Precision Spectroscopy of Helium Atoms

Yu Sun
孙羽
Institute of Advanced Science Facilities, Shenzhen

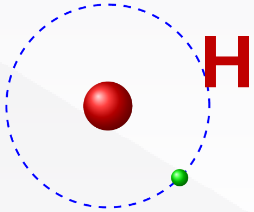
International Symposium on Stored Ions for Precision Measurements
ShangHai 2023/11/14

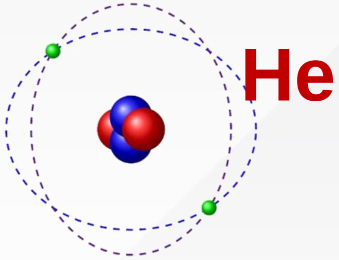
Introduction : Simple Atom, Fundamental Physics

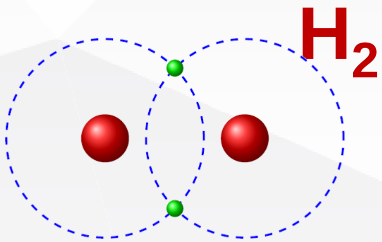
Simple, Calculable, Systems

- Full quantum, ab initio, no tunable parameters
  - Fine structure constant, $\alpha \approx 1/137$
  - Electron-Proton mass ratio, $\mu = m_e/m_p \approx 1/1836$
  - Rydberg constant, R
  - Nuclear charge radii, r_p, r_{He}

- Test of bound-state QED
- Determination of R (r_p), α, m_p/m_e
- New Physics?







$$E_{n\ell j} = R_\infty\left[-\frac{1}{n^2} + \boxed{f_{n\ell j}\left(\alpha, \frac{m_e}{m_p}, \cdots\right)} + \delta_{\ell 0}\frac{C_{NS}}{n^3} r_p^2\right]$$

$$\boxed{X_{20}\alpha^2 + X_{30}\alpha^3 + \cdots}$$

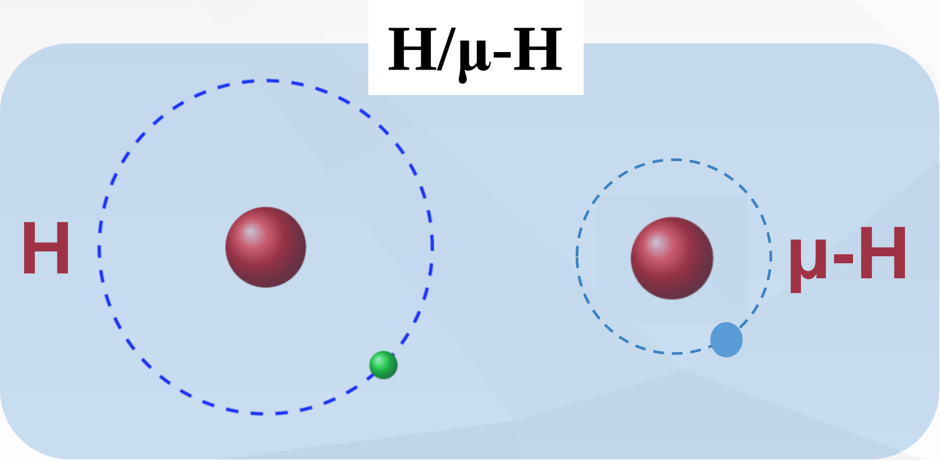
Beyer et al., Science 2017

H, He, H_2, Li^+, Be^{2+}

Introduction : Simple Atom, Fundamental Physics

Proton Structure from the Measurement of 2S-2P Transition Frequencies of Muonic Hydrogen

Science **399**,417(2013)



m_μ is 207 times that of electron

Proportional to m_r^3

$$\Delta E_{\text{finite size}} = \frac{2\pi Z\alpha}{3} r_E^2 |\Psi(0)|^2$$

μ-H :Strongly increased sensitivity
--About 10^7
H : can achieve very high precision
--About 10^{-15}

in agreement with $r_E(d) = 2.130(10)$ fm (49) from electron-deuteron scattering but more than an order of magnitude more precise. The CODATA (7) value $r_E(d) = 2.1424(25)$ fm is in disagreement, because it is dominantly based on the 7σ discrepant $r_E(p)$ value of CODATA combined with

"Proton Size Puzzle"

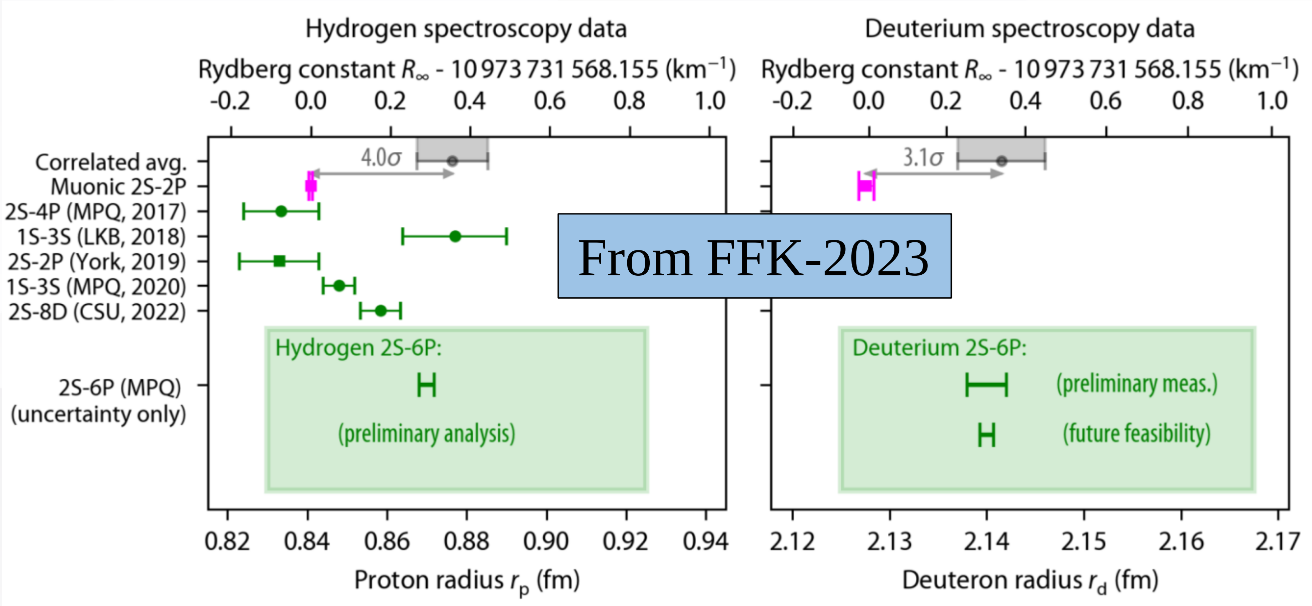
Introduction : Simple Atom, Fundamental Physics

深圳综合粒子设施研究院
Institute of Advanced Science Facilities, Shenzhen

"Proton Size Puzzle"

The tension between the two approaches determining r_p and r_d has not been fully resolved. In fact, to obtain consistency among the many input data that contribute to the determination of R_∞, r_p, and r_d, a multiplicative expansion factor of 1.6 is applied to their uncertainties. Further experiments are needed.

