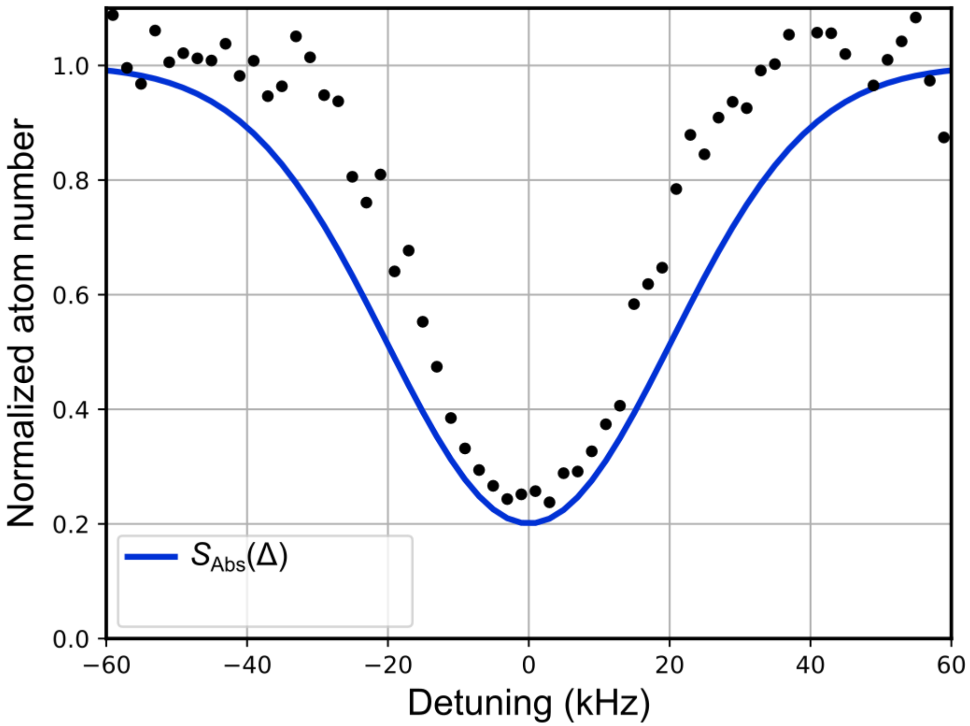
$$S(\Delta) \propto \int\int \rho_g \, \delta(\omega - \omega_0) d^3\vec{r}\, d^3\vec{k}$$

Fermi-Dirac ***resonance***

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

- Expect Doppler broadening: $FWHM \leftrightarrow T_F$

- But wait, reduced linewidth!



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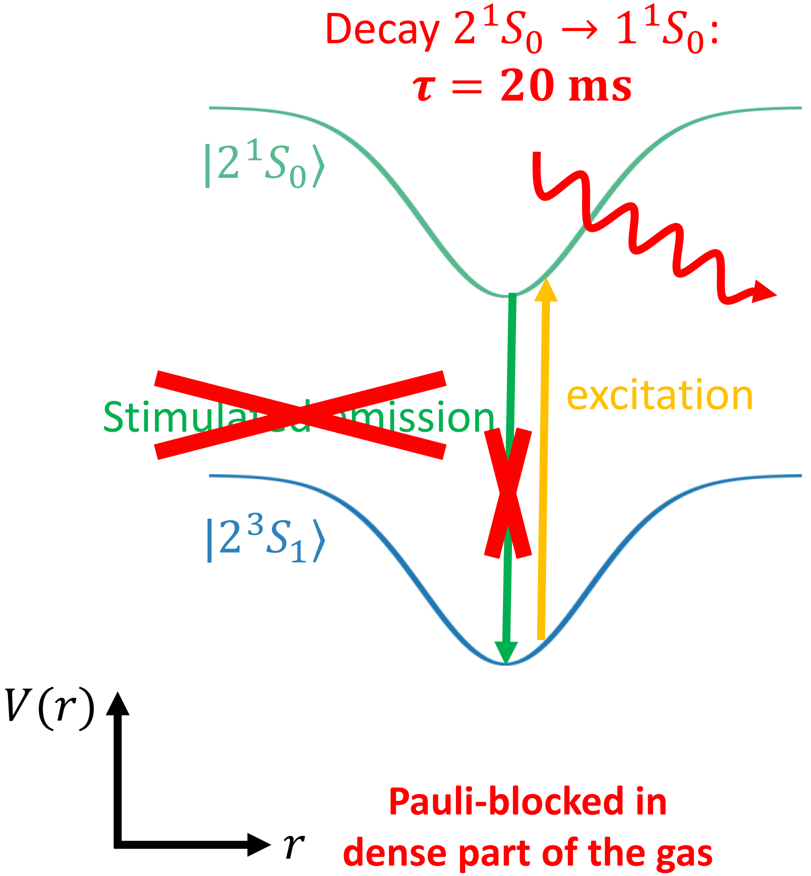
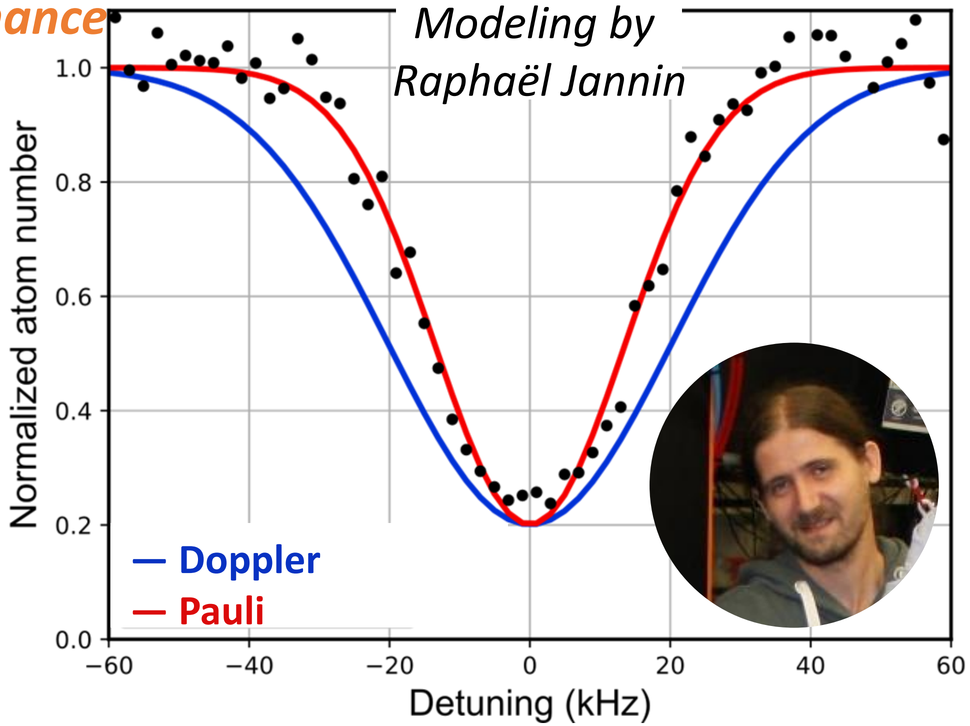
Understanding the spectral lineshape

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

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



Pauli-blocked in dense part of the gas



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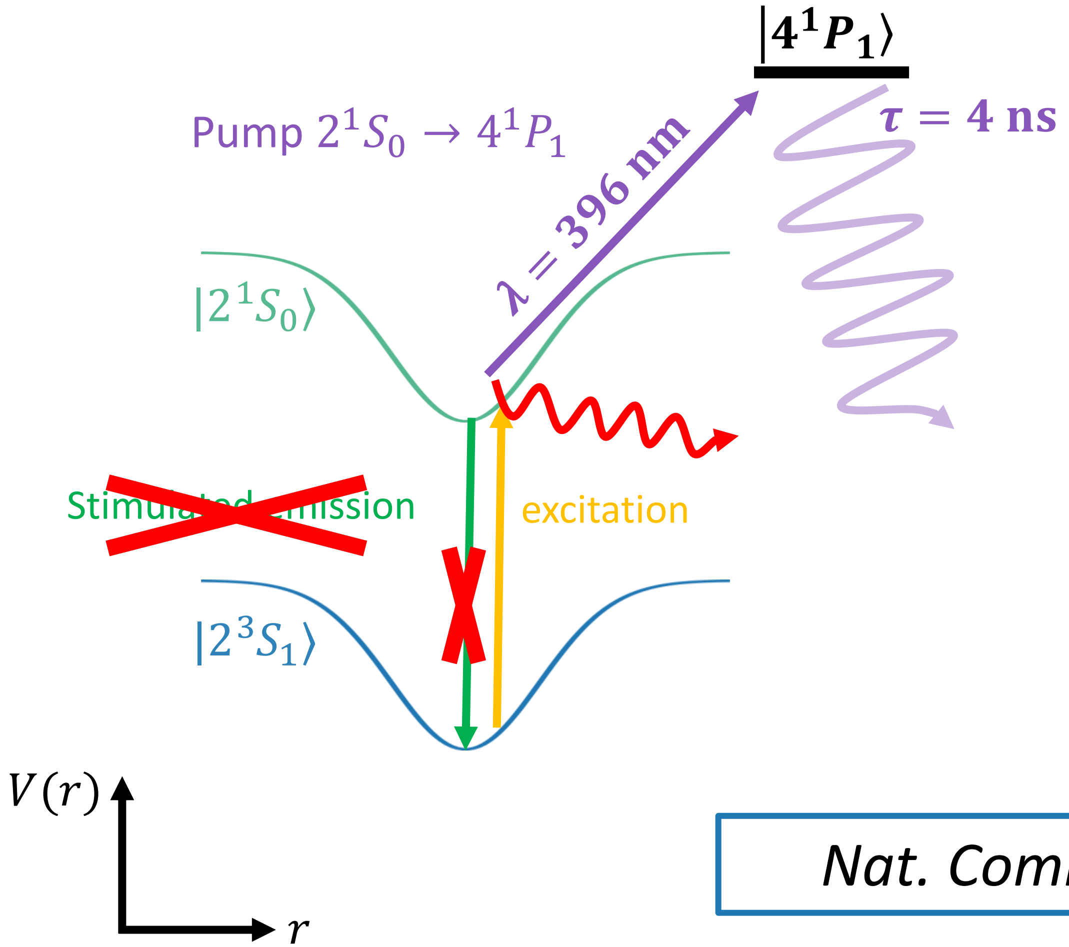
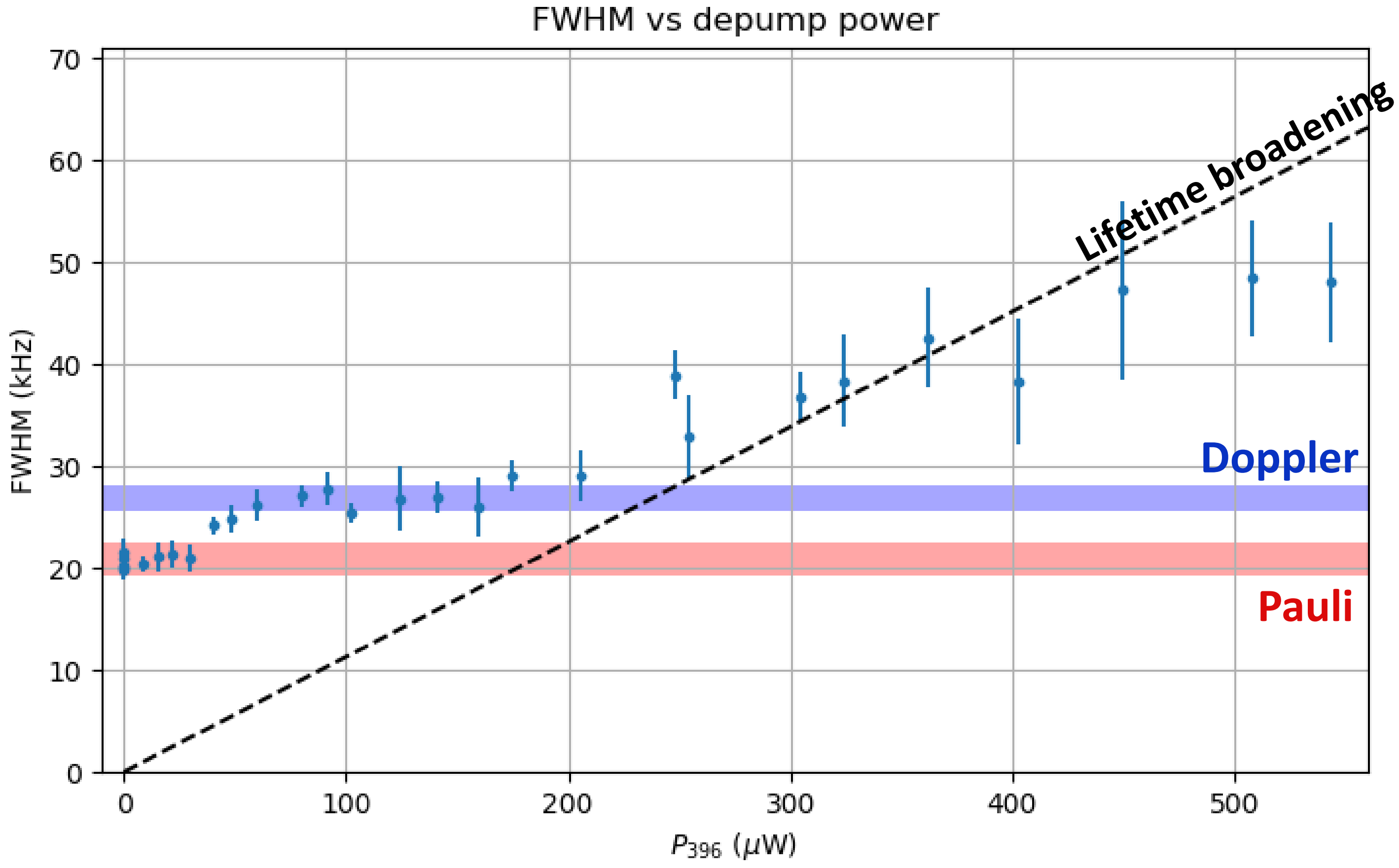
Testing the lineshape model





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

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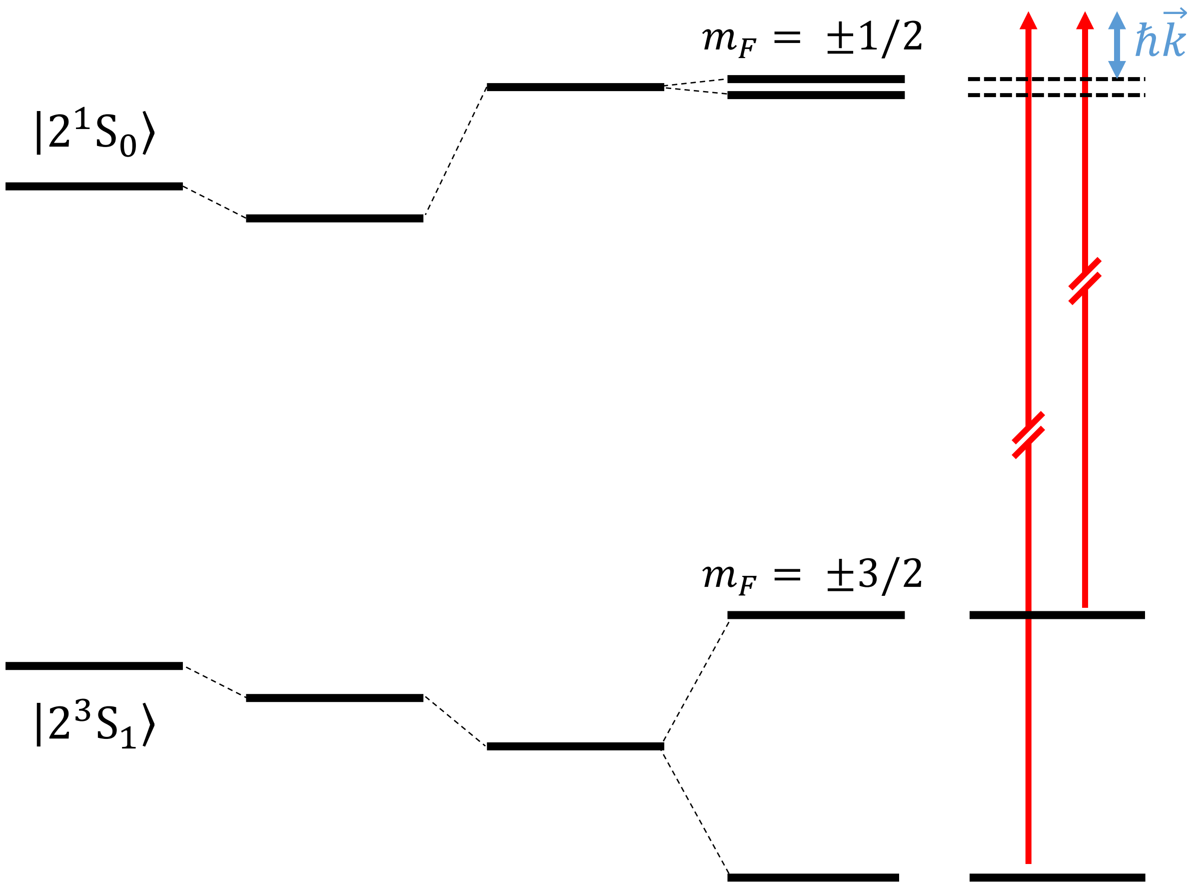
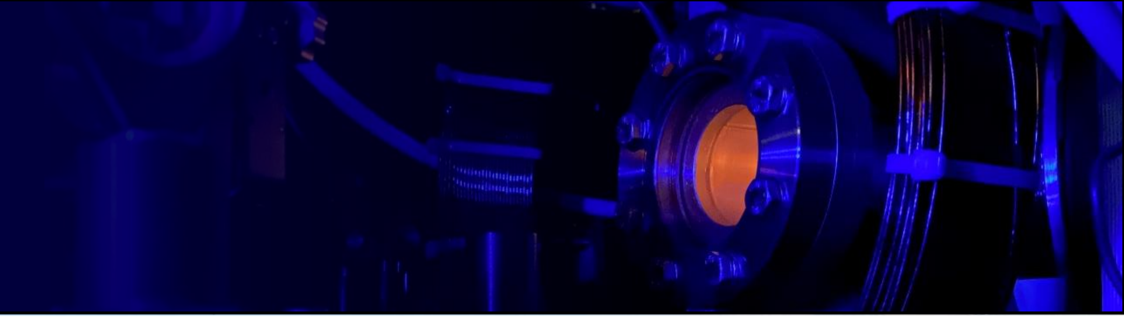
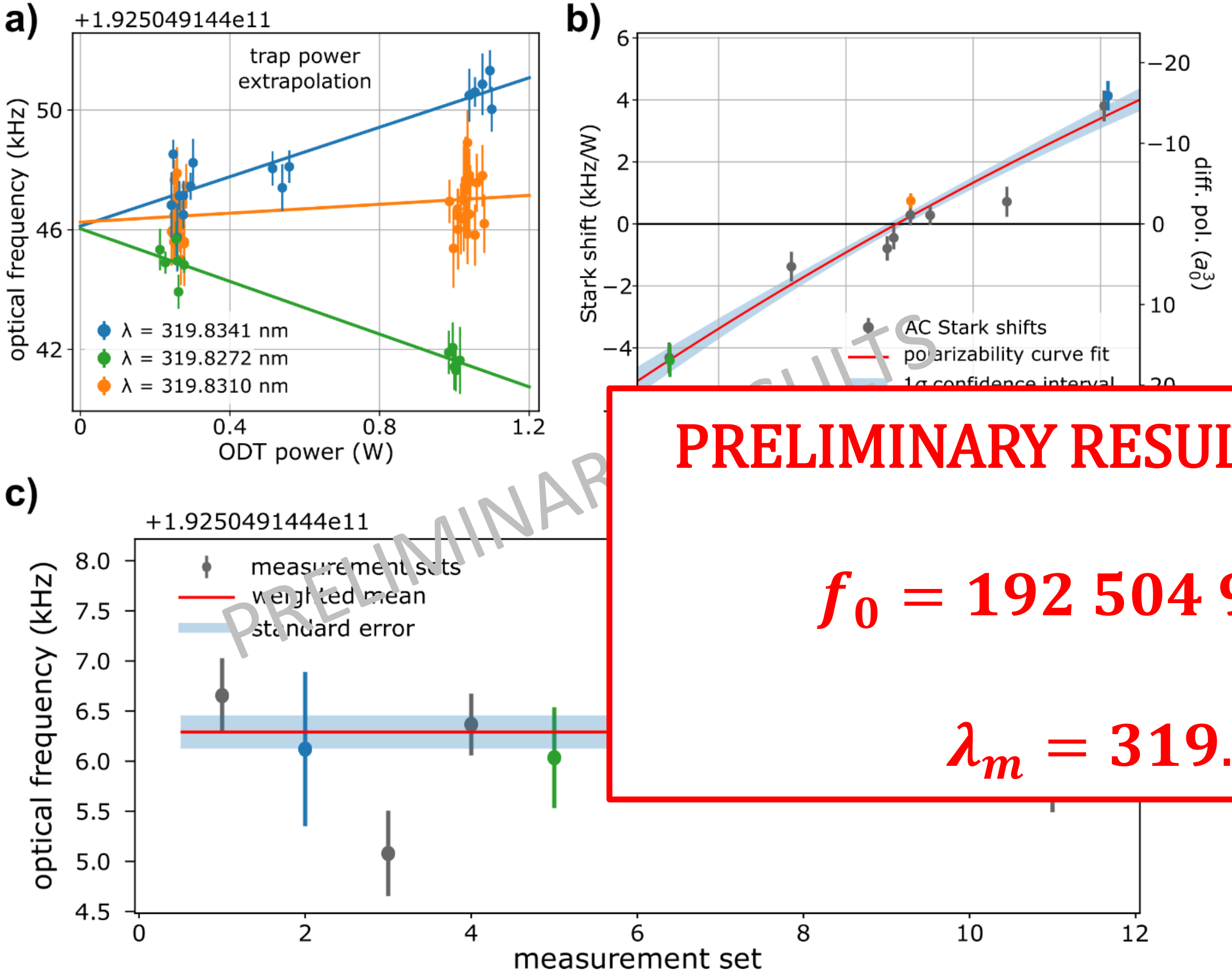
Precision spectroscopy

- 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

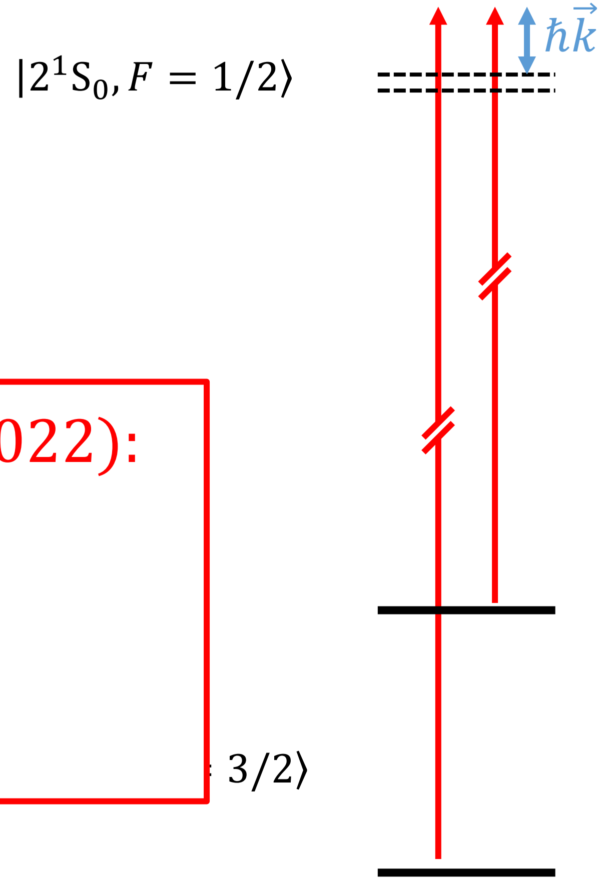




PRELIMINARY RESULT ^{3}He $2^3S_1 \rightarrow 2^1S_0$ (2022):

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

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



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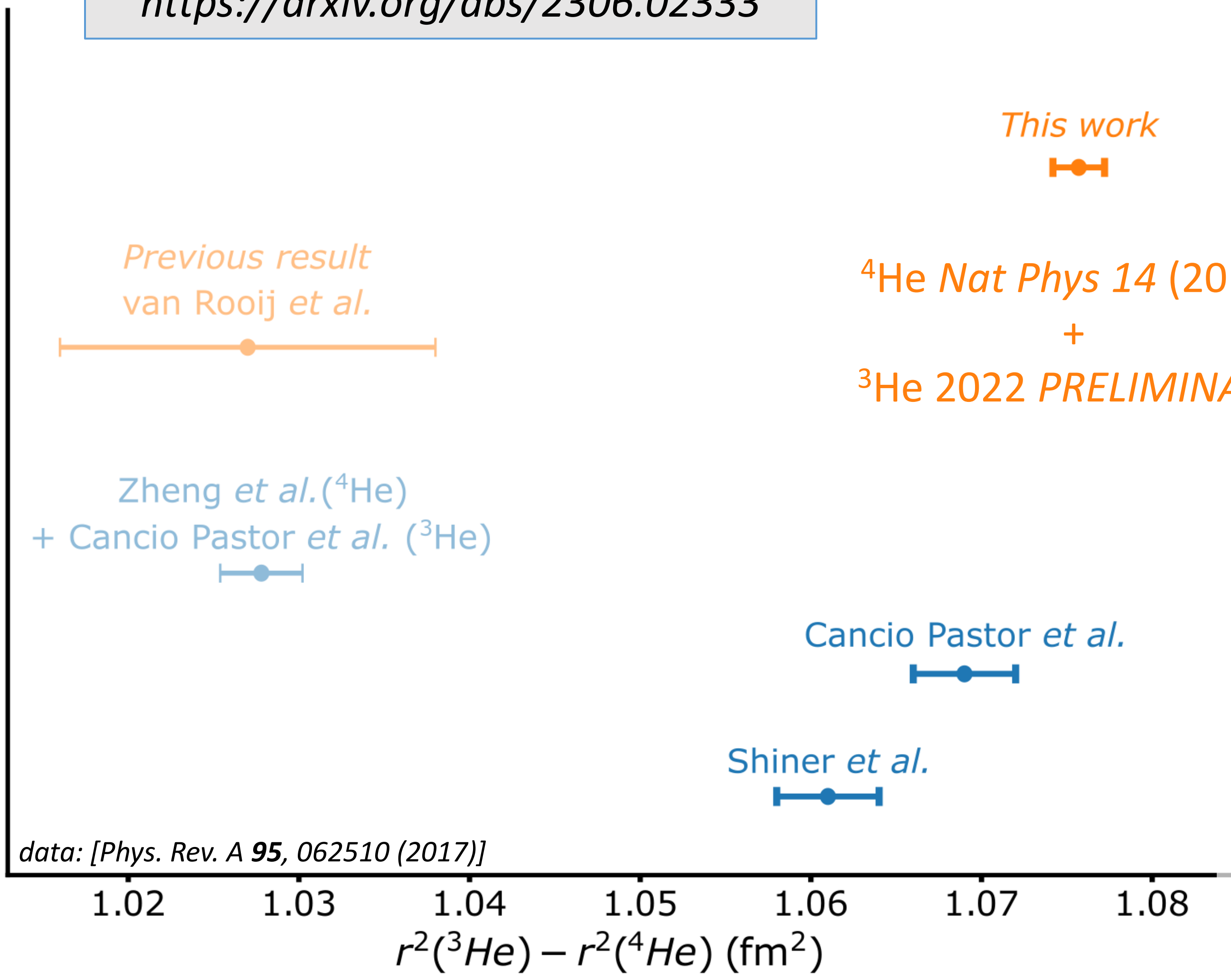
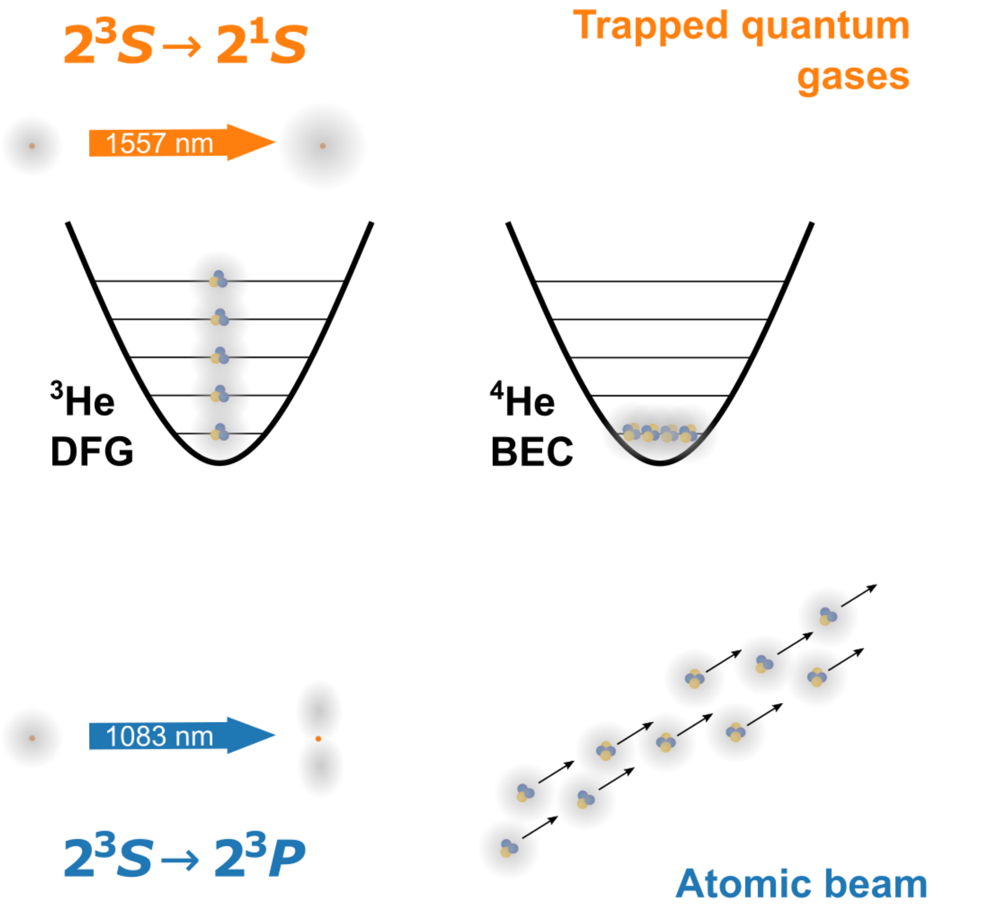
Nuclear Charge Radius Difference

https://arxiv.org/abs/2306.02333





PRELIMINARY RESULTS

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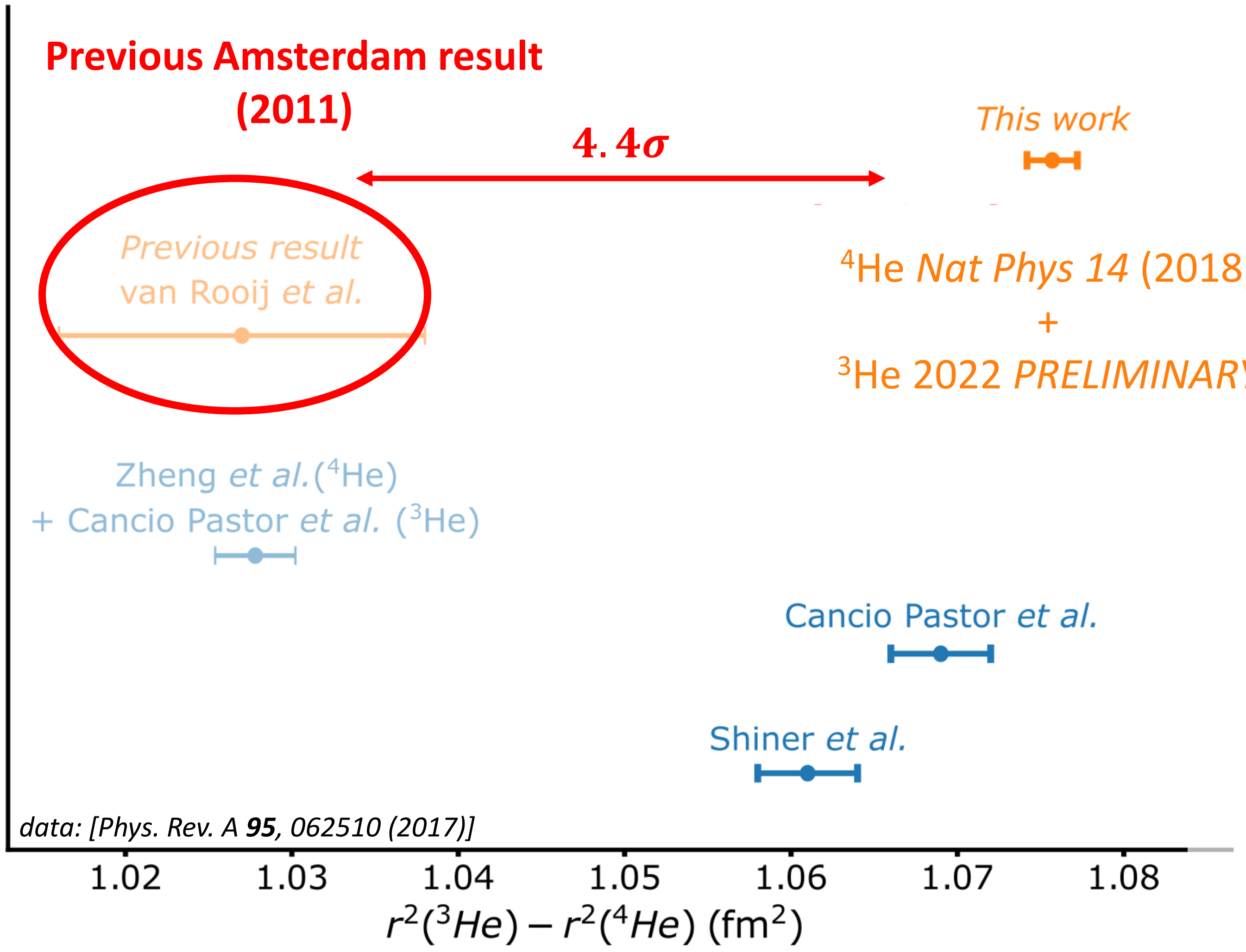
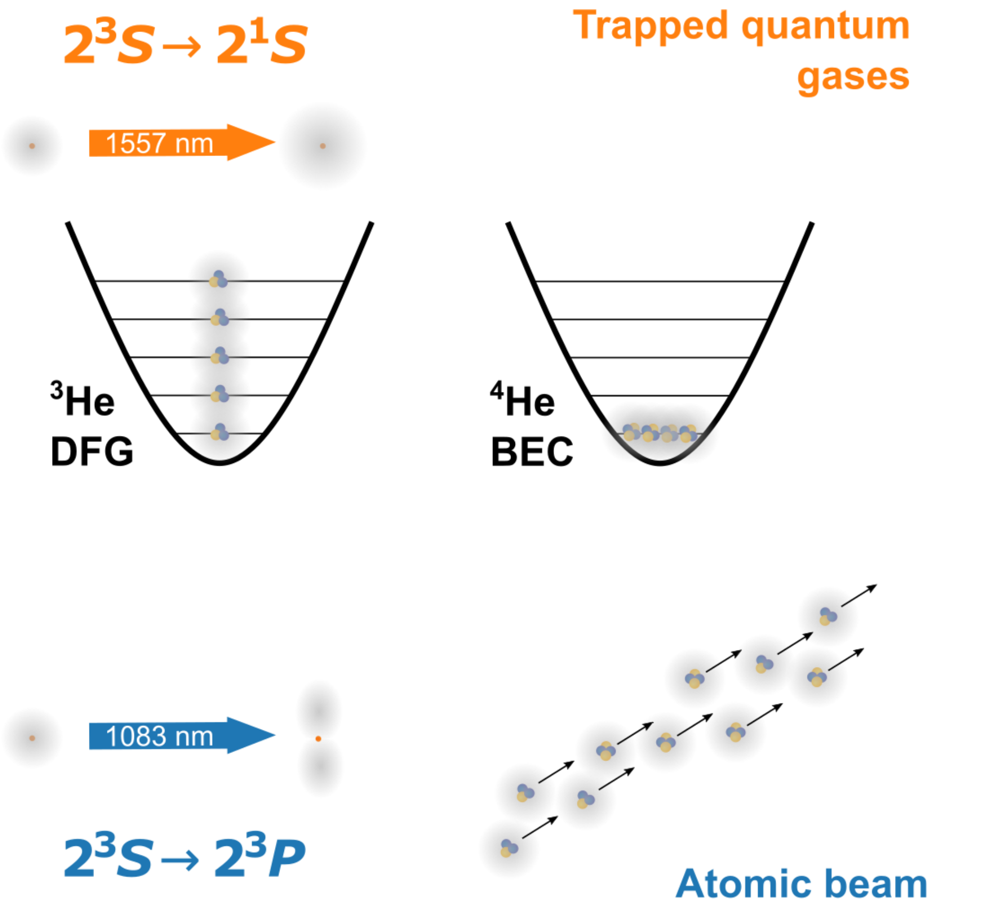
Nuclear Charge Radius Difference