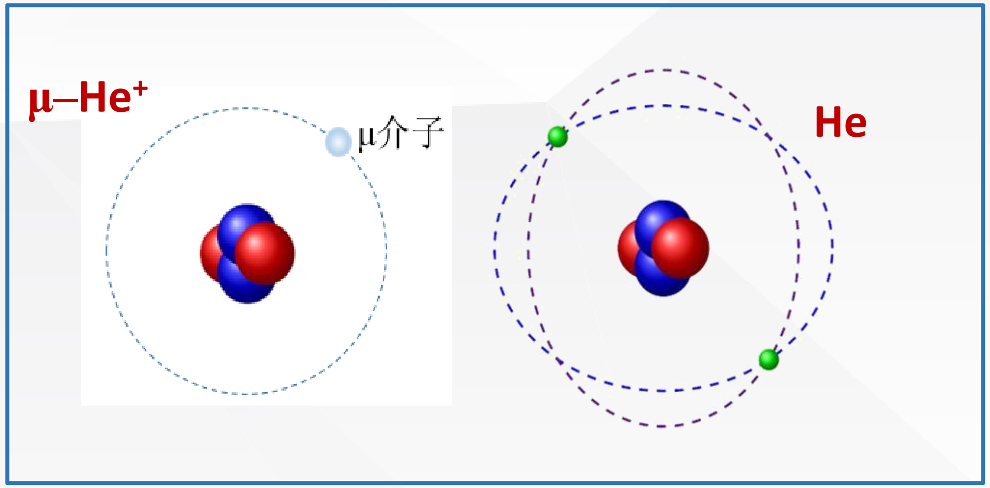
CODATA-2018

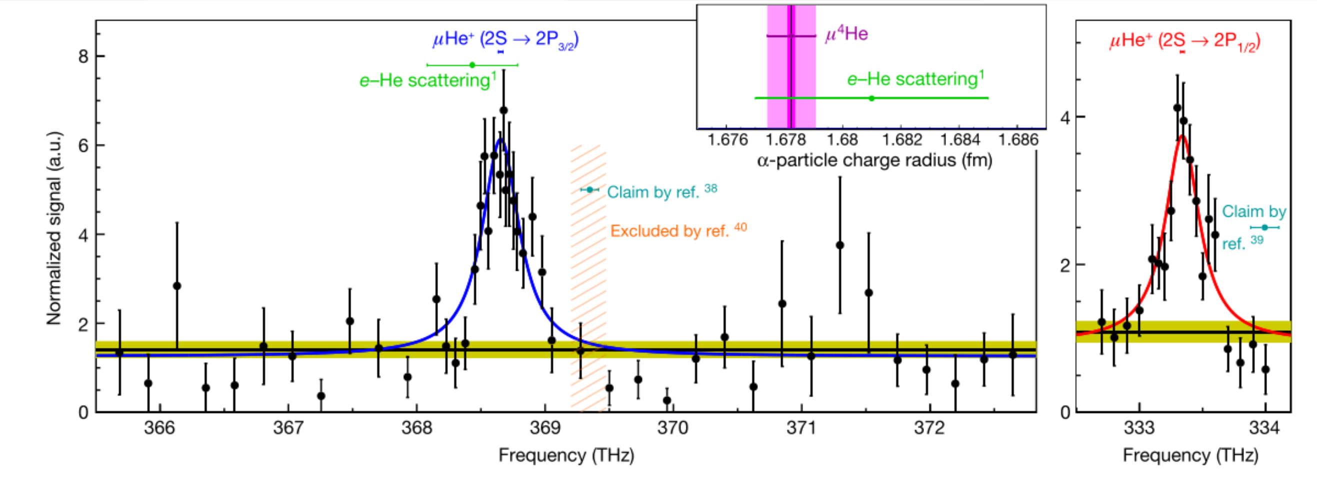


From FFK-2023

Nuclear Radius of μ-He$^+$

Nature (2021) **589** 527





μ-He$^+$/He

Testing fundamental interactions on the helium atom

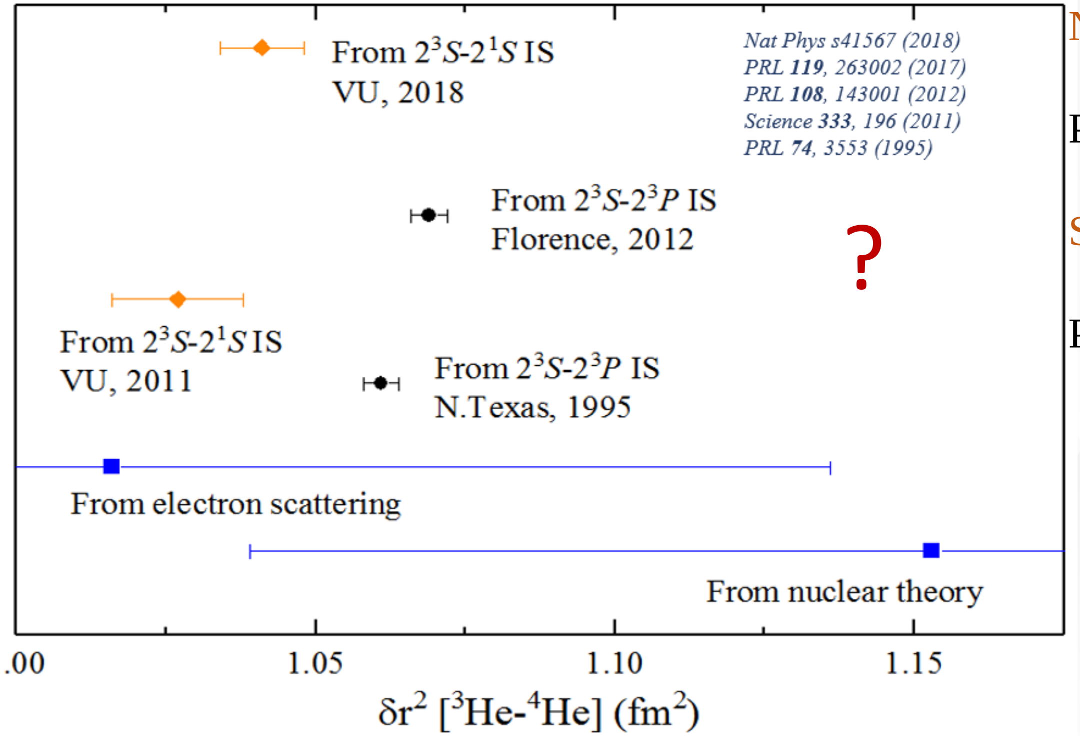
Krzysztof Pachucki,[1] Vojtěch Patkóš,[2] and Vladimir A. Yerokhin[3]

- Physical Review A **95**,062510 (2017)

Test of fundamental physics can be obtained not only from the hydrogenic systems **but also from the few body atomic Systems, such as He and He-like ions.**

Find New Physics in He and He-like System

Isotope Shift and Differential Nuclear Charge Radius



Nat Phys s41567 (2018)

PRL **108**, 143001 (2012)

Science 333, 196 (2011)