PRELIMINARY RESULTS

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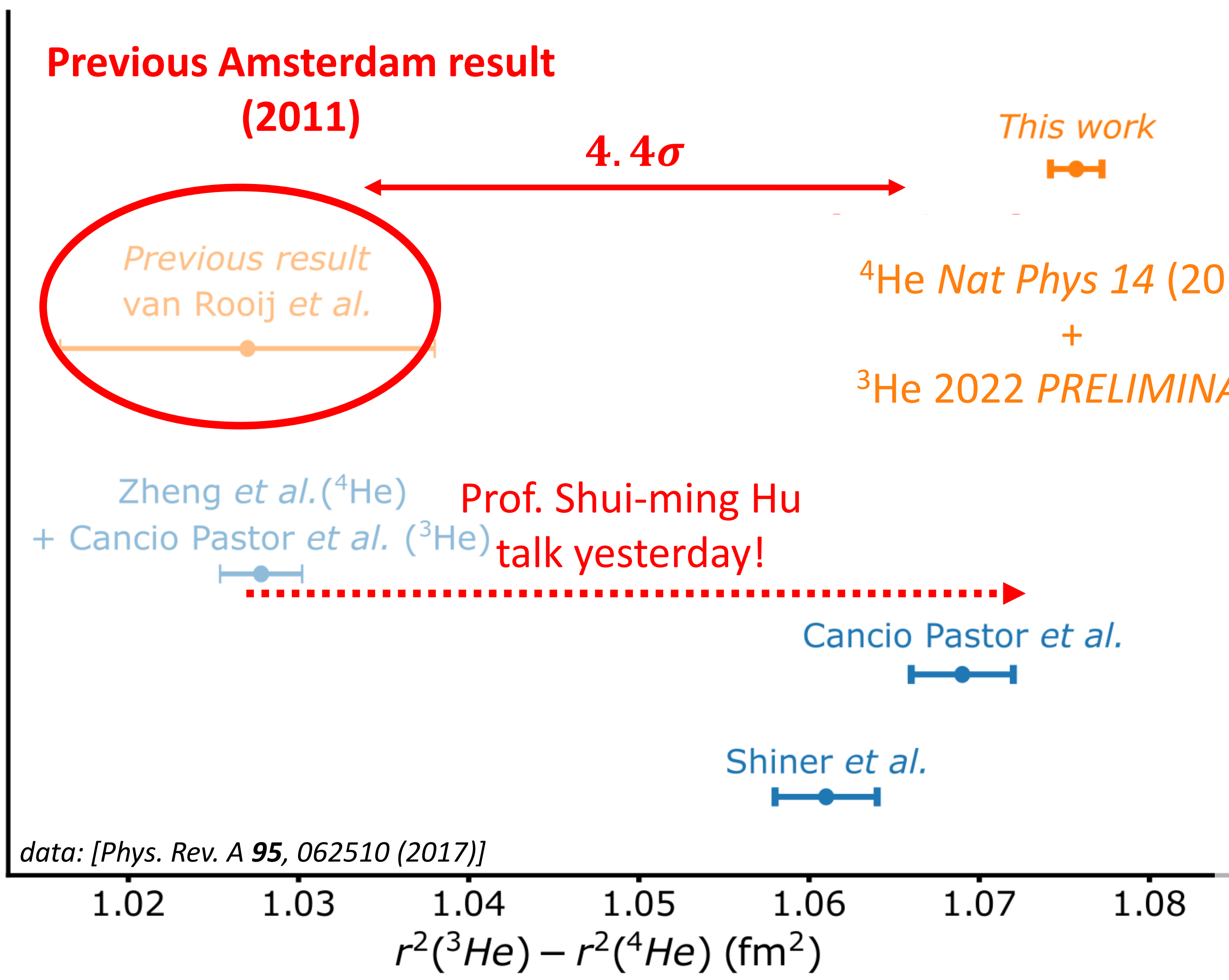
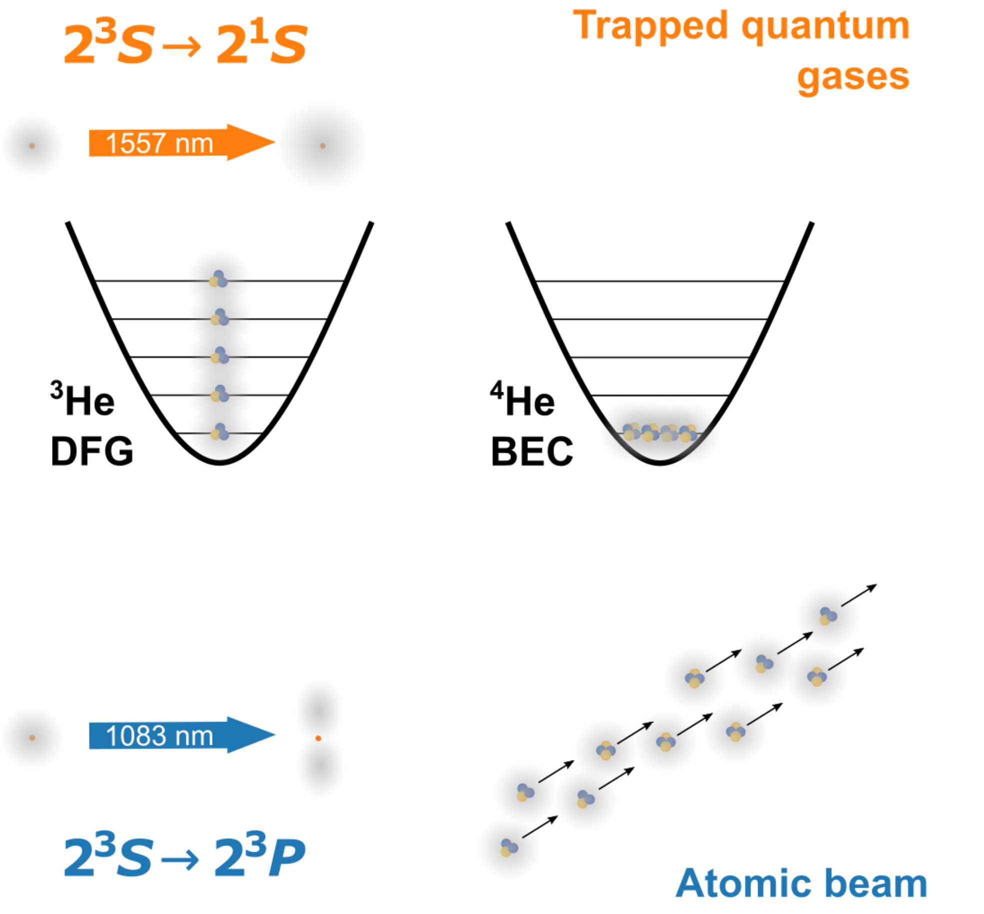
Nuclear Charge Radius Difference





PRELIMINARY
RESULTS

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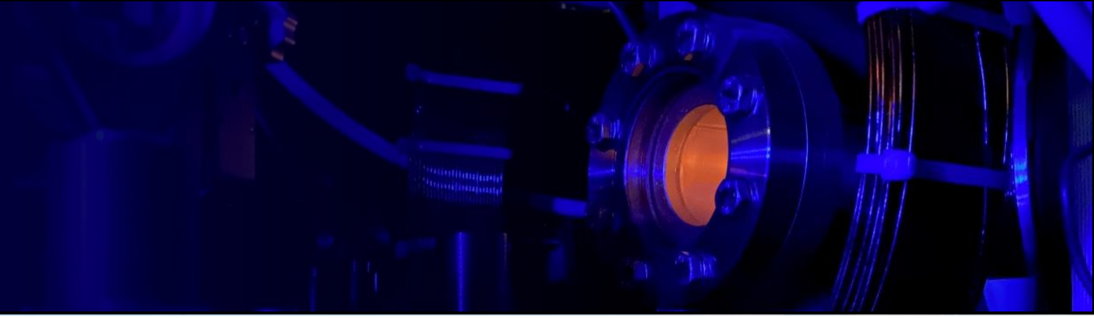
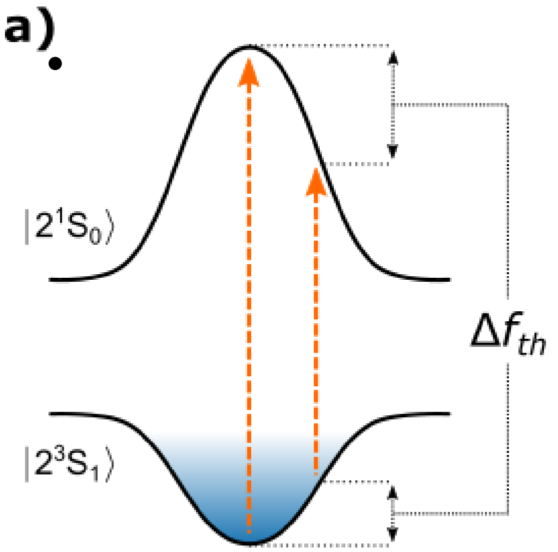
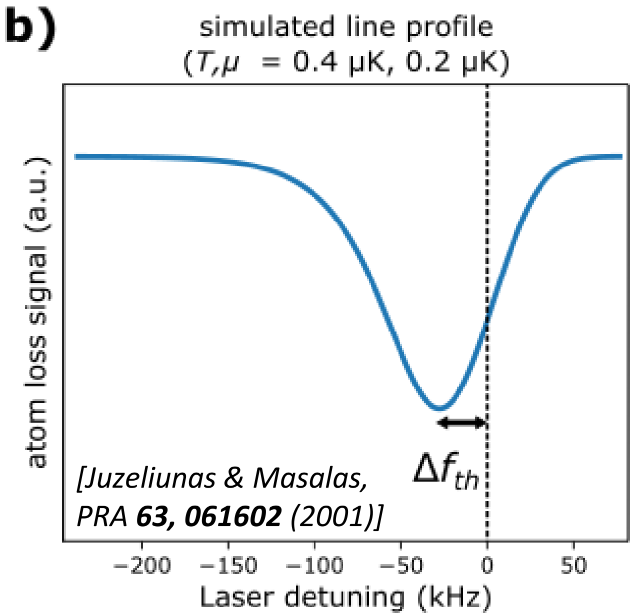
7 kHz (4.4 σ) deviation?

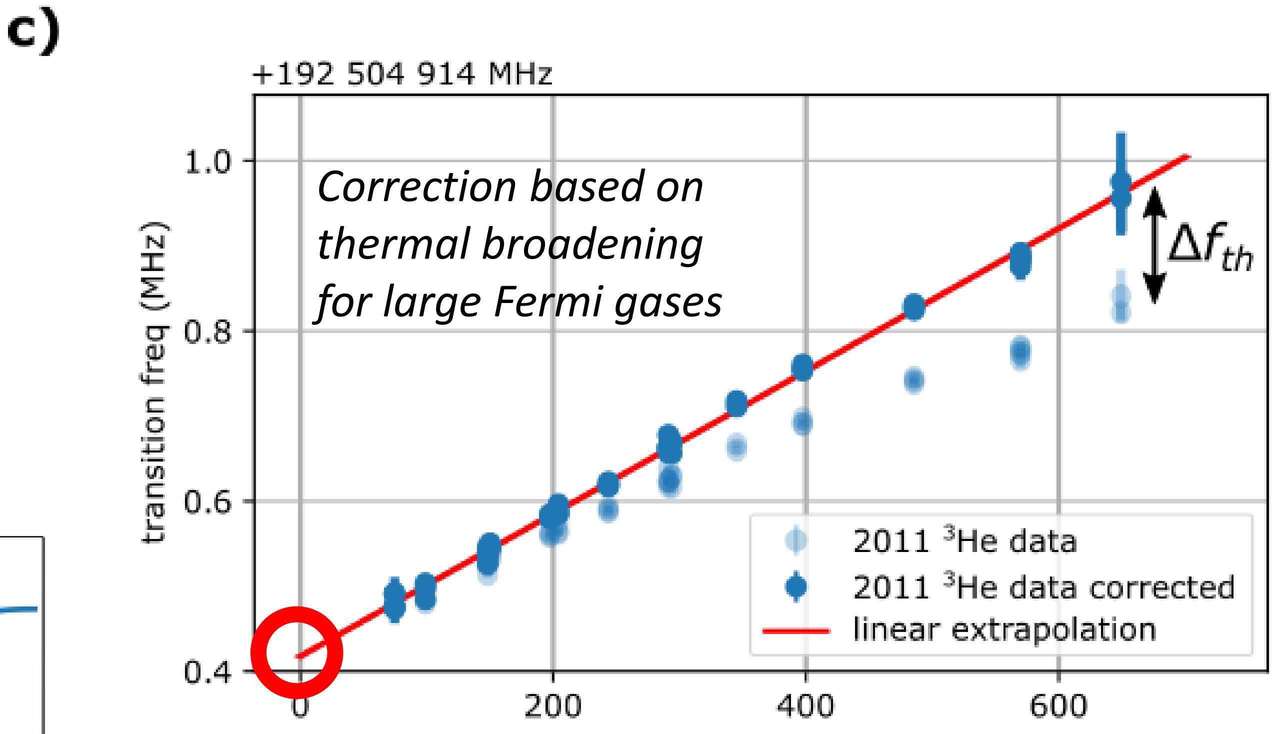


Previous Result: non-magic wavelength

- 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

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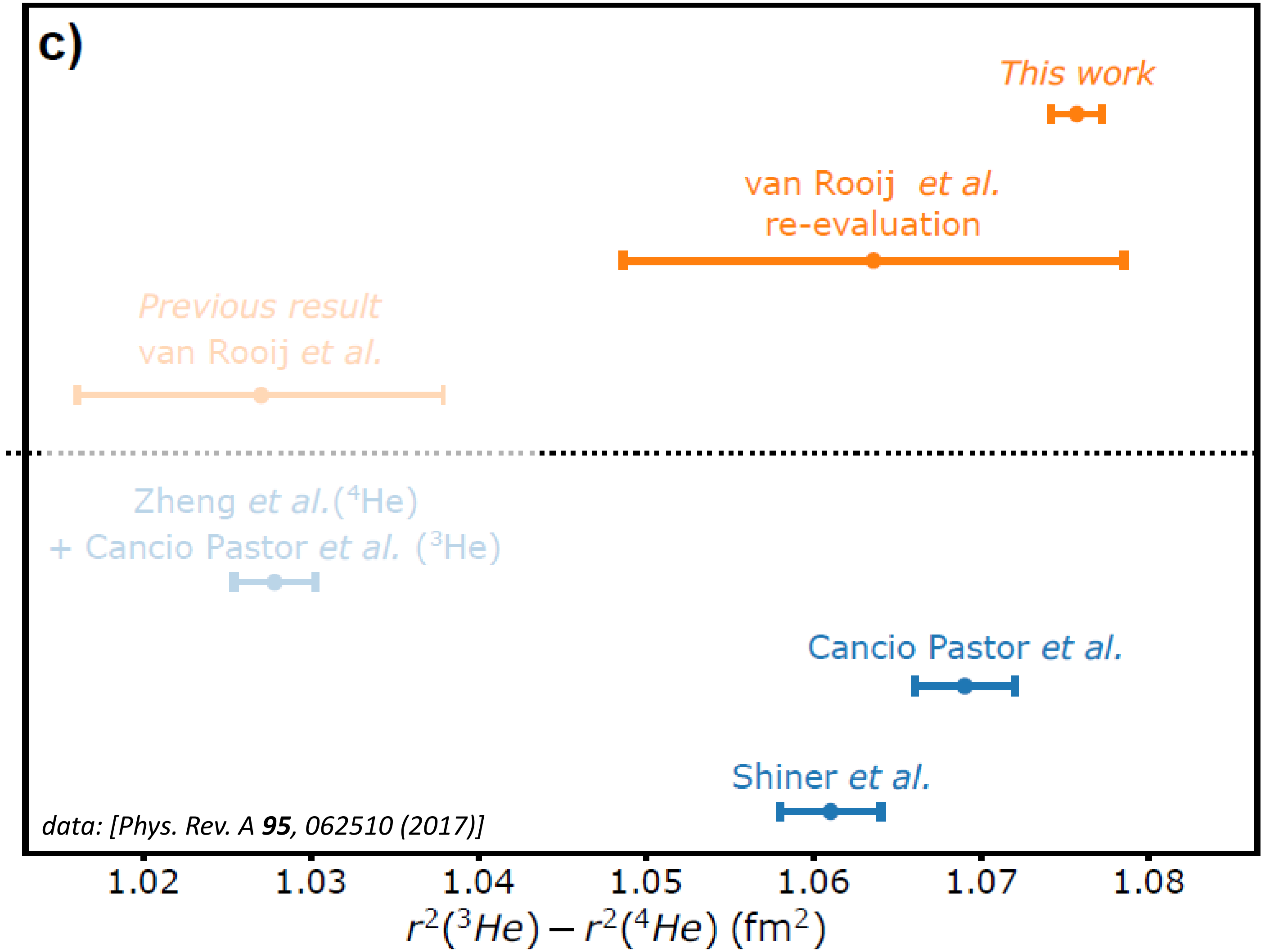
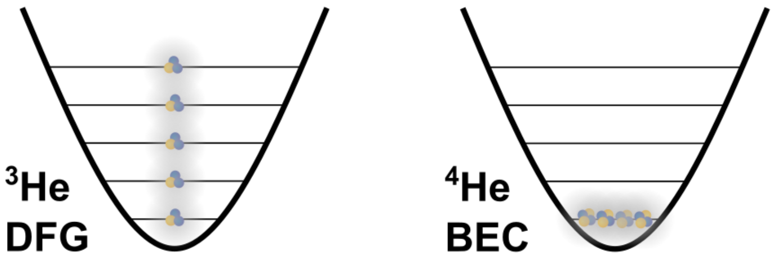
Nuclear Charge Radius Difference

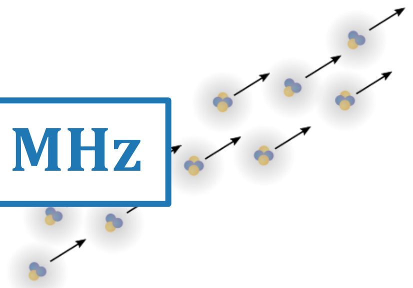


$2^3S \rightarrow 2^1S$

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

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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

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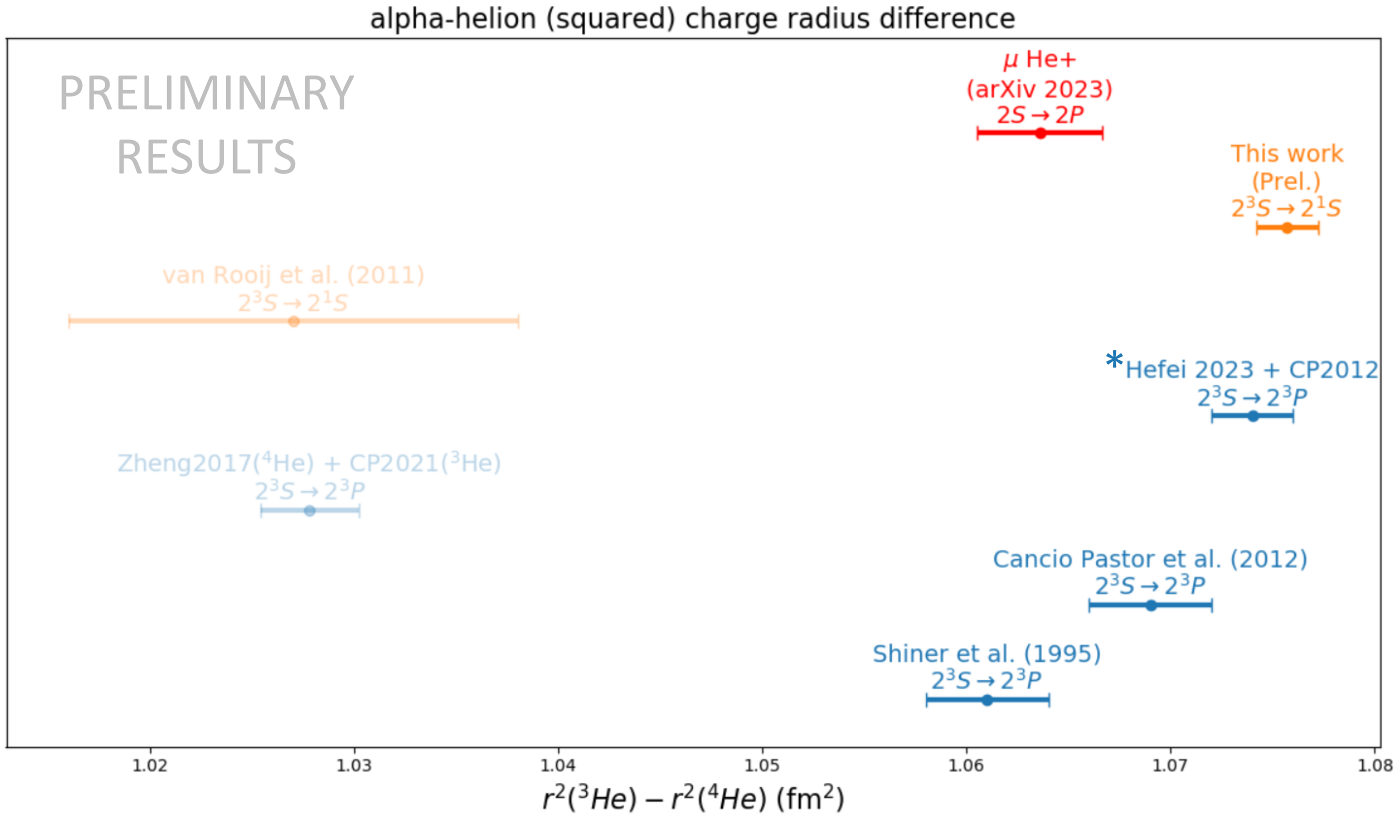
- He nuclear charge radii from $\mu\mathrm{He}^+$ spectroscopy
  - ^{4}He: $1.67824(83)$ fm *[Krauth et al. Nature **589**, p. 527–531 (2021)]*
  - **New result:** ^{3}He $1.97007(94)$ fm https://arxiv.org/abs/2305.11679



**Also new:*
Preliminary Hefei 2023
Shuiming Hu, FFK Vienna 2023

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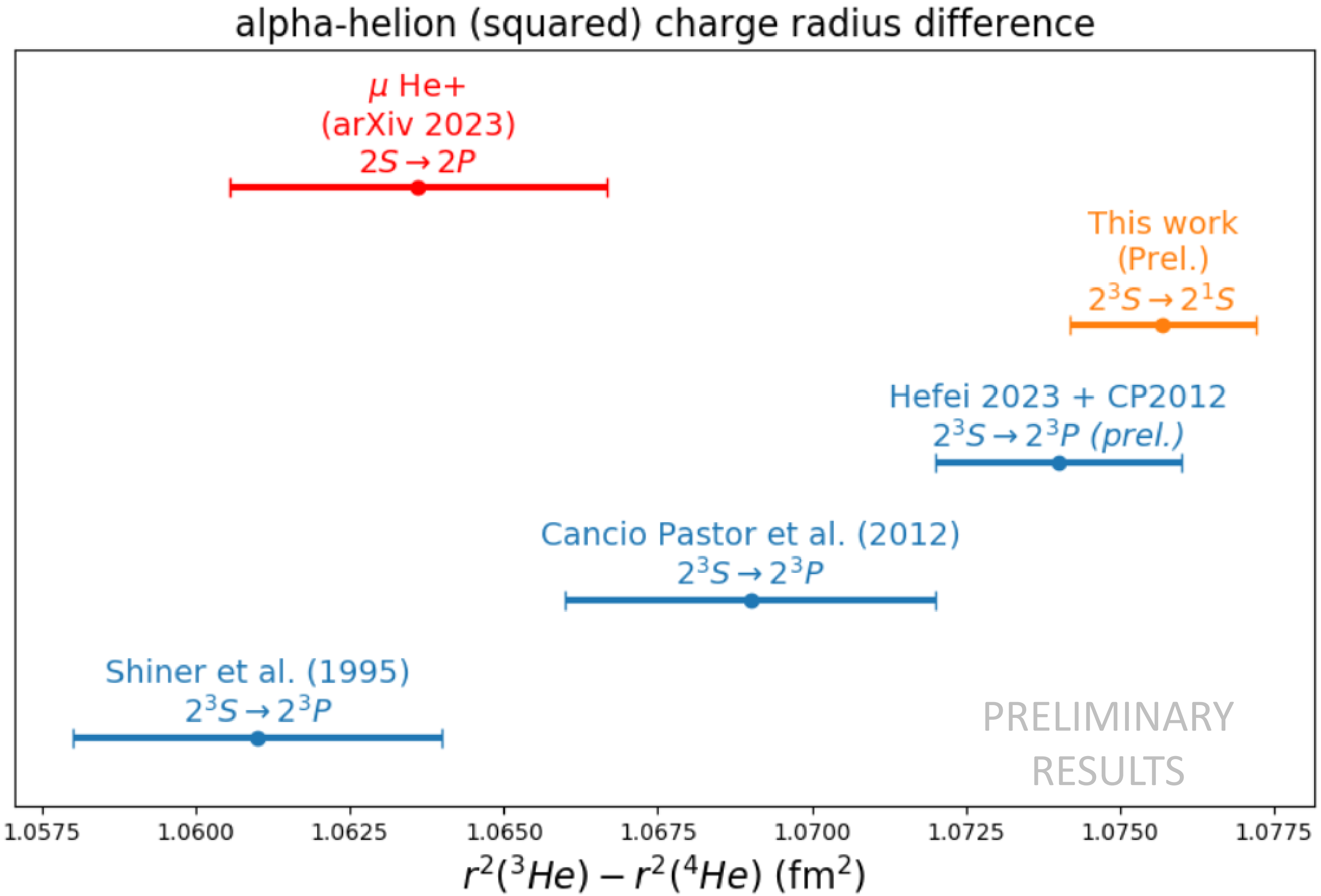
Electrons vs. Muons



- 3.6σ from $\boldsymbol{\mu}\mathbf{He}^{+}$
- $2\sigma - 4\sigma$ from $\mathbf{2^3S \rightarrow 2^3P}$
- Hefei ^{3}He?
- 1.9 kHz shift for 1σ agreement with muonic

- Discrepancies:
  - *New physics? Well……………….*
  - Very different systematics
  - Theory: triplet vs. singlet
  - Muonic: higher-order QED

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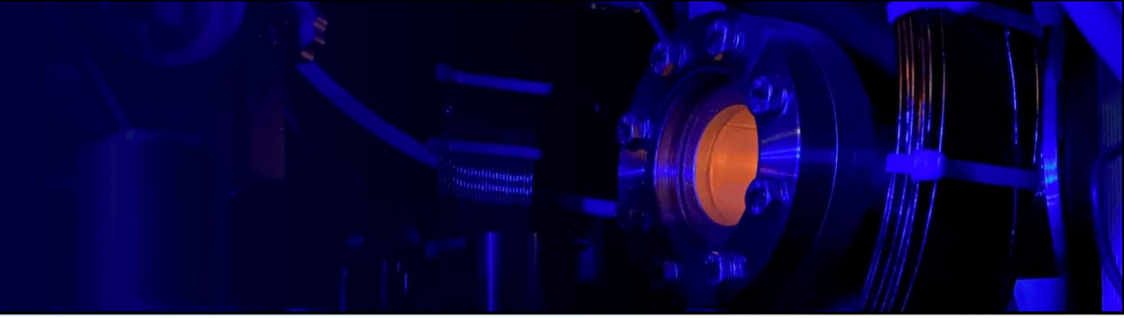
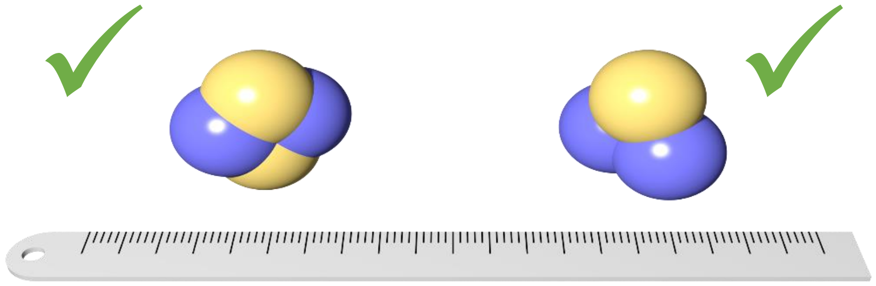
In conclusion



- 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***



https://arxiv.org/abs/2306.02333

- Exploring the 'Quantum Frontier'?
  - 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?

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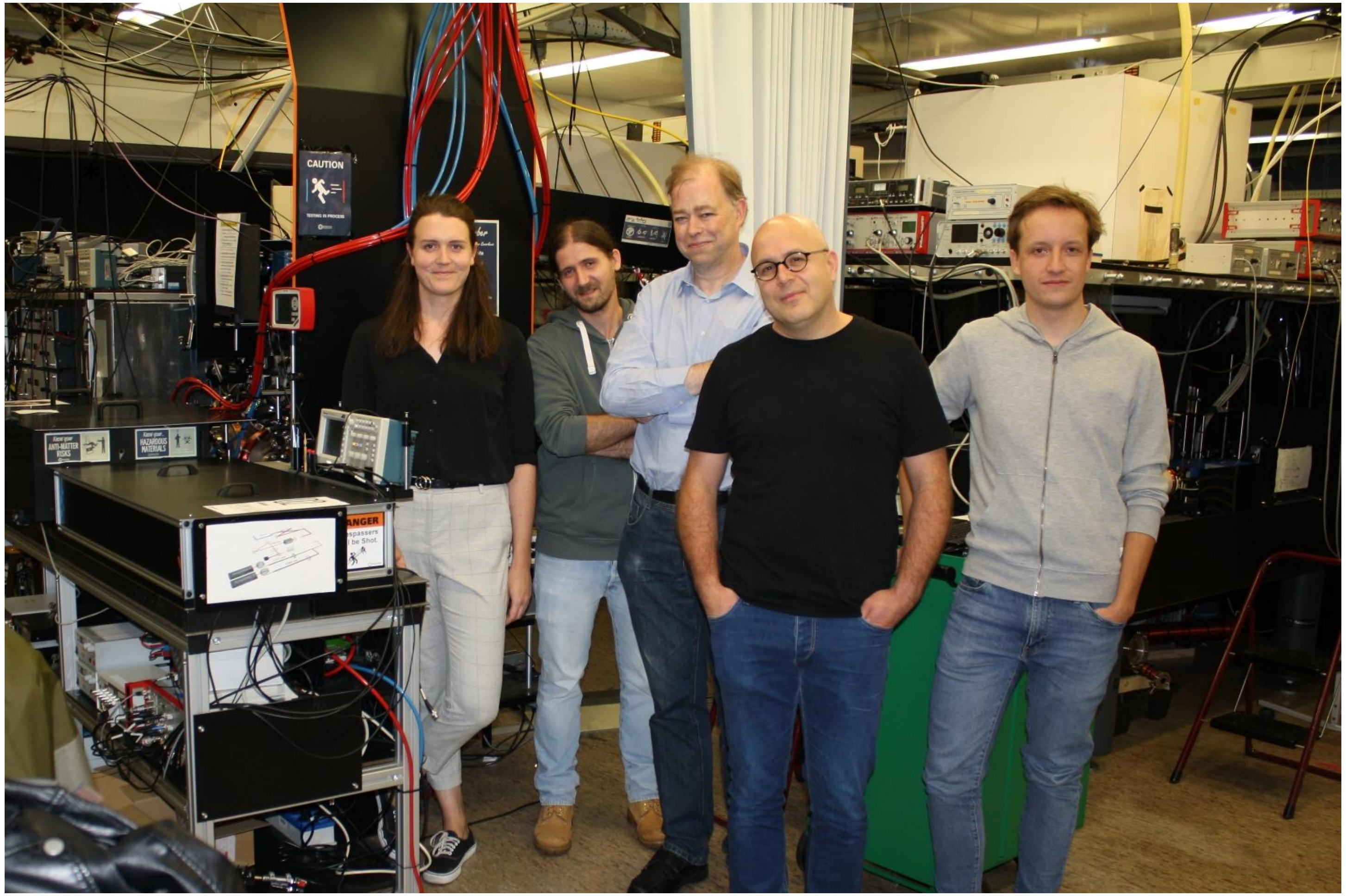
Thanks for your attention!