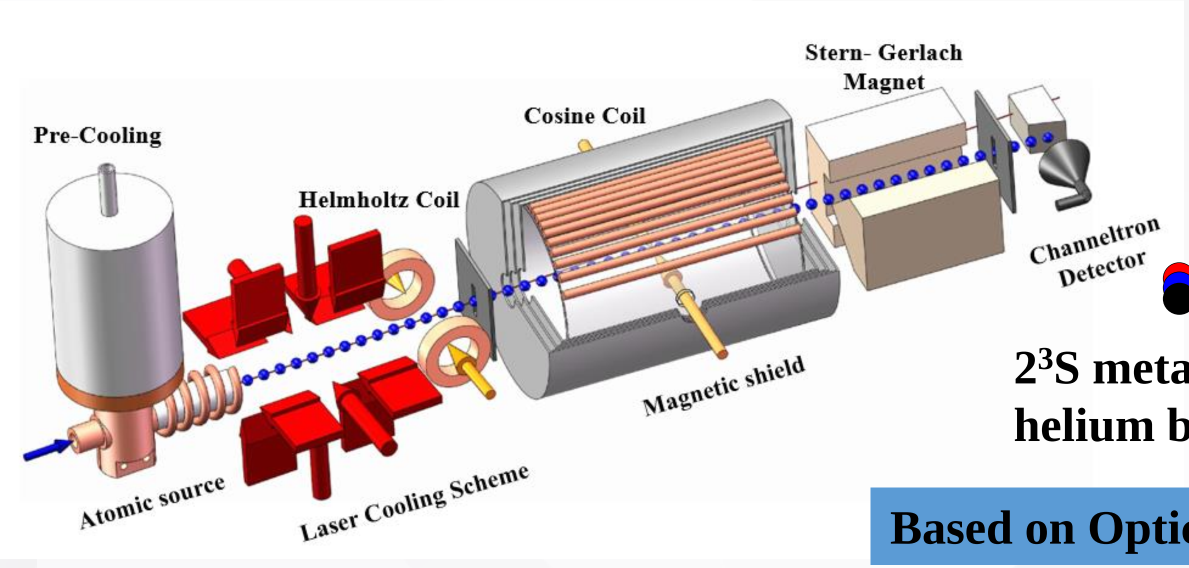
PRL **74**, 3553 (1995)

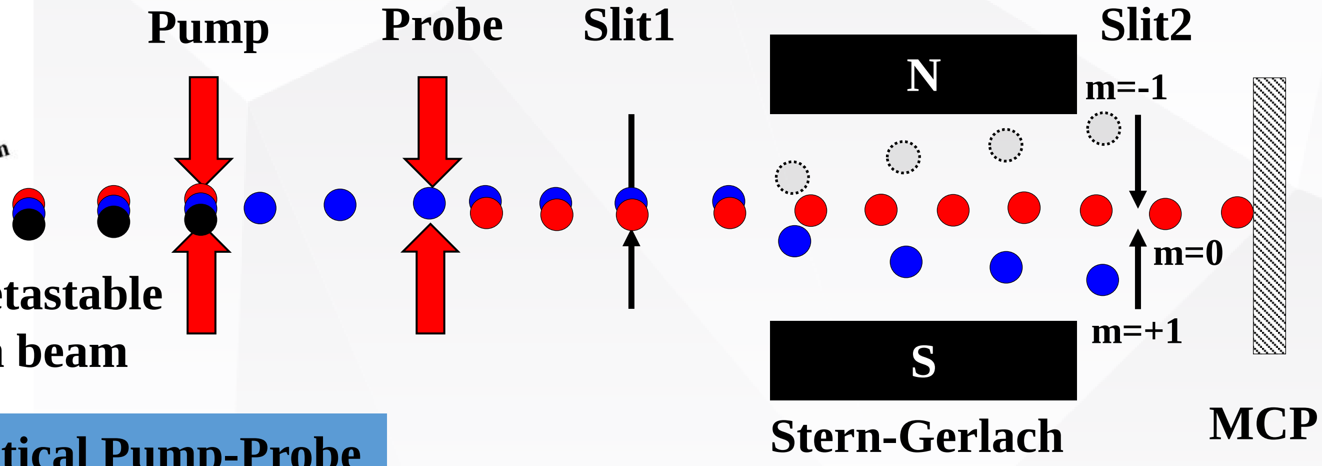
- Differential Nuclear Charge Radius
- $\delta r^2 = r_{He\text{-}3}^2 - r_{He\text{-}4}^2$
- Most Difficult Terms Drop Out
- Sufficient to Compare with μ-He
- Results from 2S-2P Different from 2^1S-2^3S
- Need More Independent Experiment to Test

Precision Measurement of Helium

Laser cooling based atomic beam system

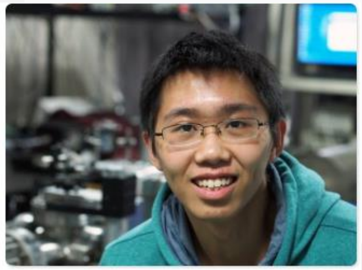
[Shui-ming Hu, Zheng-Tian Lu, Zong-Chao Yan, Front. Phys. China, 2009,4(2), 165]
Physical Review A **91**, 030502(R) (2015)