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- Yuri van der Werf
- Rick Bethlem
- Kjeld Eikema
- Bob Rengelink

Technical support:
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- Lex van der Gracht

Funding & facilities:

Wim Vassen:
† *11-2-2019*

NWO

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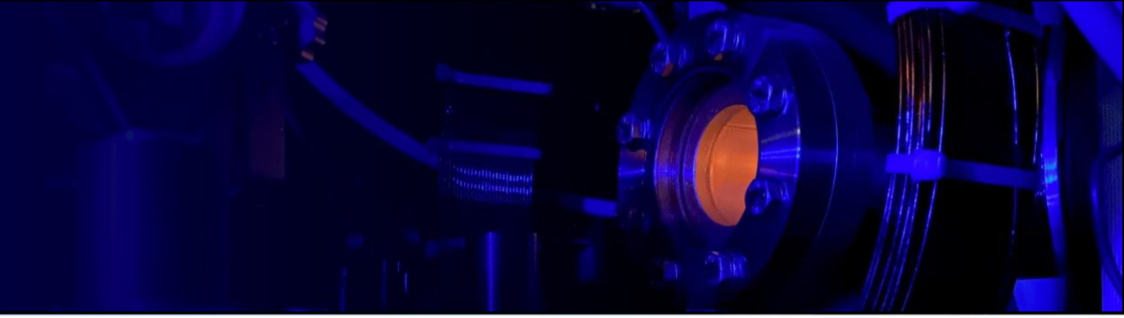
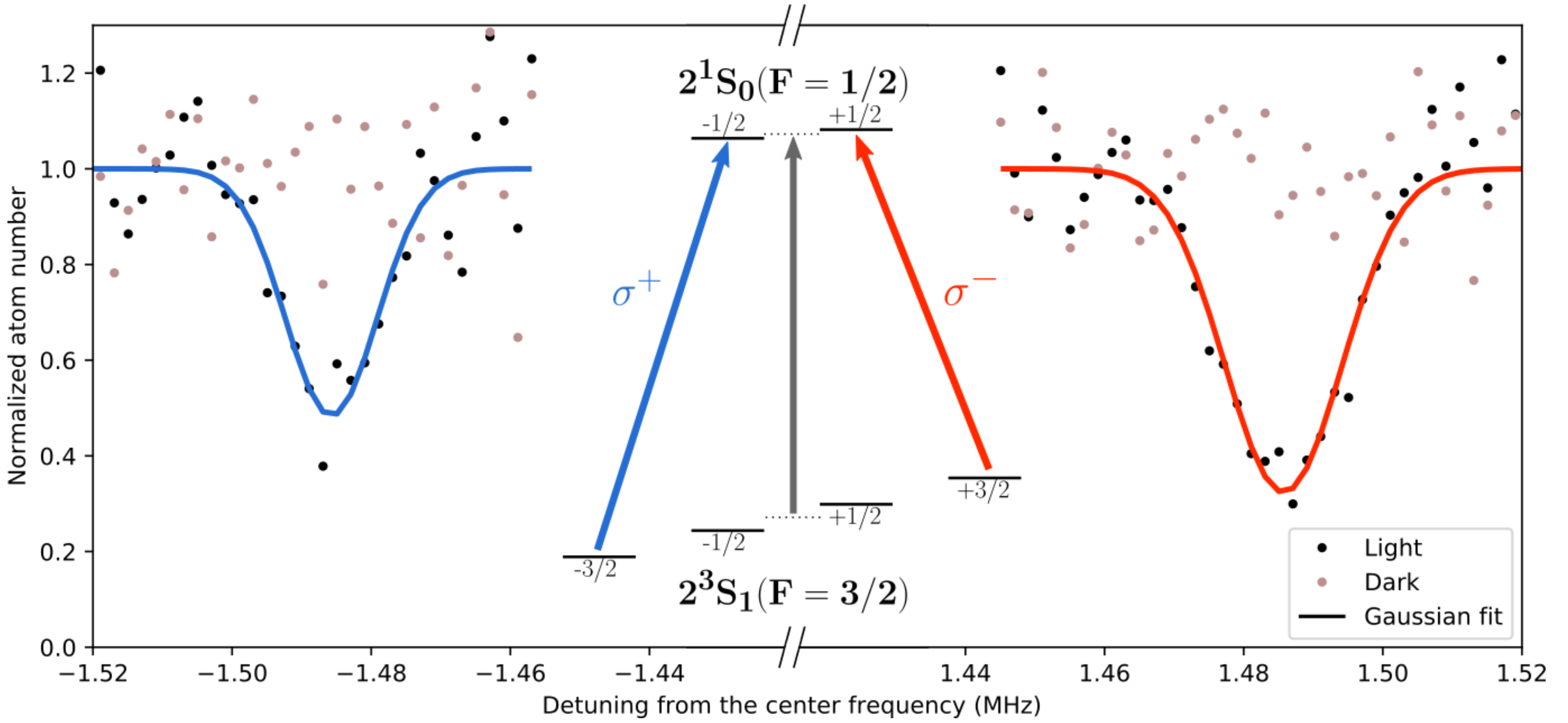


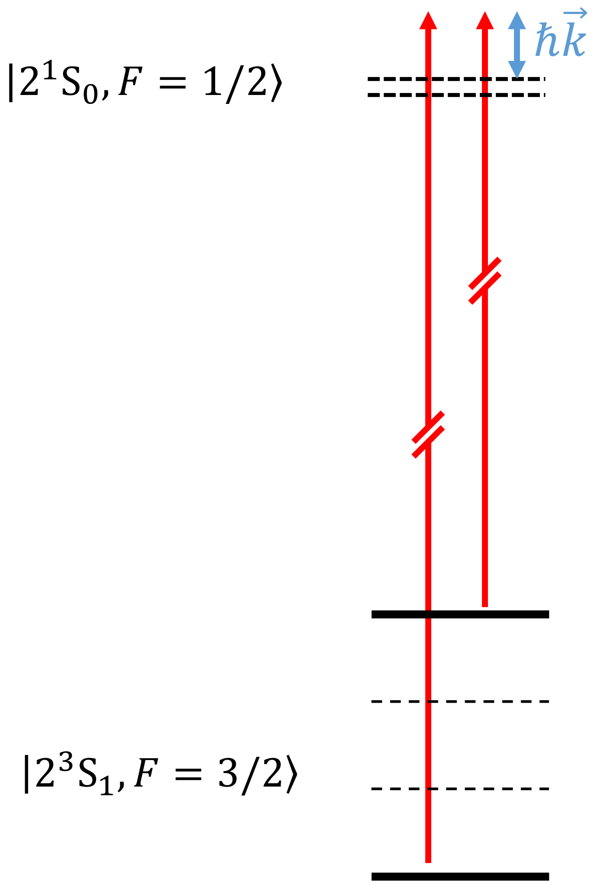
Questions?

Email: y.vander.werf@vu.nl

Precision spectroscopy

- Systematics analysis: **Zeeman shift**





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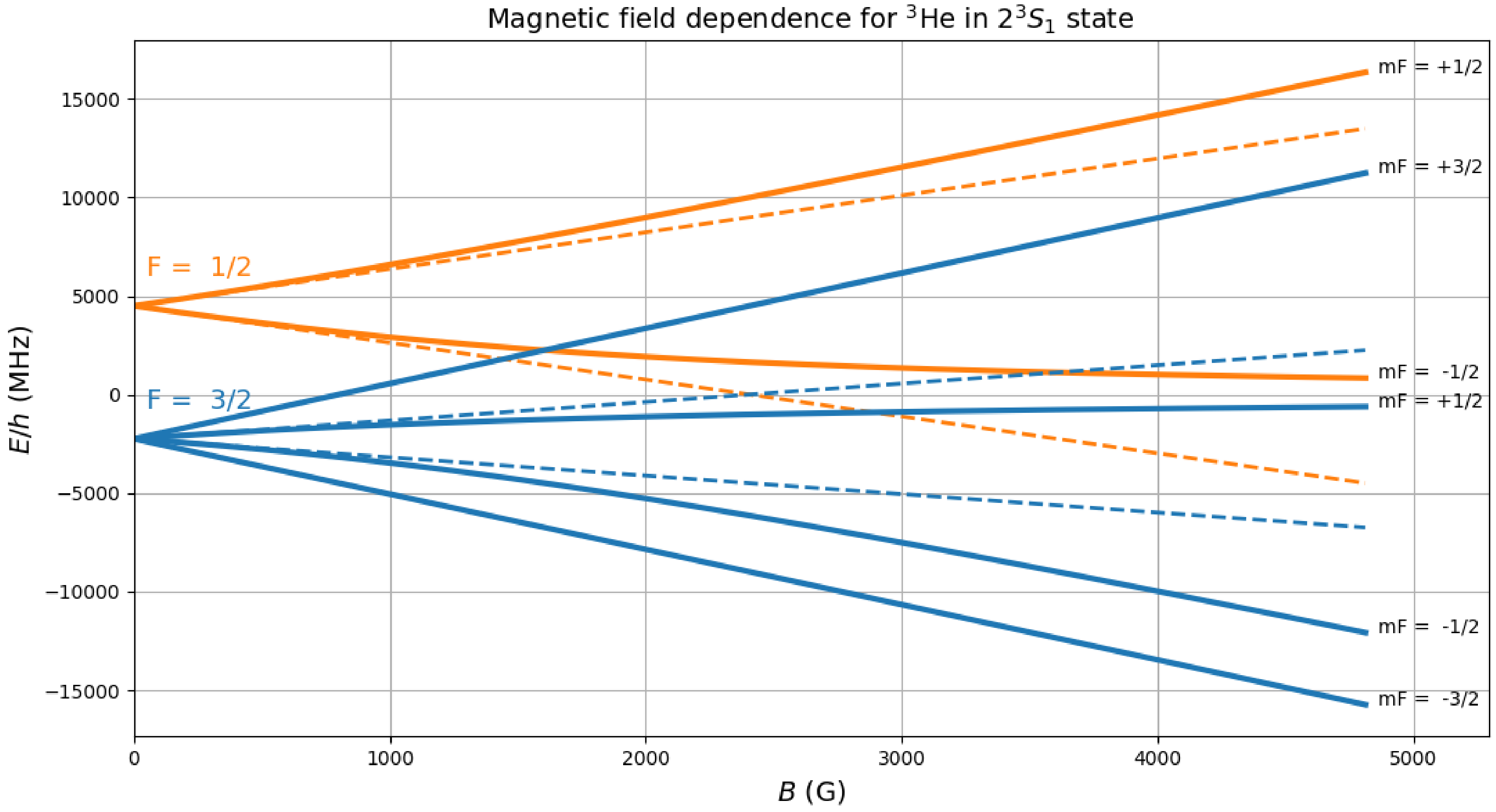
Systematic analysis

- 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: $< 4\ \mathrm{mHz/G^2}$

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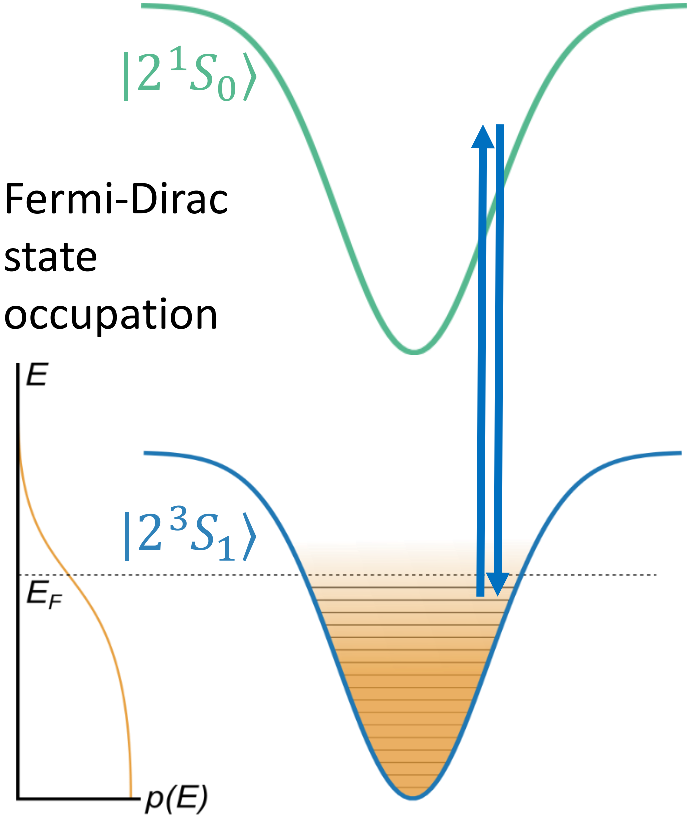
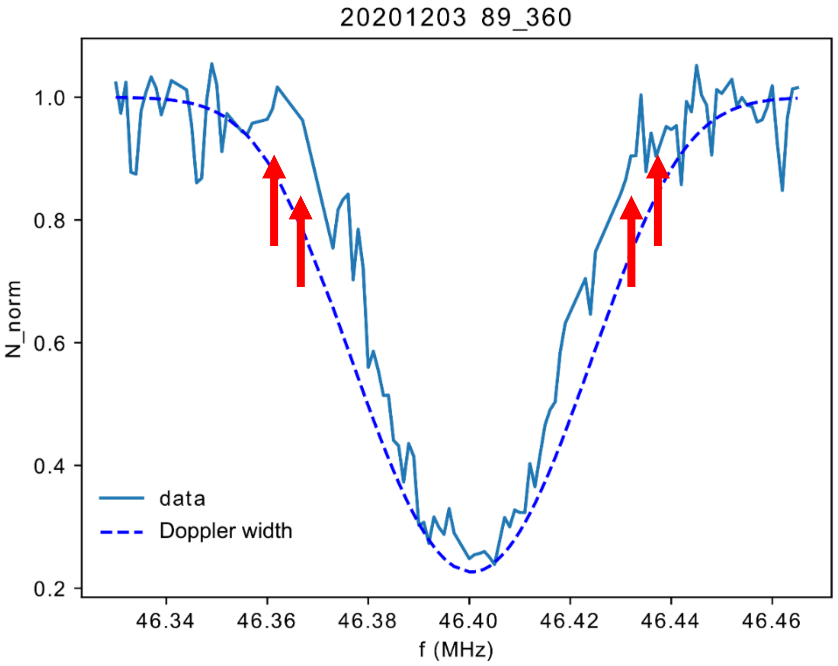
Reduced linewidth

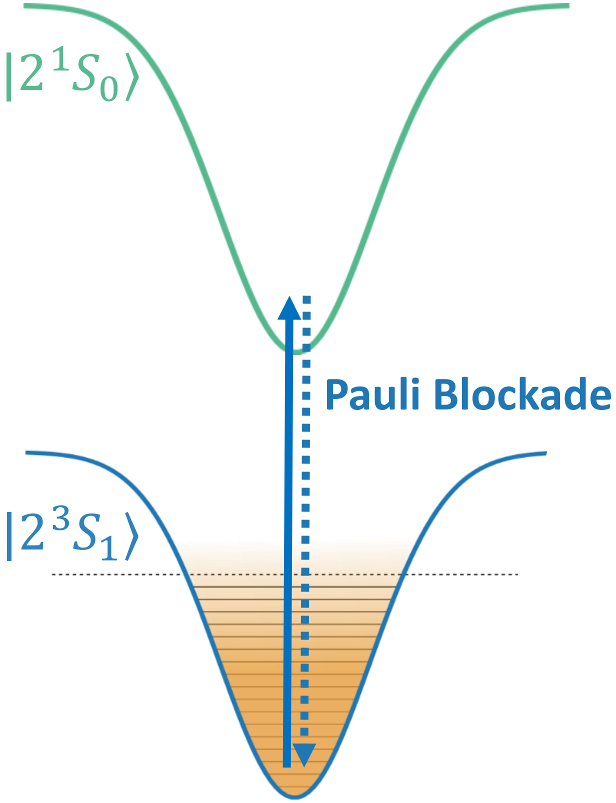
Tails of spectrum: ***reduced loss***



We measure the remaining He*



Center of spectrum: high loss



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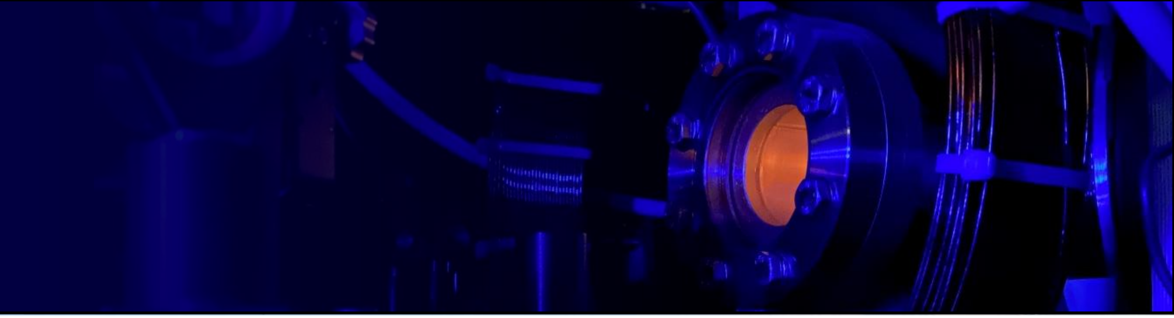
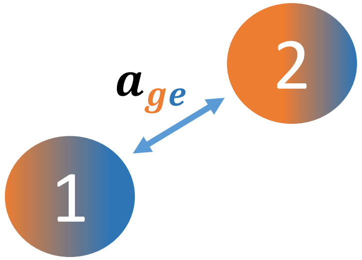
Systematic analysis



- Cold collision shift?

  IDENTICAL cold* fermions don't collide

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



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

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

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

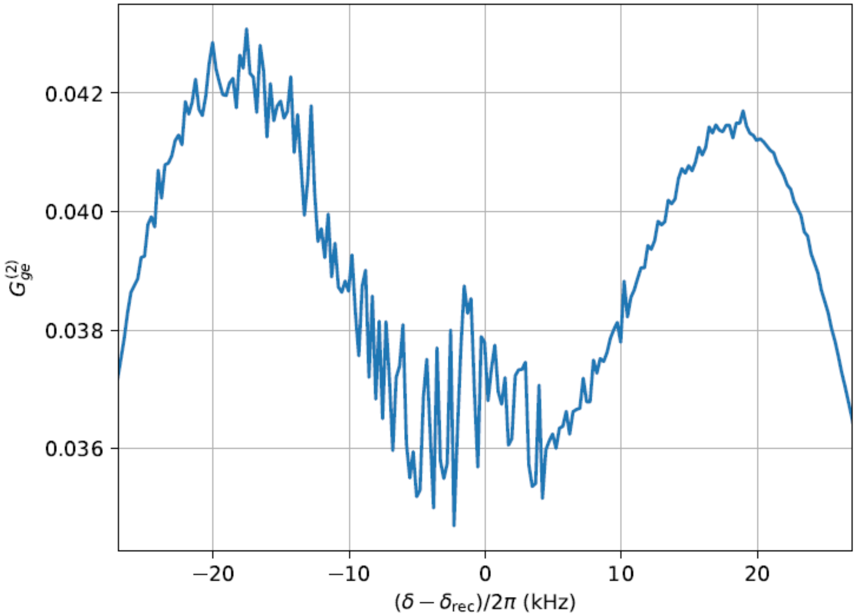


Figure 2: Time-averaged correlation as a function of the detuning of the spectroscopy laser.

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

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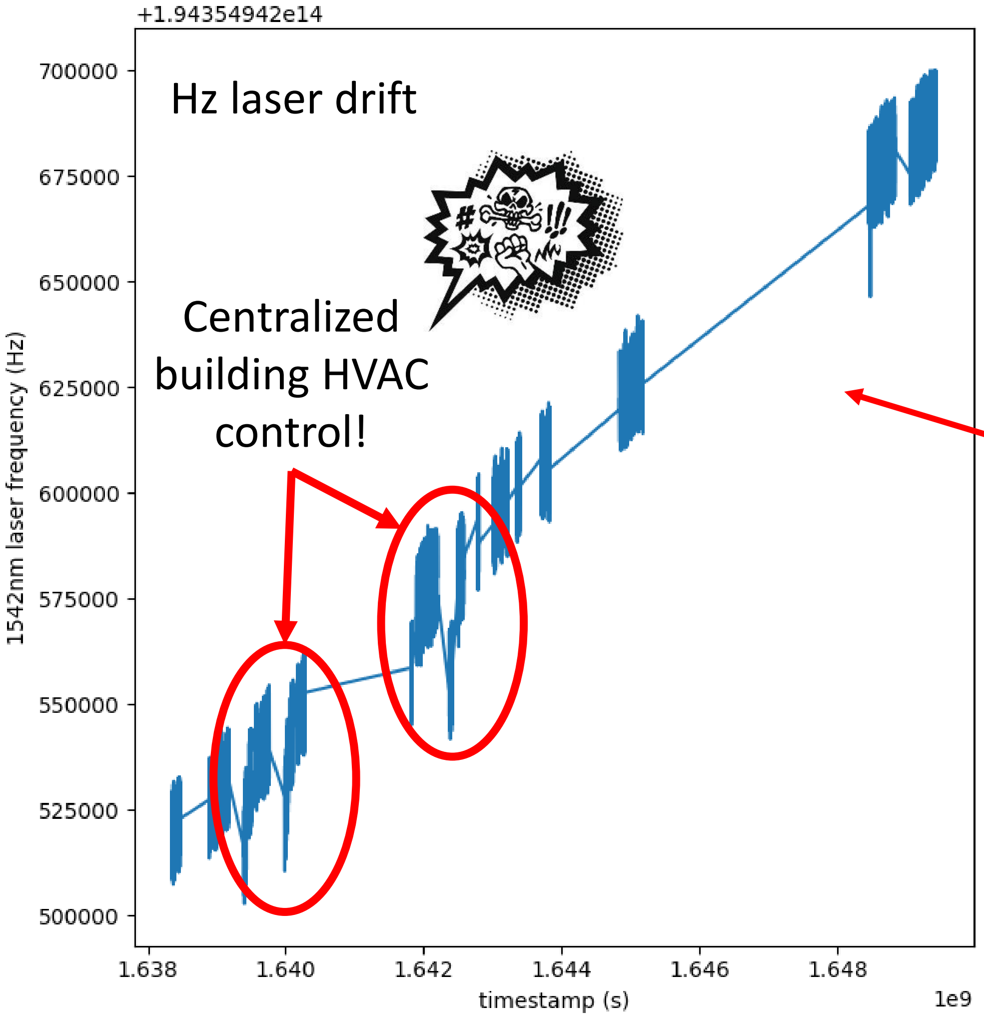
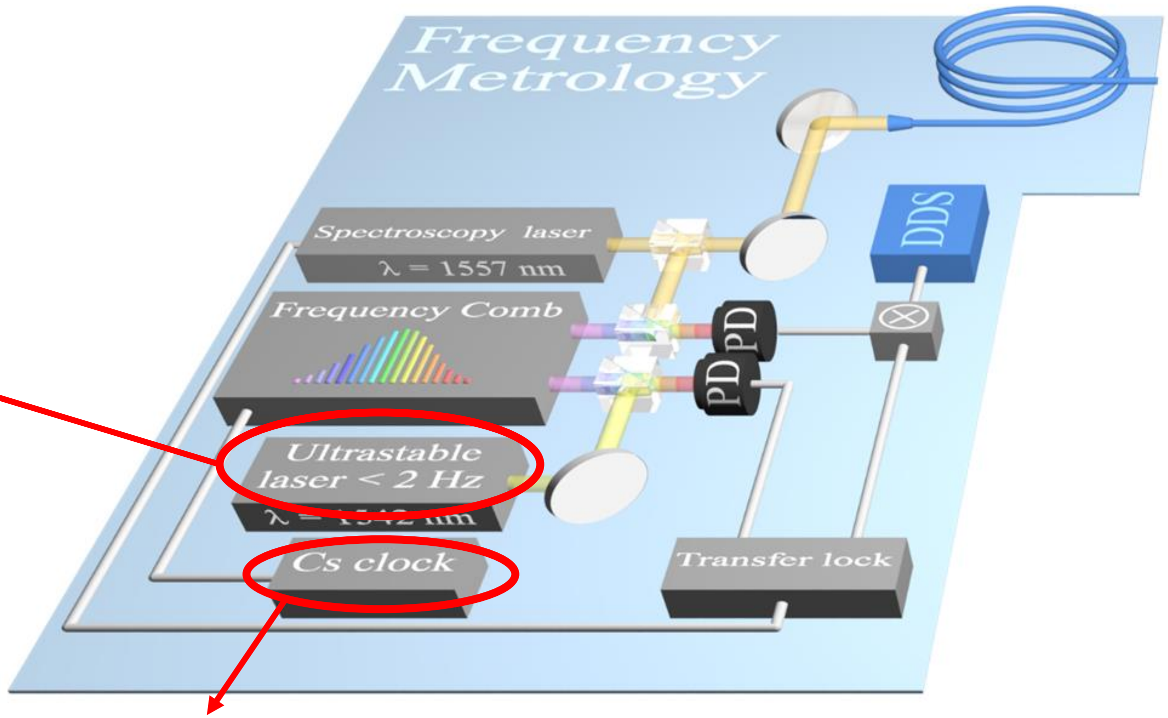
Frequency metrology





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

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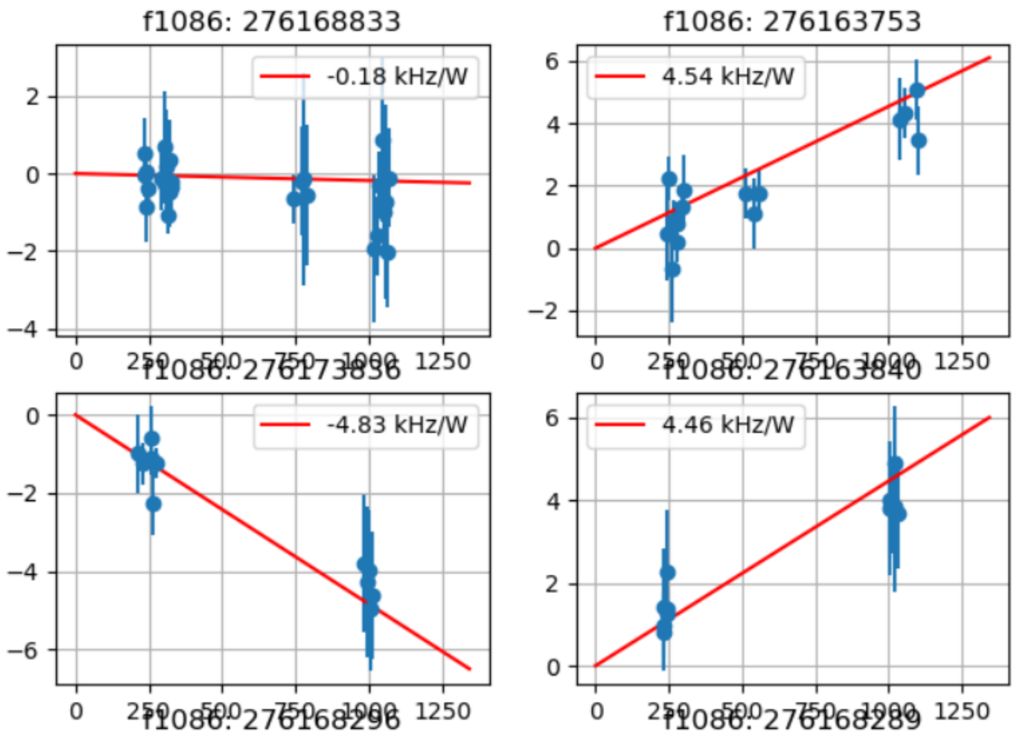
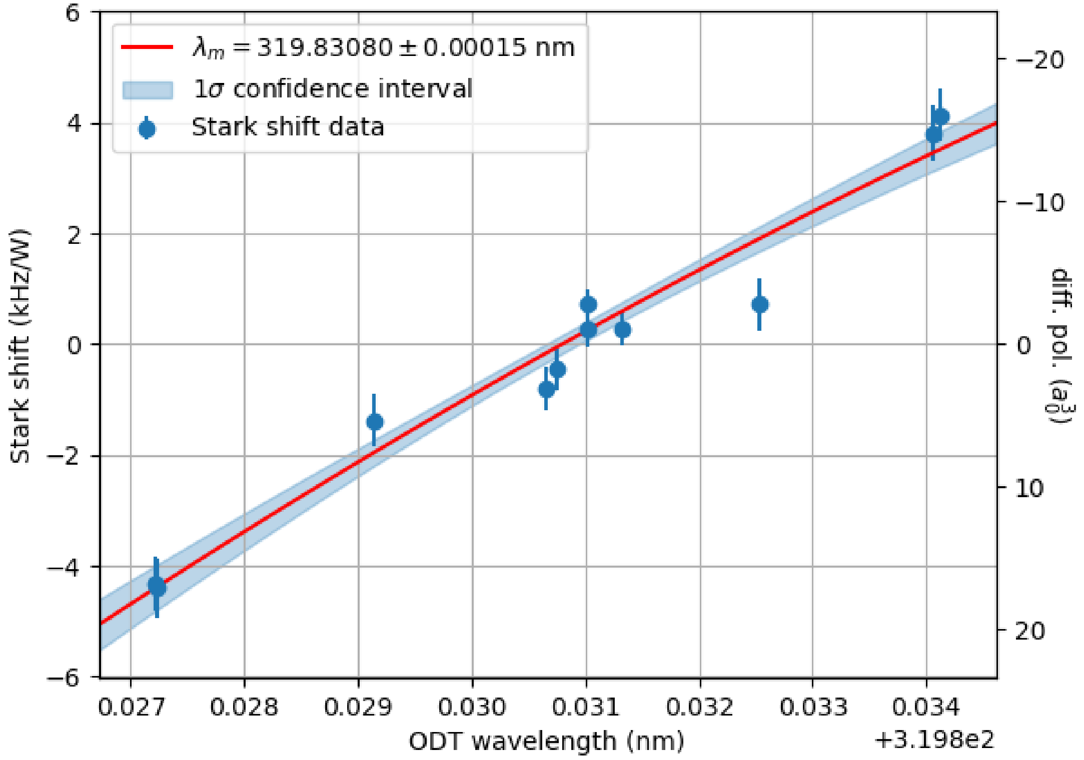
Finding the magic wavelength

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





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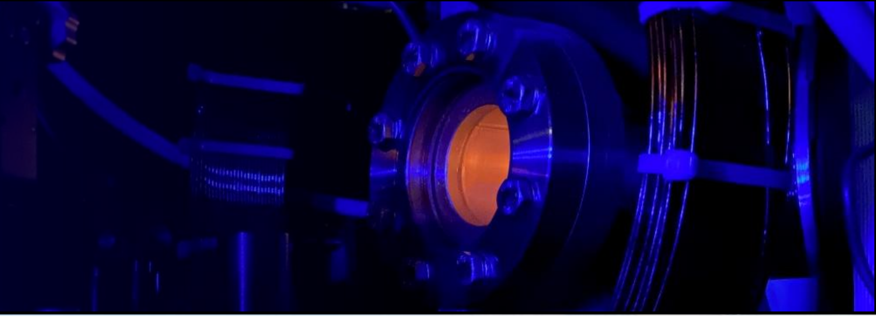
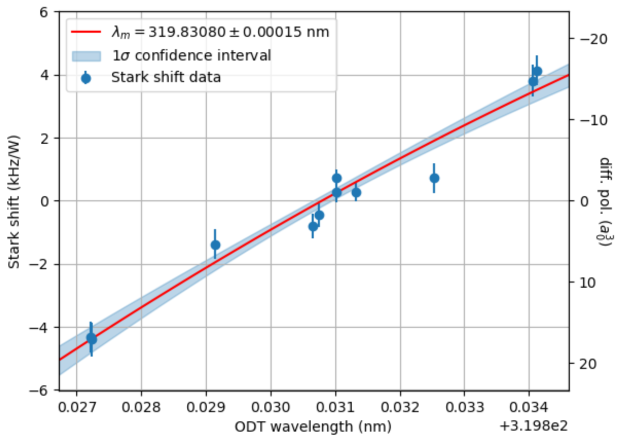
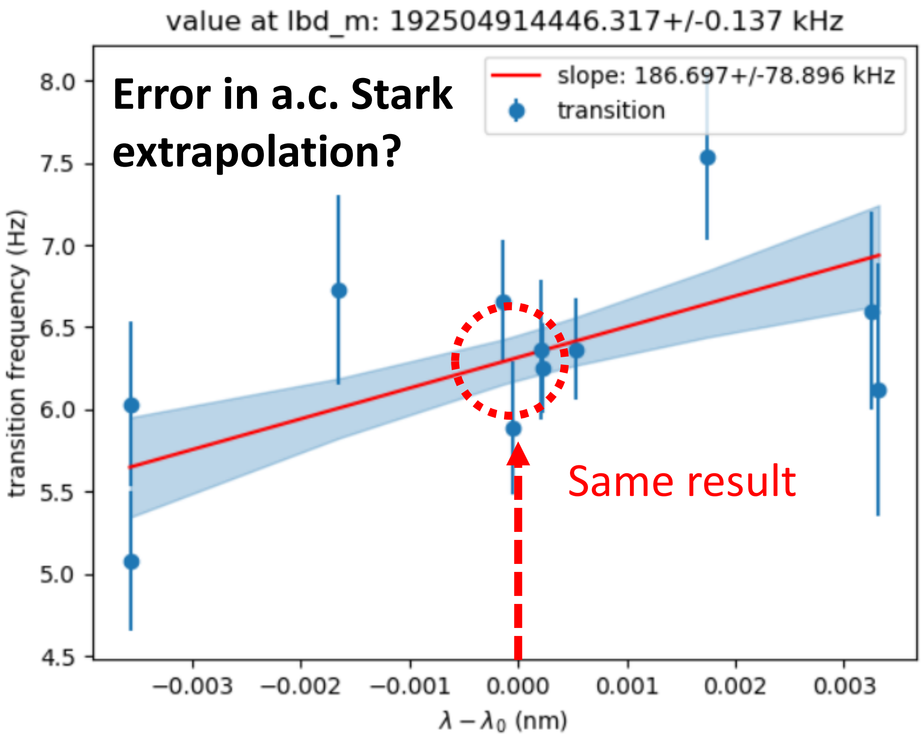
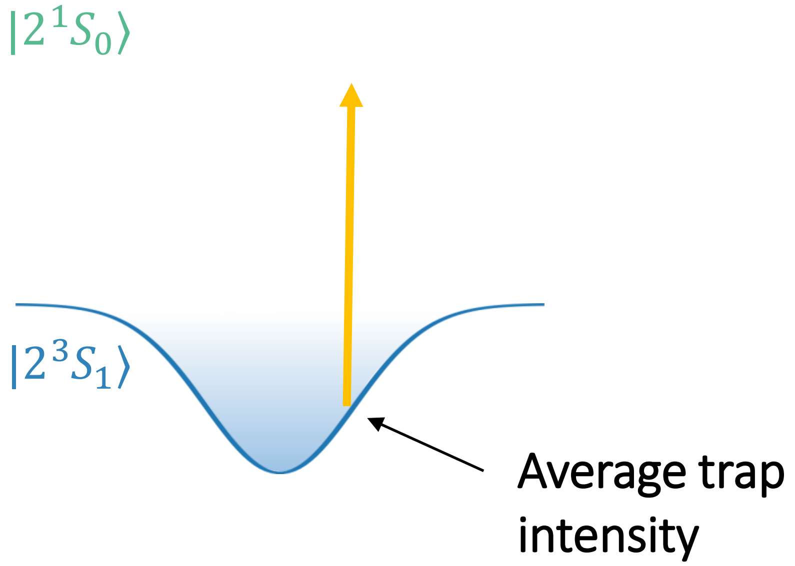
Thermodynamic shift: @320nm