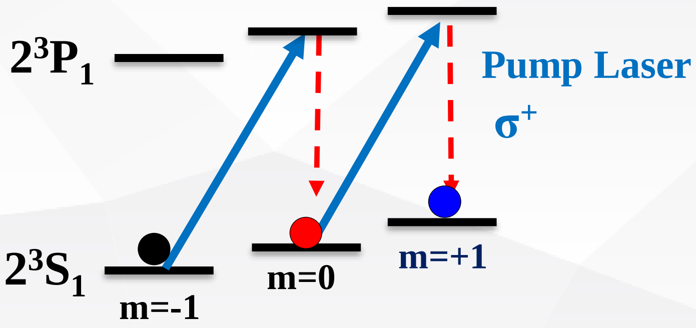


2^3S metastable helium beam

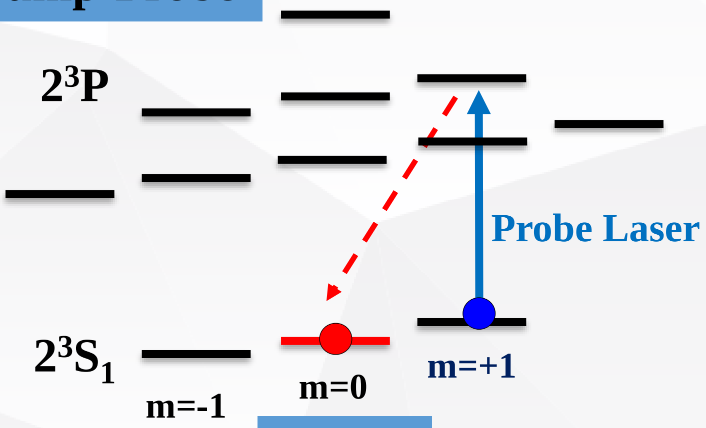
Based on Optical Pump-Probe



X. Zheng



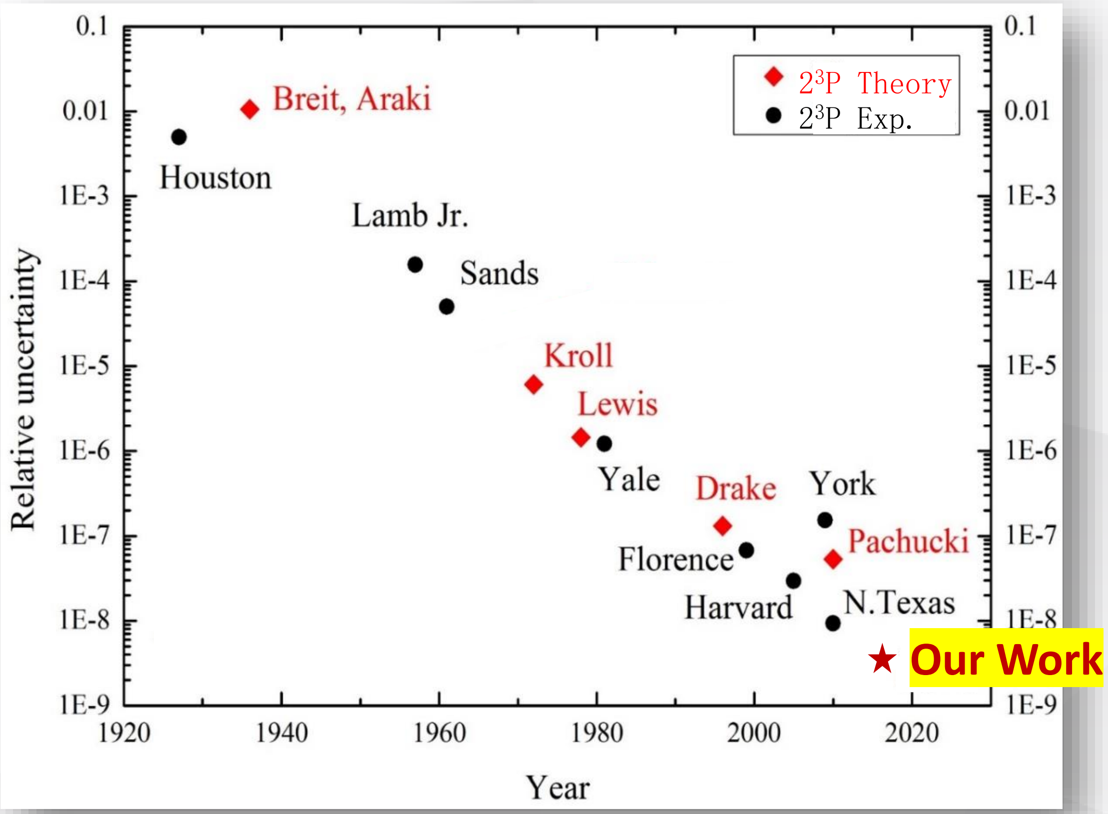
Pump



Probe

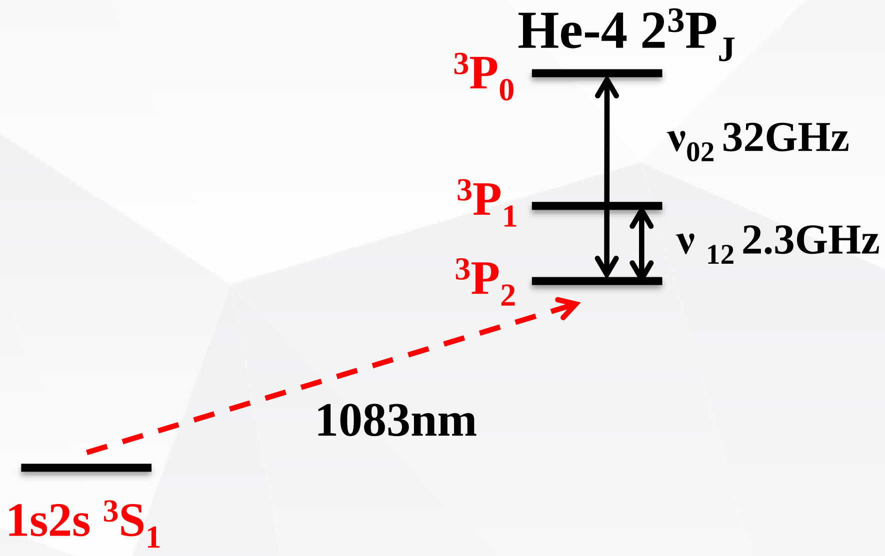
2^3S helium Atoms can directly detect by the MCP

2^3P_2 -2^3P_0Fine-Structure Splitting Measurement



Physical Review Letters **118**,063001 (2017)

- The uncertainty of the ν_{02} interval is reduced to 0.13kHz
- Confirmation of the α^5Ry QED corrections
- Would allow an independent determination of the α
- with a precision of about 2E-9

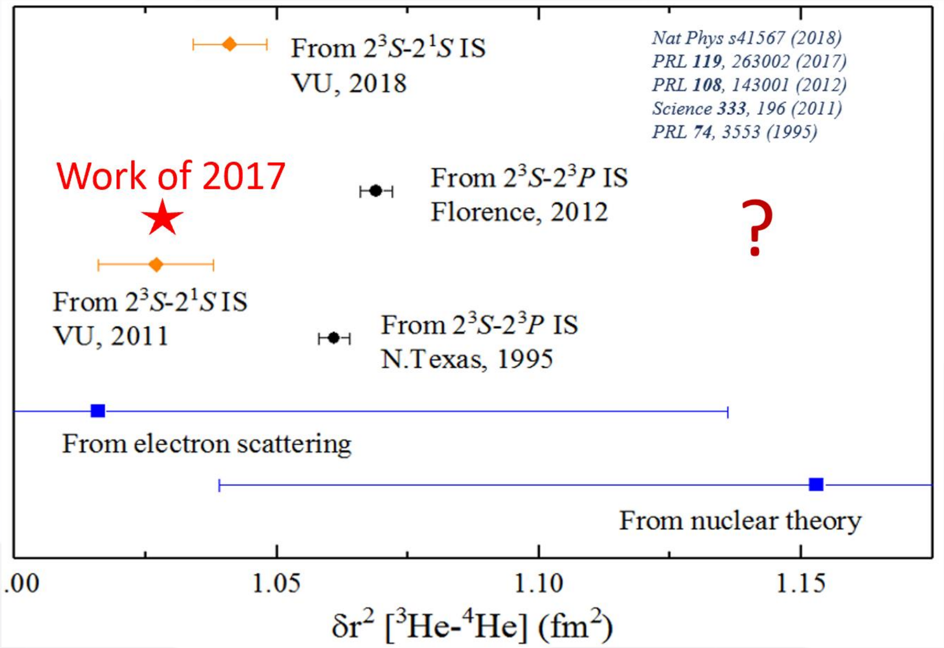


Precision Measurement of Helium

Uncertainty Budget of 2S-2P transition frequency Measurement

Uncertainty	Correction [kHz]	uncertainty [kHz]	Rel.uncertainty [10^{-12}]
Statistics	-	0.50	1.8
Frequency calibration	-	0.55	2.0
First-Order Doppler	-	1.00	3.6
Line-Profile	-	0.40	1.2
Second-order Doppler	+0.70	0.15	0.5
Laser Power	-	0.10	0.3
Quantum Interference	+0.60	0.10	0.3
Scattering light	-	0.05	0.2
Zeeman effect	-	0.01	0.04
Light-force-induced shift	+0.5	0.8	3
Recoil shift	-42.20	-	
Total	-40.90	1.6	5.0

Physical Review Letters **119**, 263002 (2017)