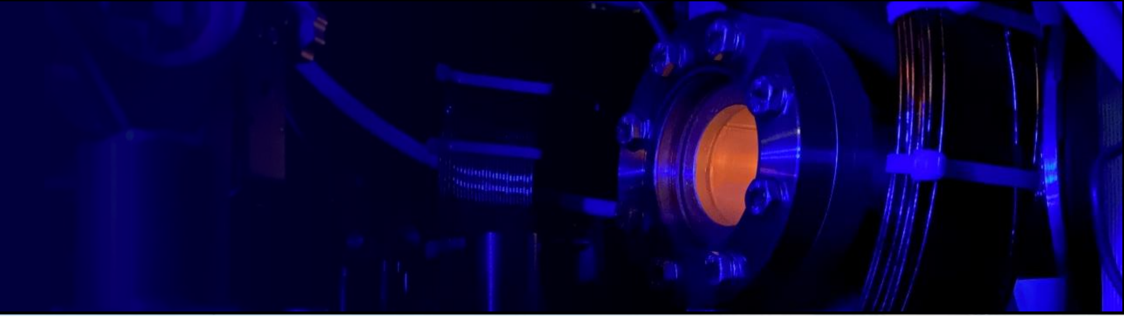
$$\langle I_{320} \rangle = \Delta f_{Stark}/\alpha \approx 5.5 \times 10^7 \ \mathrm{Wm}^{-2} \ ^*$$
$$I_{peak} \approx 10^8 \ \mathrm{Wm}^{-2}$$

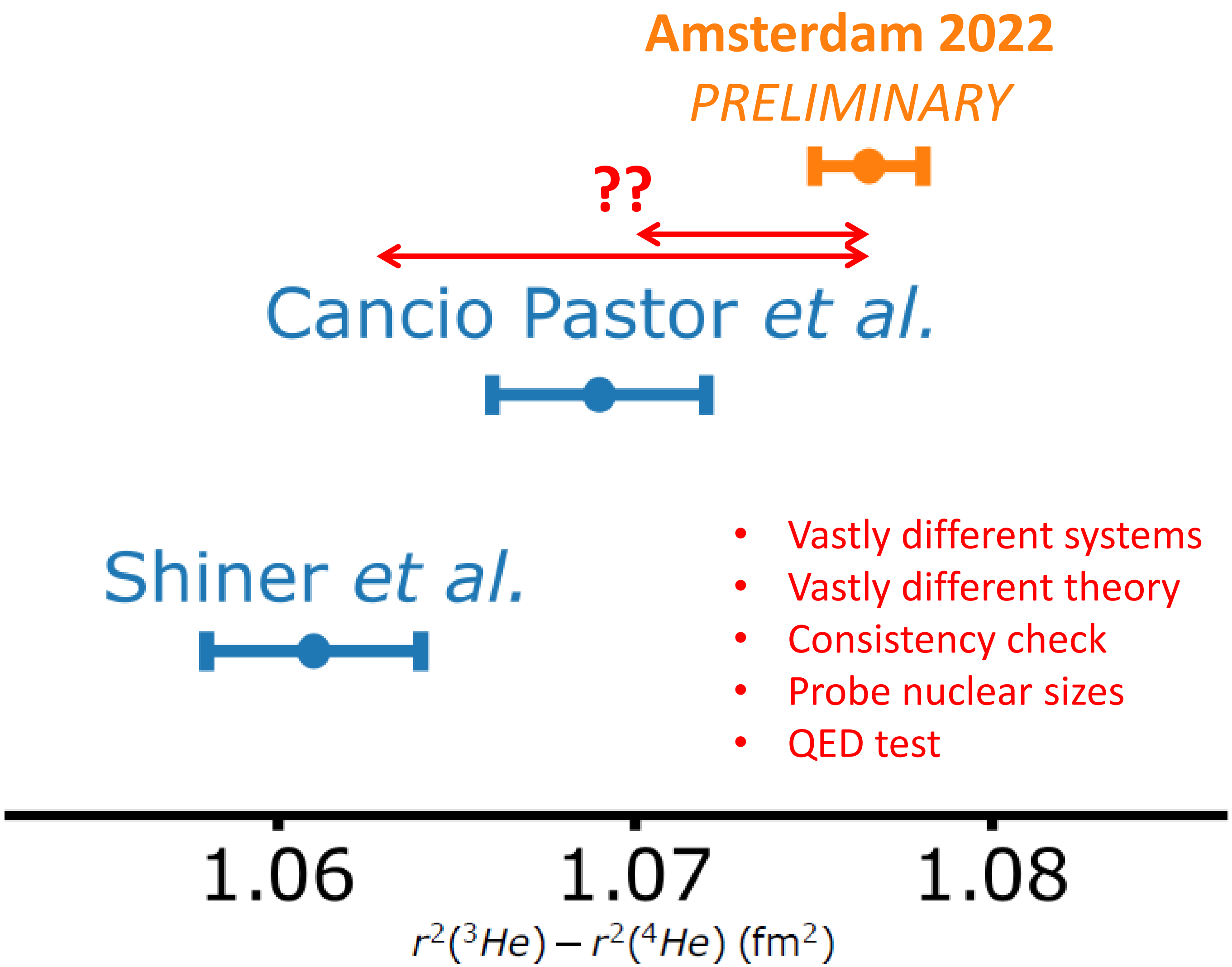




* @ 1W UV power

Electrons vs Muons?



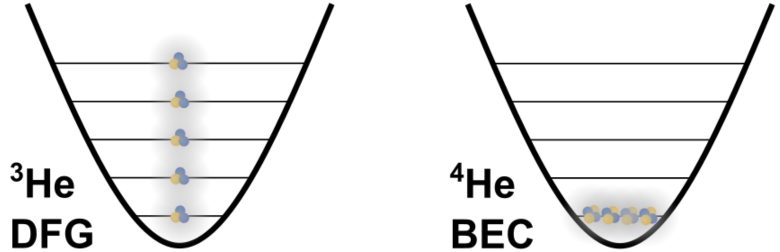


- Vastly different systems
- Vastly different theory
- Consistency check
- Probe nuclear sizes
- QED test

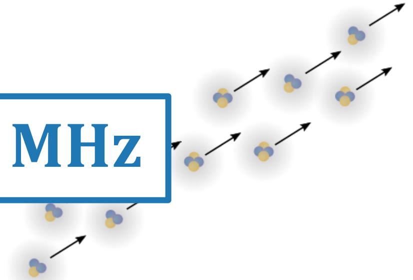
$2^3S \rightarrow 2^1S$

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

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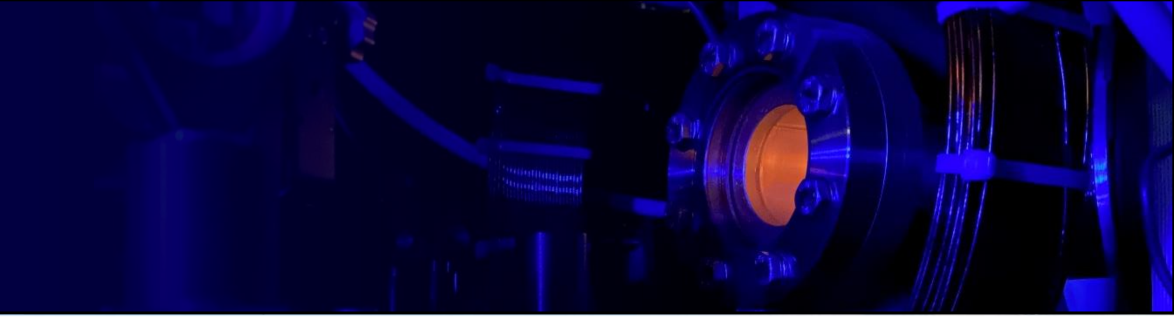
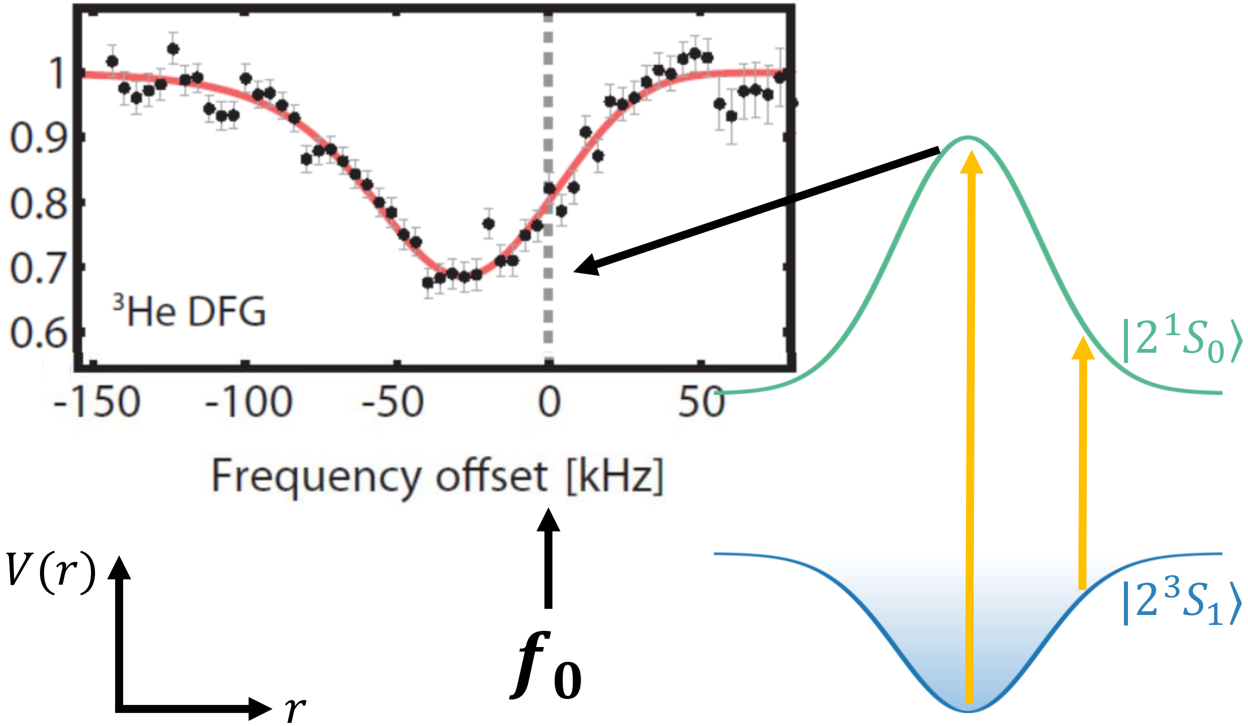


4.4 σ deviation?

2011 result:

1557 nm dipole trap + direct frequency comb lock

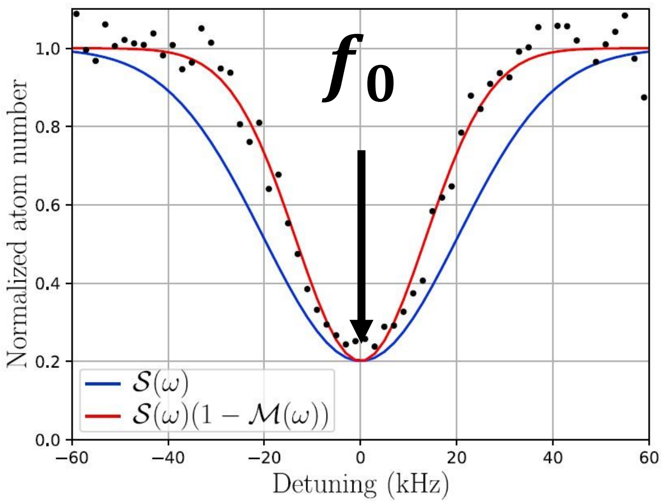
- Fermi-Dirac: AC Stark shift asymmetry
- Not resolved within laser bandwidth
- Verified now with new spectroscopy laser

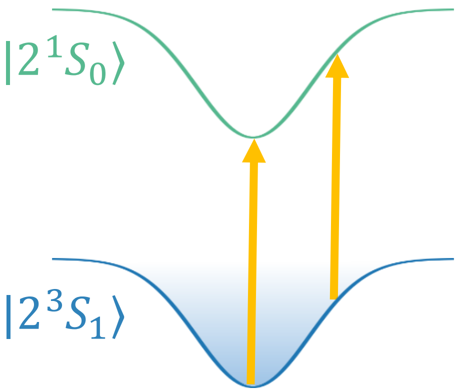


2022 result:

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

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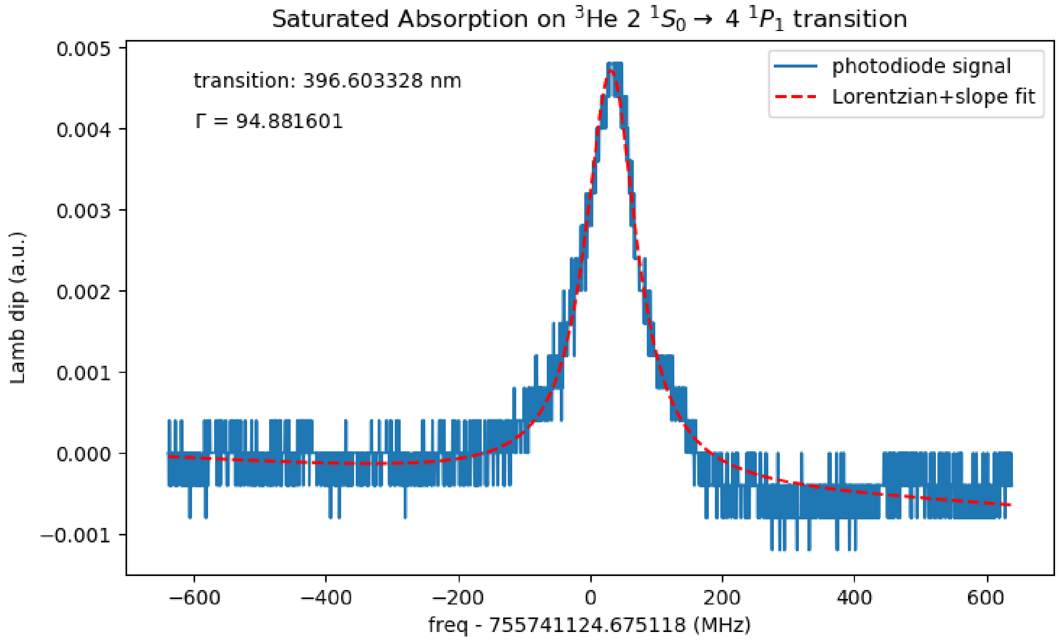
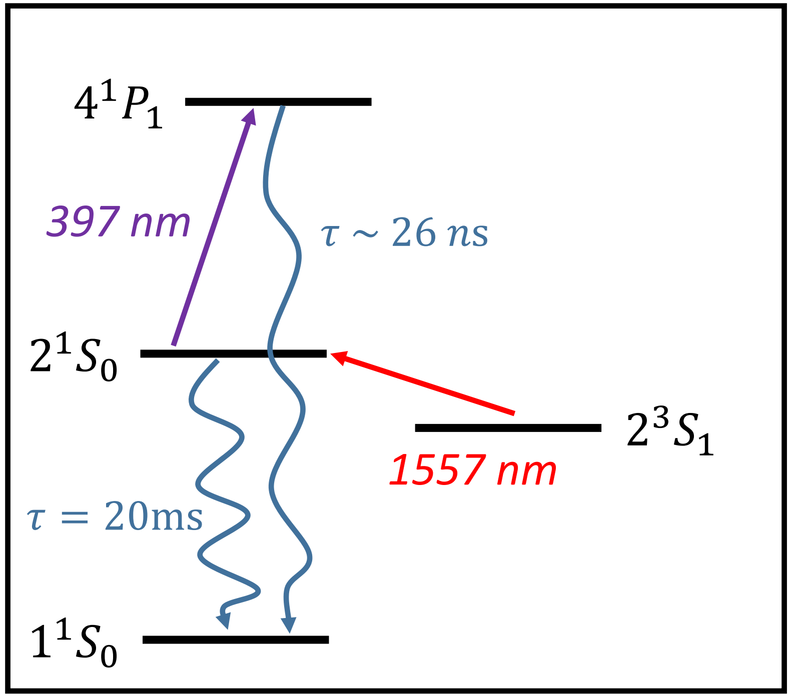
Testing the model