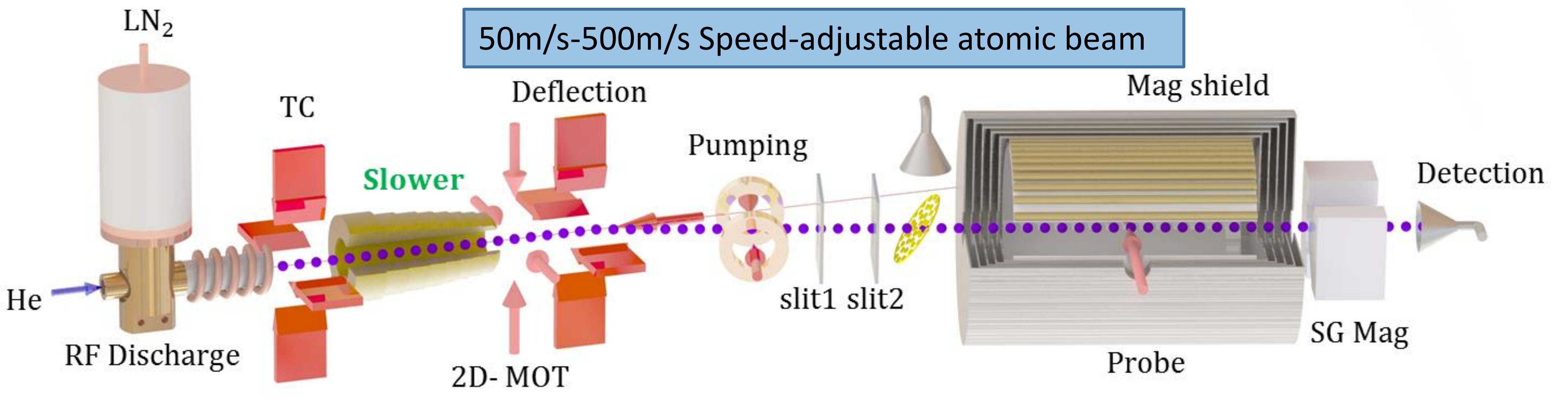
Design New Experiment Method

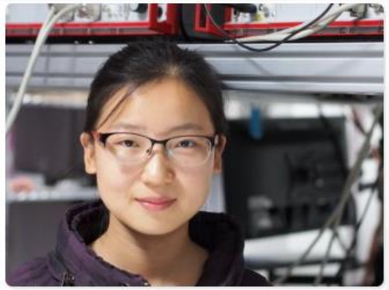
Systematic effect:

- ➢ First Order Doppler Effect:
- ➢ Light Force shift

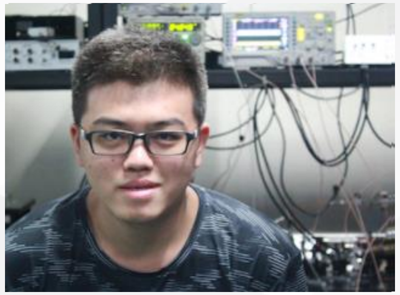
Bright, Speed-adjustable atomic beam of metastable helium

PRA **101**, 053824 (2020)

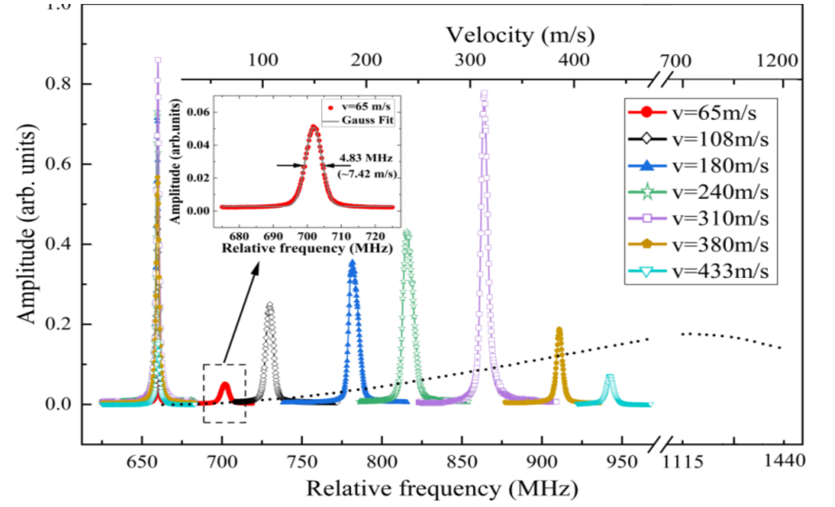




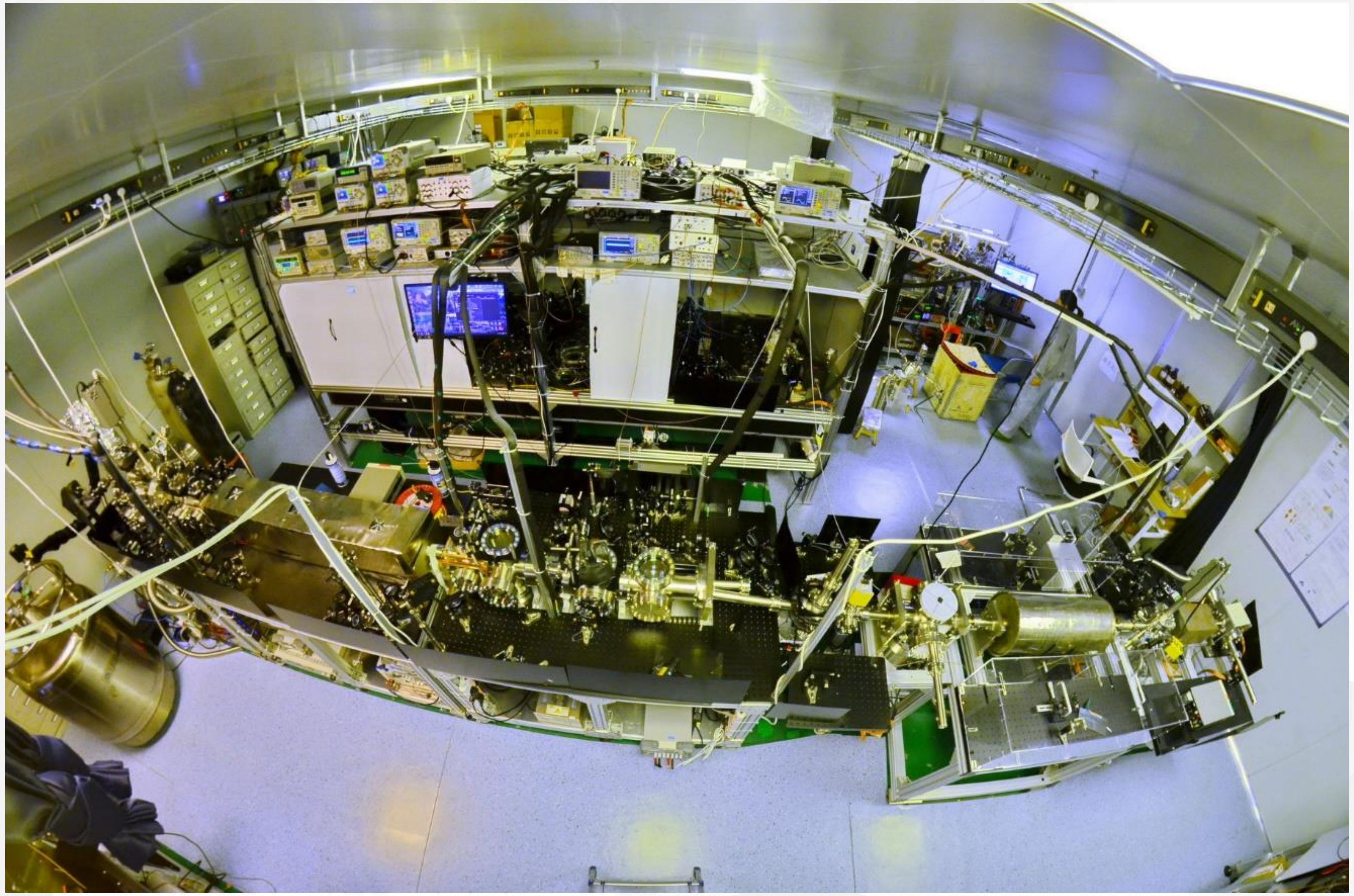
J.-J. Chen



J.-L.Wen



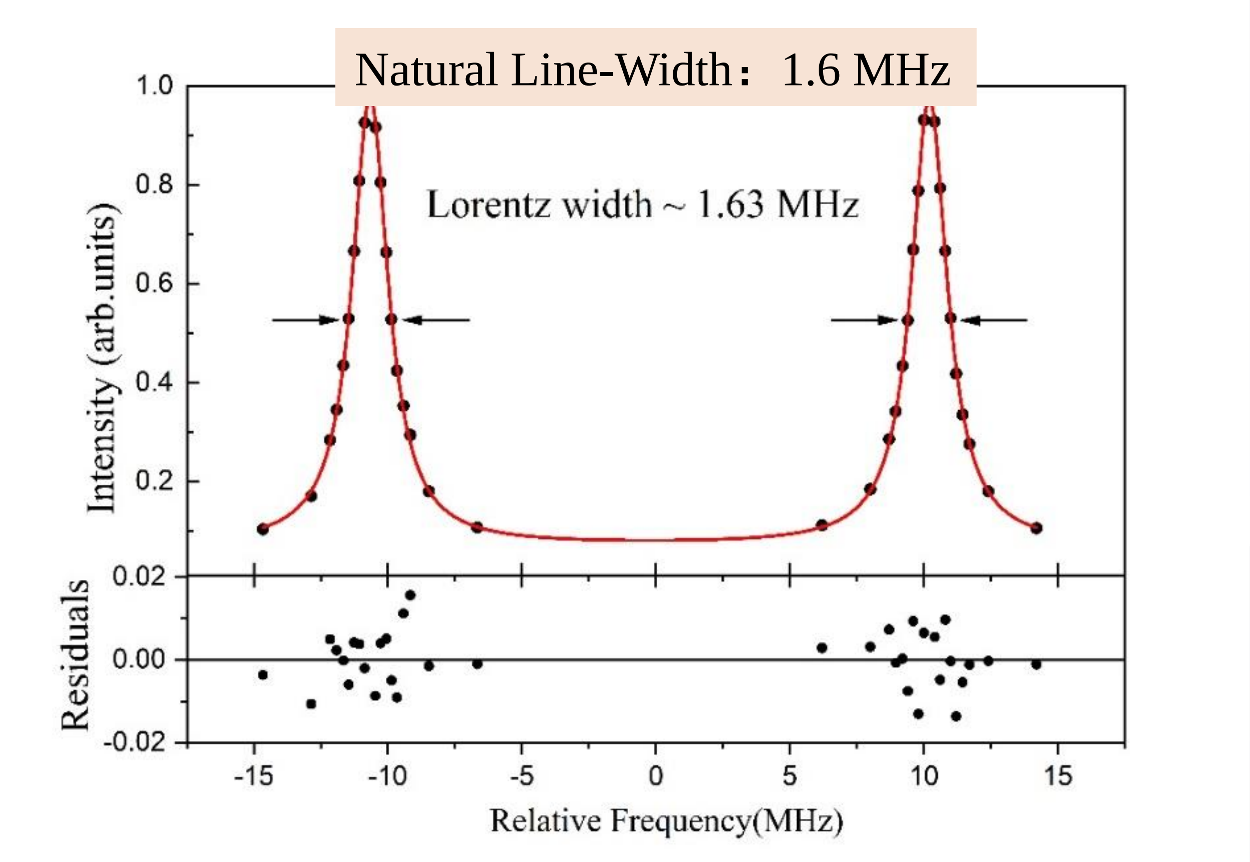
Precision Measurement of Helium



- Longitude velocity:50m/s to 500m/s
- Reduce one order of first order doppler
- Speed-adjustable atomic beam
- Better determine the uncertainty

Precision Measurement of Helium

- ✓ Bright atomic Beam， SNR~300/min
- ✓ Reduce the laser power need, push the line-width approach 1.6Mhz
- ✓ Adjustable longitude velocity, better determine the systematic error

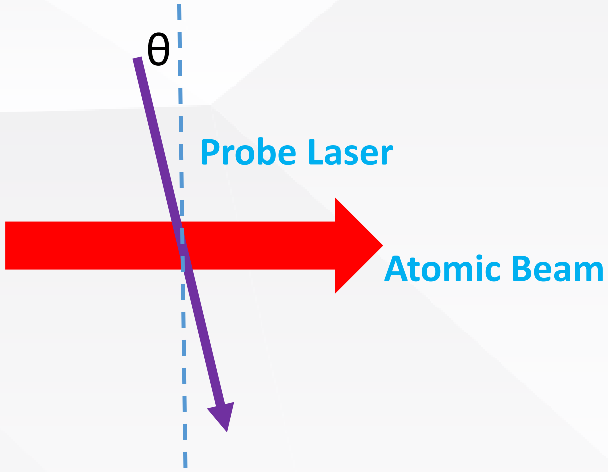


Uncertainty Budget of 2S-2P transition frequency Measurement

Uncertainty	Correction [kHz]	uncertainty [kHz]	Rel.uncertainty [10^{-12}]
Statistics	-	0.50	1.8
Frequency calibration	-	0.55	2.0
First-Order Doppler	-	1.00	3.6
Line-Profile	-	0.40	1.2
Second-order Doppler	+0.70	0.15	0.5
Laser Power	-	0.10	0.3
Quantum Interference	+0.60	0.10	0.3
Scattering light	-	0.05	0.2
Zeeman effect	-	0.01	0.04
Light-force-induced shift	+0.5	0.8	3
Recoil shift	-42.20	-	
Total	-40.90	1.6	5.0