- Enhanced ground state decay through 4^1P_1 state

  Eliminate the stimulated emission channel

  Lift Pauli Blockade effect





PRELIMINARY RESULT

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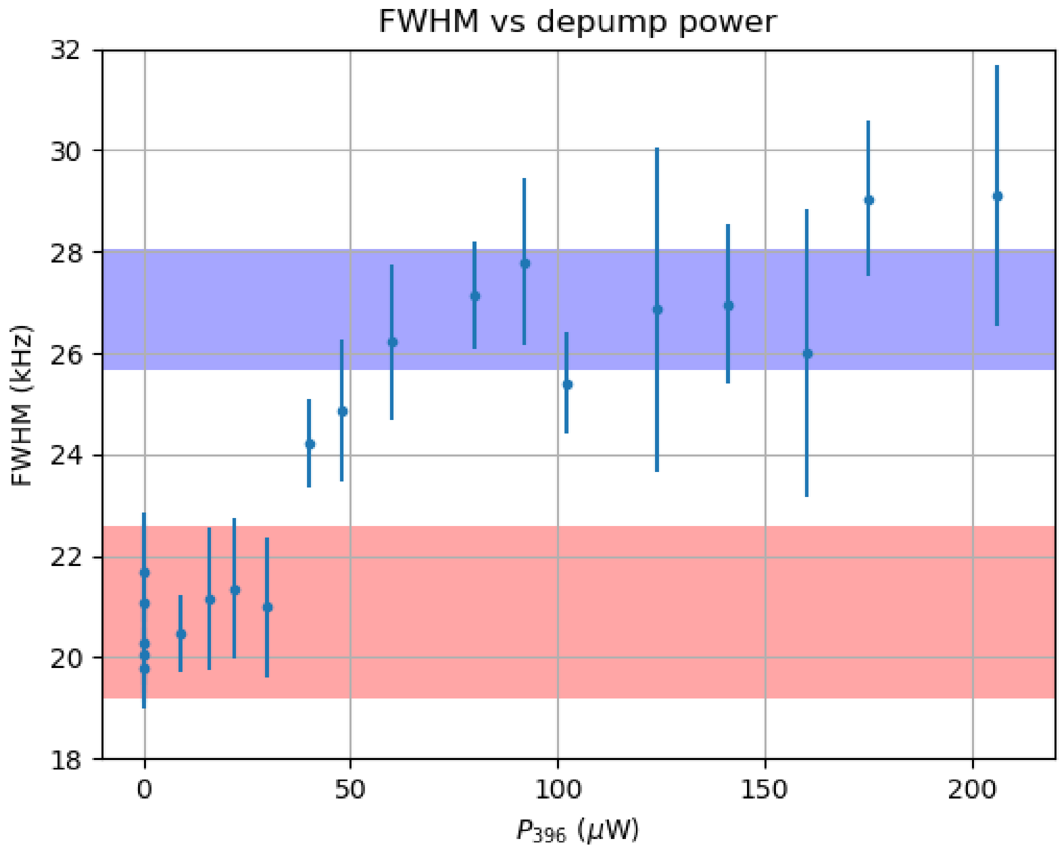
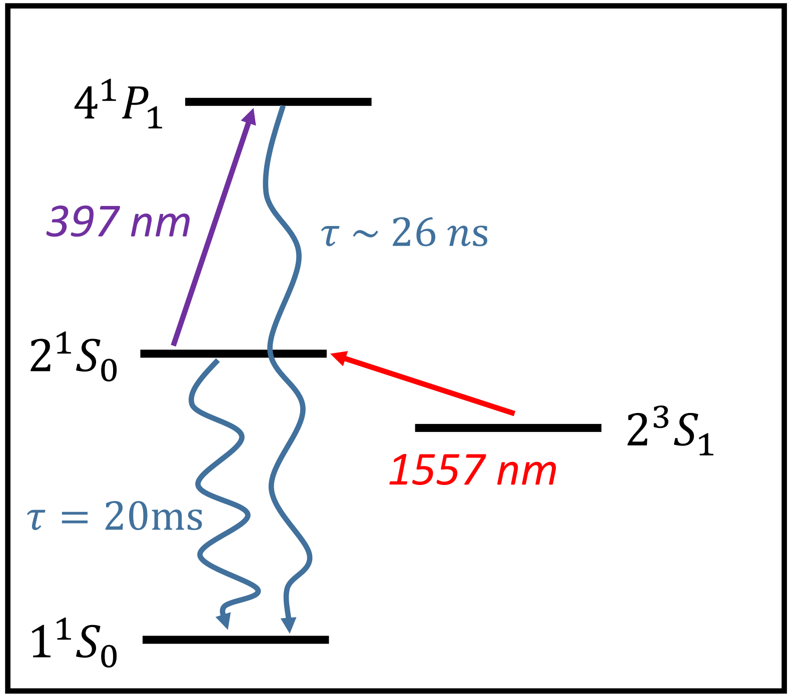
Testing the model

- Enhanced ground state decay through 4^1P_1 state





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

PRELIMINARY RESULT

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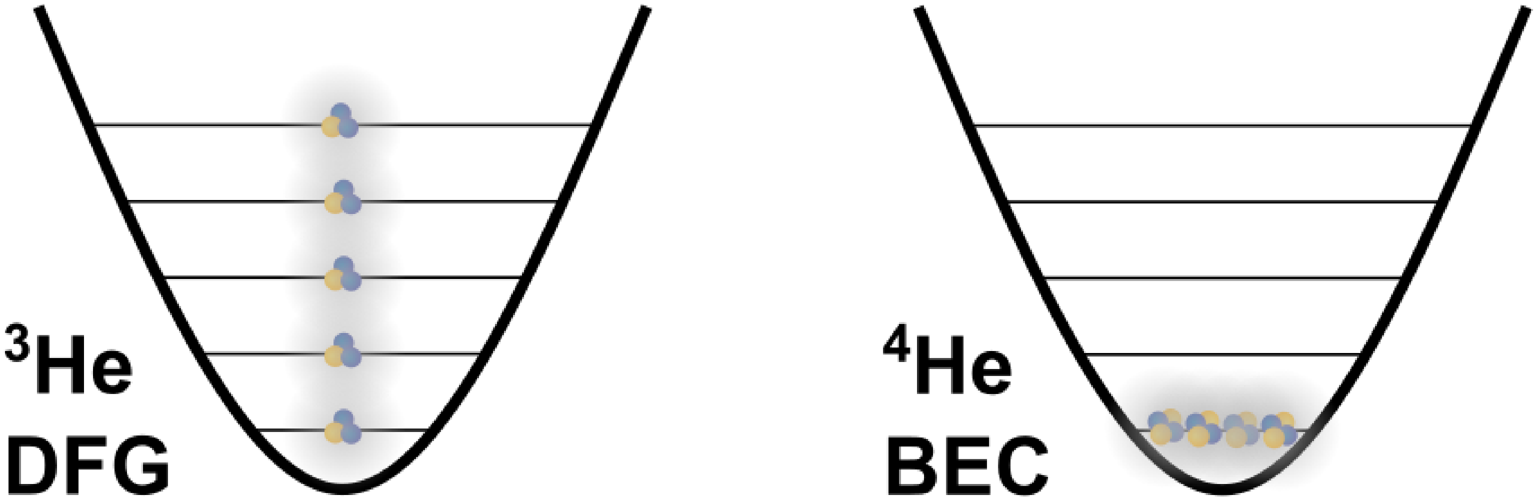
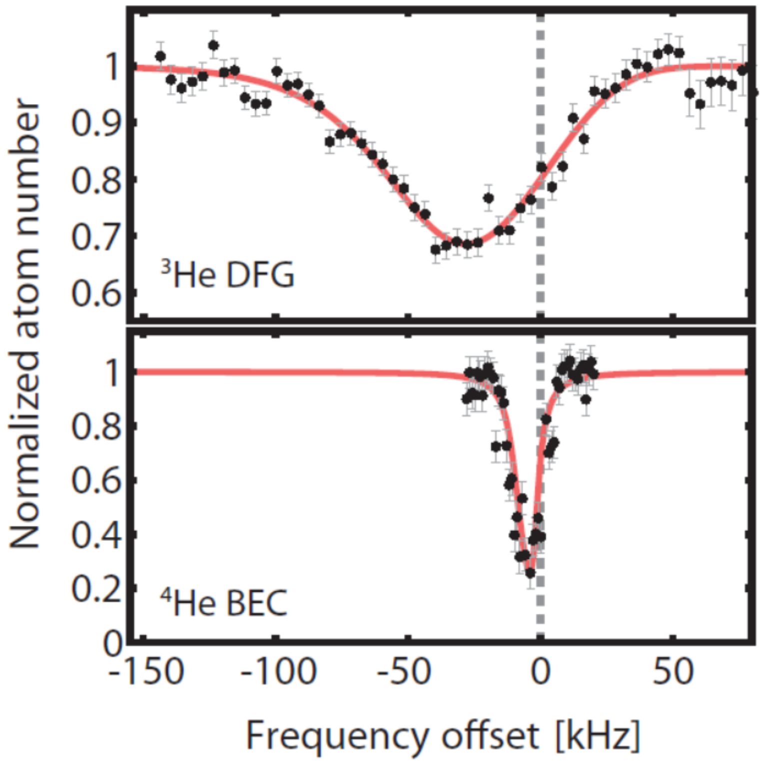
Understanding the spectral lineshape

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





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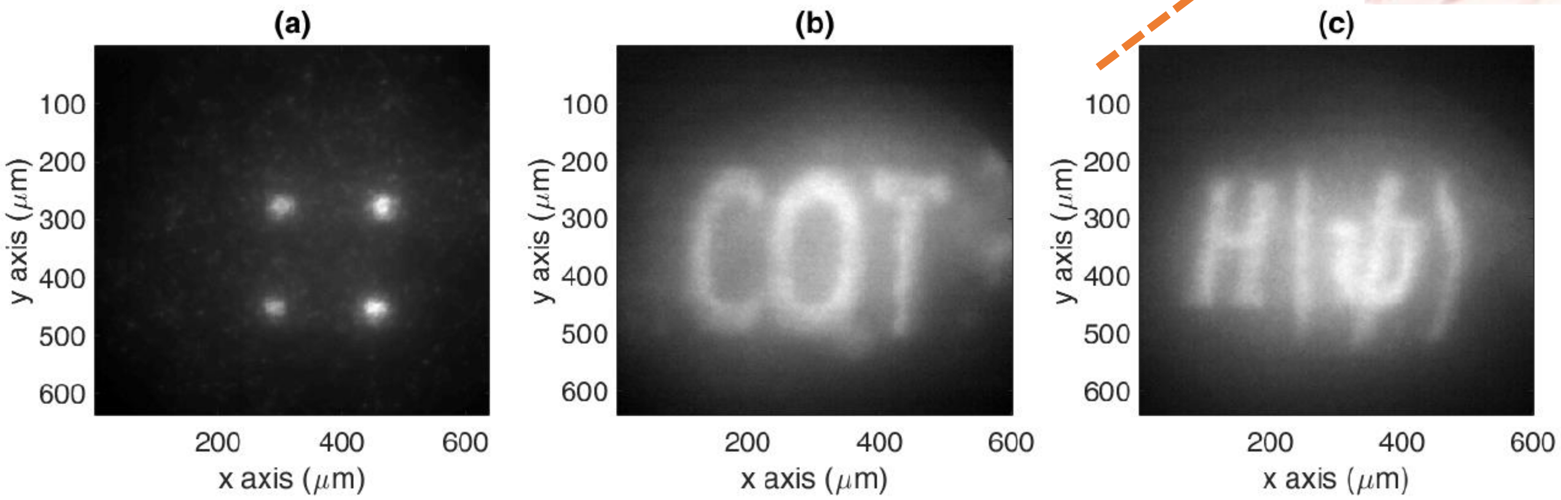
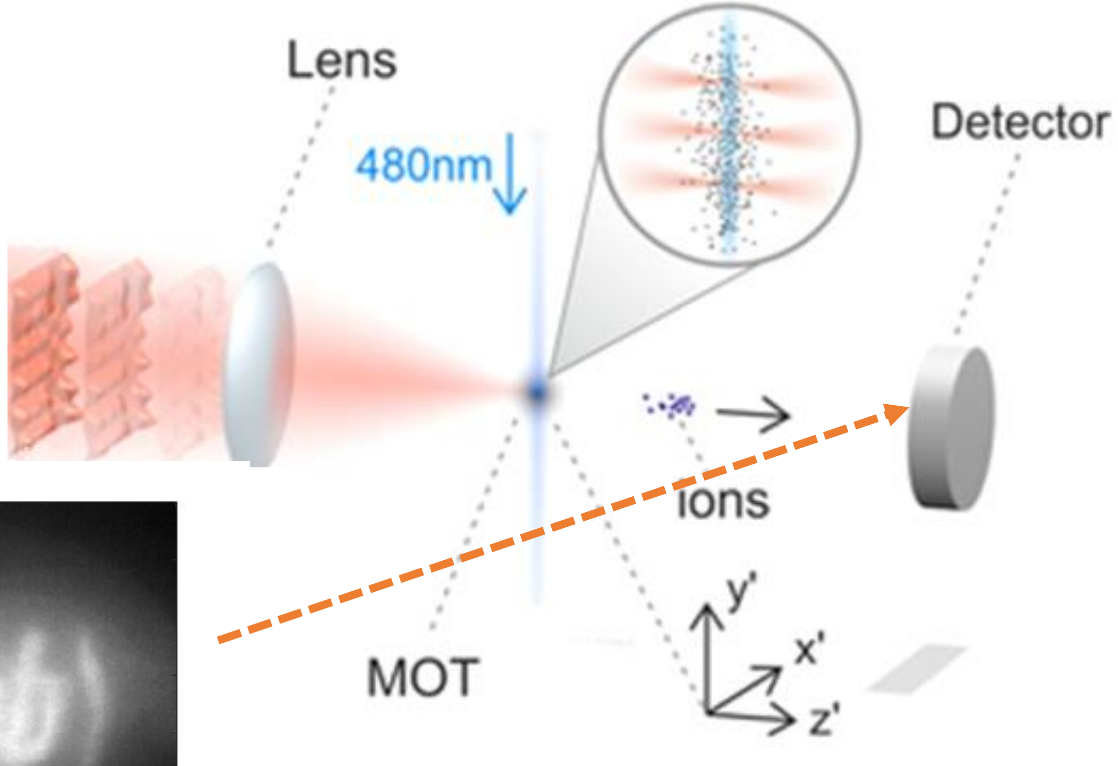
Before PhD

- Master thesis work at Eindhoven University of Technology

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





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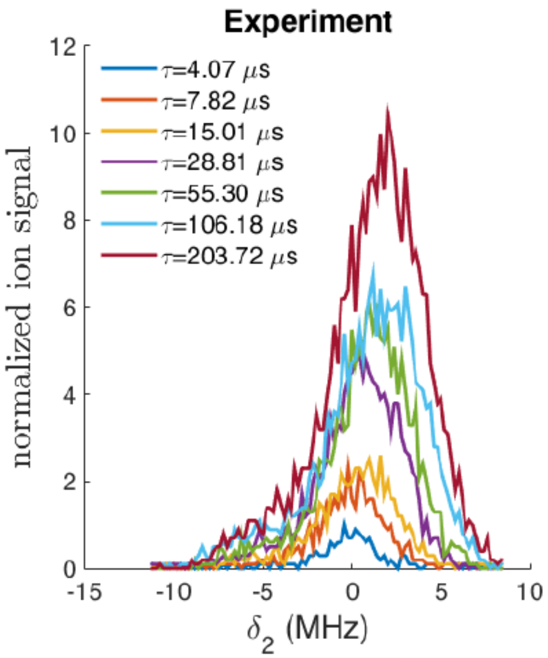
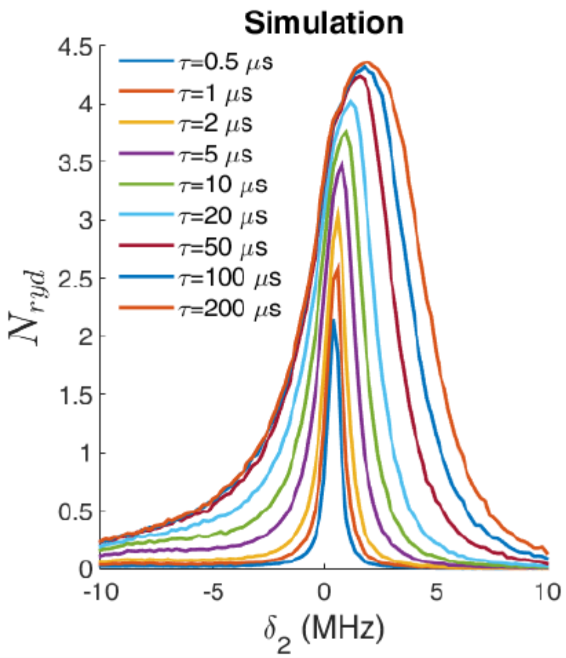
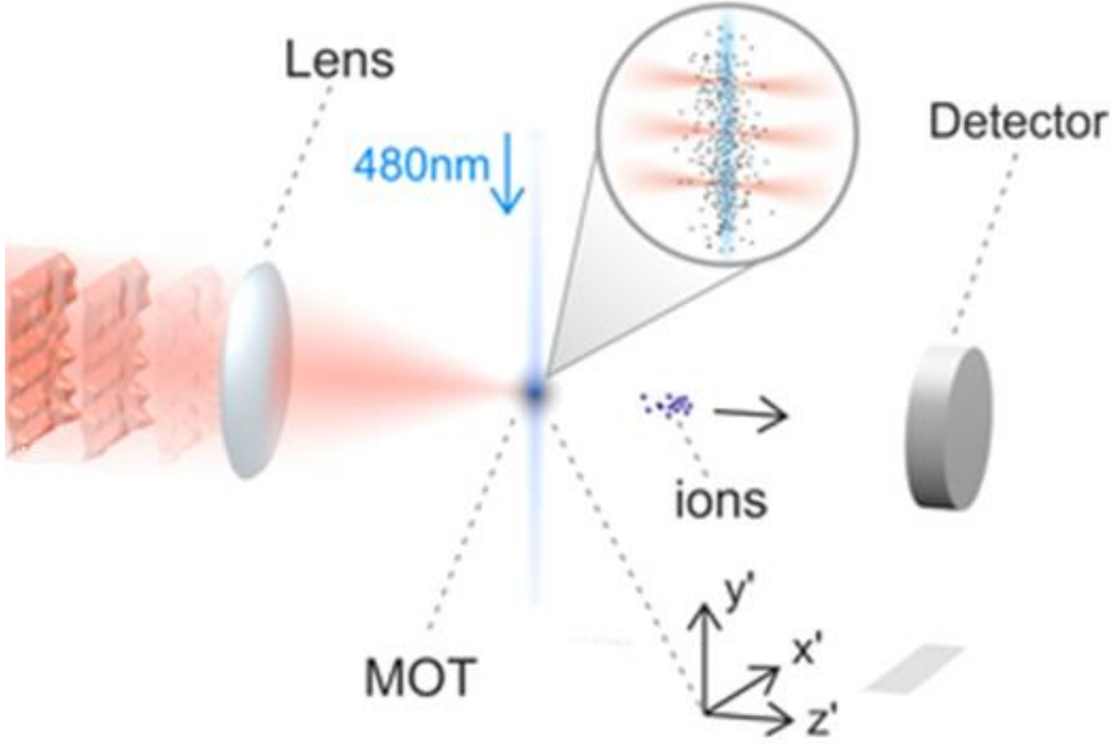
Before PhD

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







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