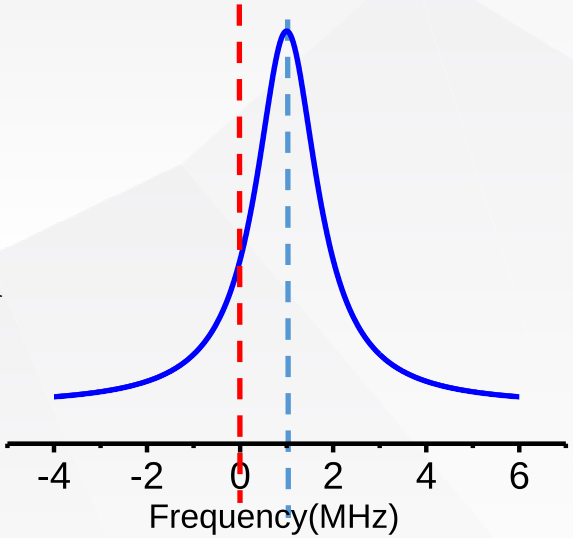
Precision Measurement of Helium

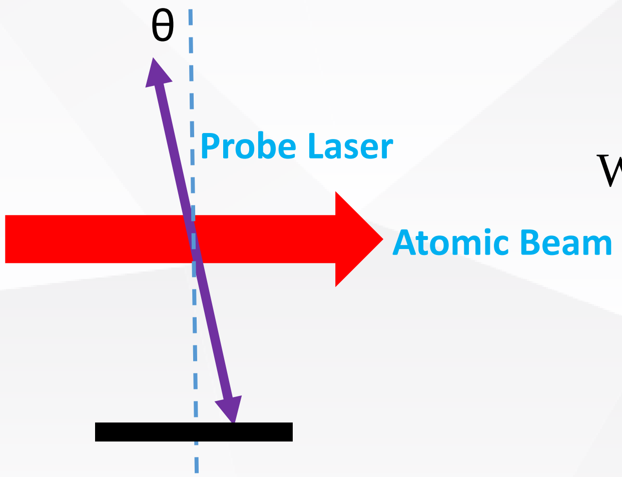
- First Order Doppler



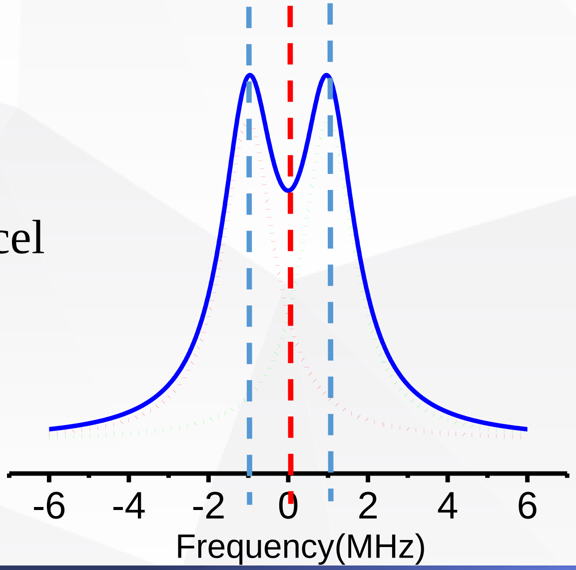
$$\Delta\nu_D = kv \cdot \theta$$

No Doppler cancel





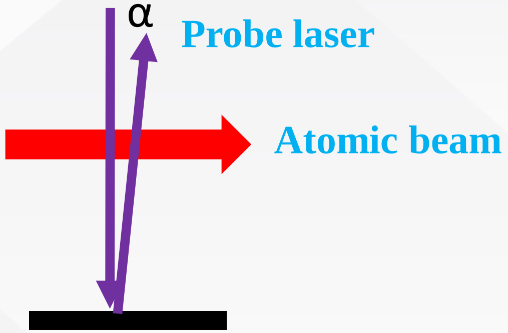
With Doppler cancel



Precision Measurement of Helium

深圳综合粒子设施研究院
Institute of Advanced Science Facilities, Shenzhen

- **First Order Doppler**

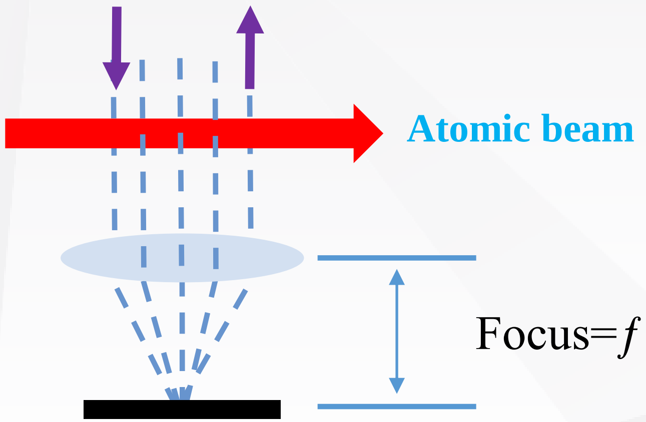


$$\Delta\nu_D \approx \frac{1}{2} kv \cdot \boldsymbol{\alpha}$$

10urad correspond to about 3kHz derivation

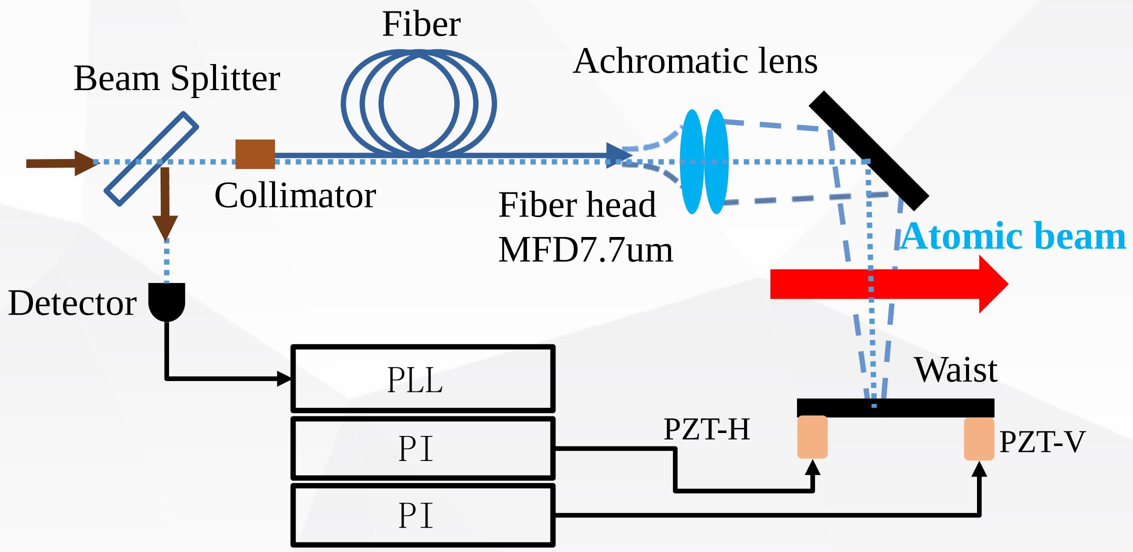
➢ **Cancel Mechanism**

✓ Cat's eye optical method



Physical Review Letters ***92***,*023001 (2004)*
Can. J. Phys. ***83***,*301 (2005)*
Physical Review Letters ***105***,*123001 (2010)*

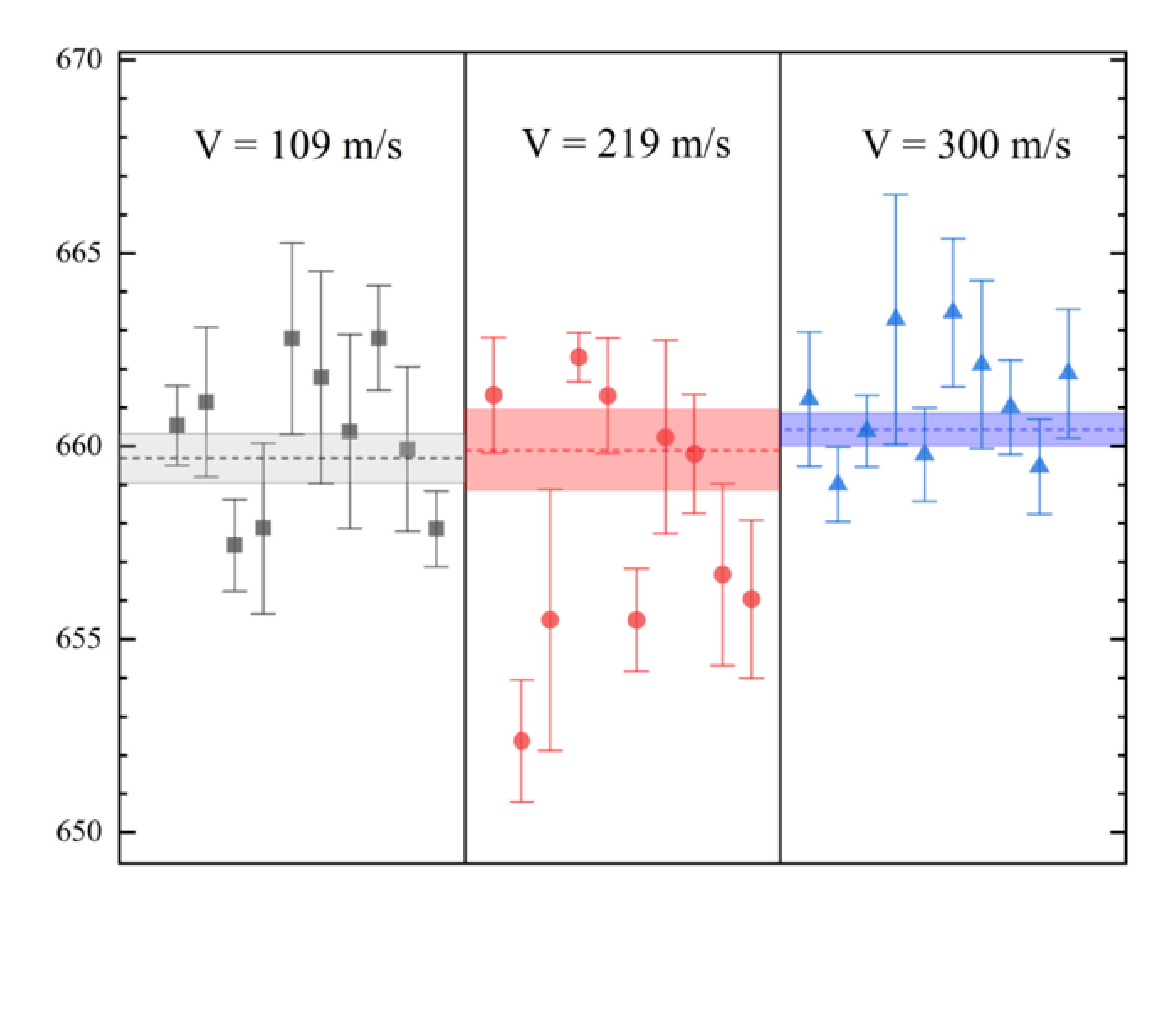
✓ Active Feedback method



Optics Express ***24***,*17470 (2016)*

Precision Measurement of Helium

Systematic effect :First Order Doppler Effect



$$\Delta f = \vec{k} \cdot \vec{v}$$

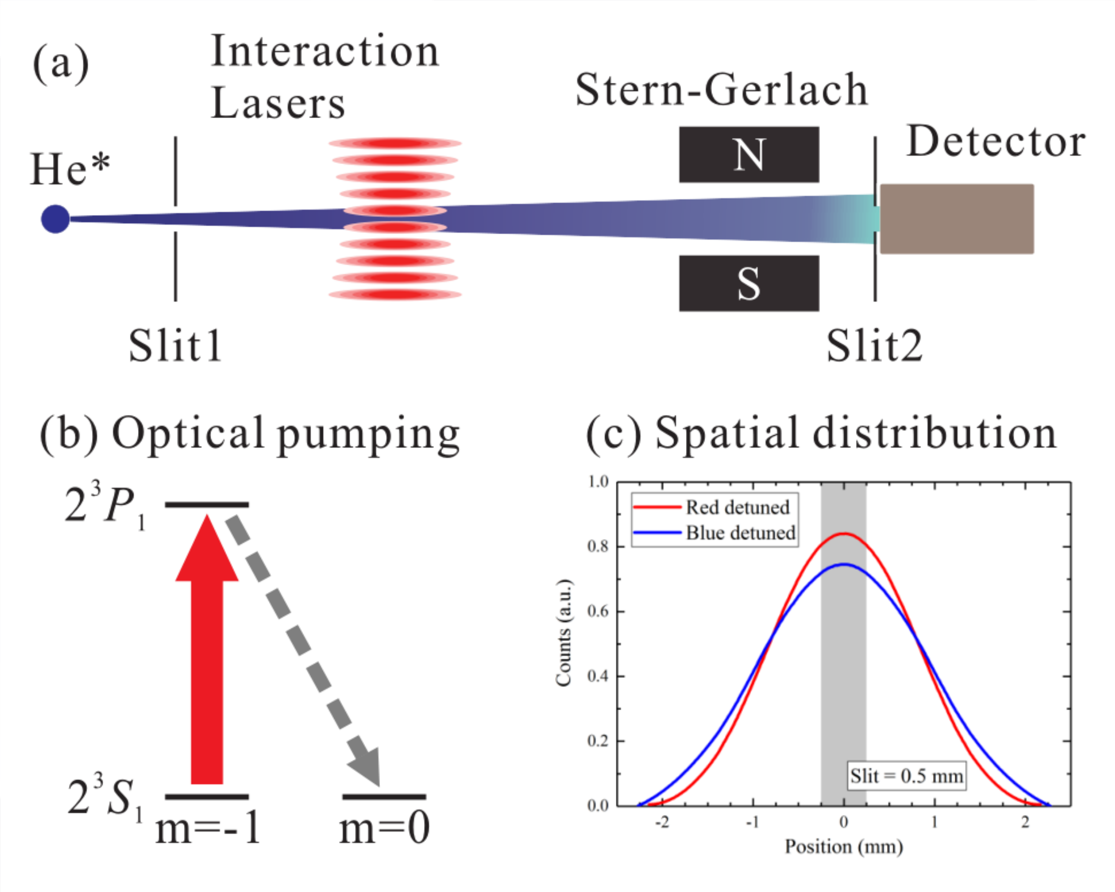
- Tune to different velocity
- Better estimate the effect of doppler
- Consistent with 2017 result
- The derivation is not from doppler effect

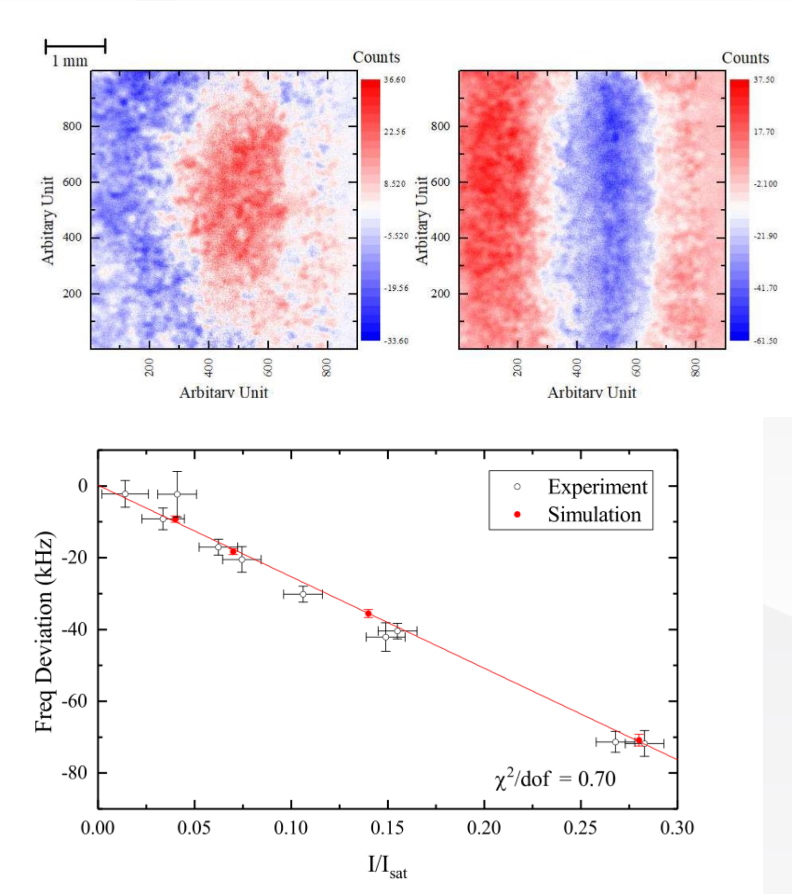
深圳综合粒子设施研究院
Institute of Advanced Science Facilities, Shenzhen

Uncertainty Budget of 2S-2P transition frequency Measurement

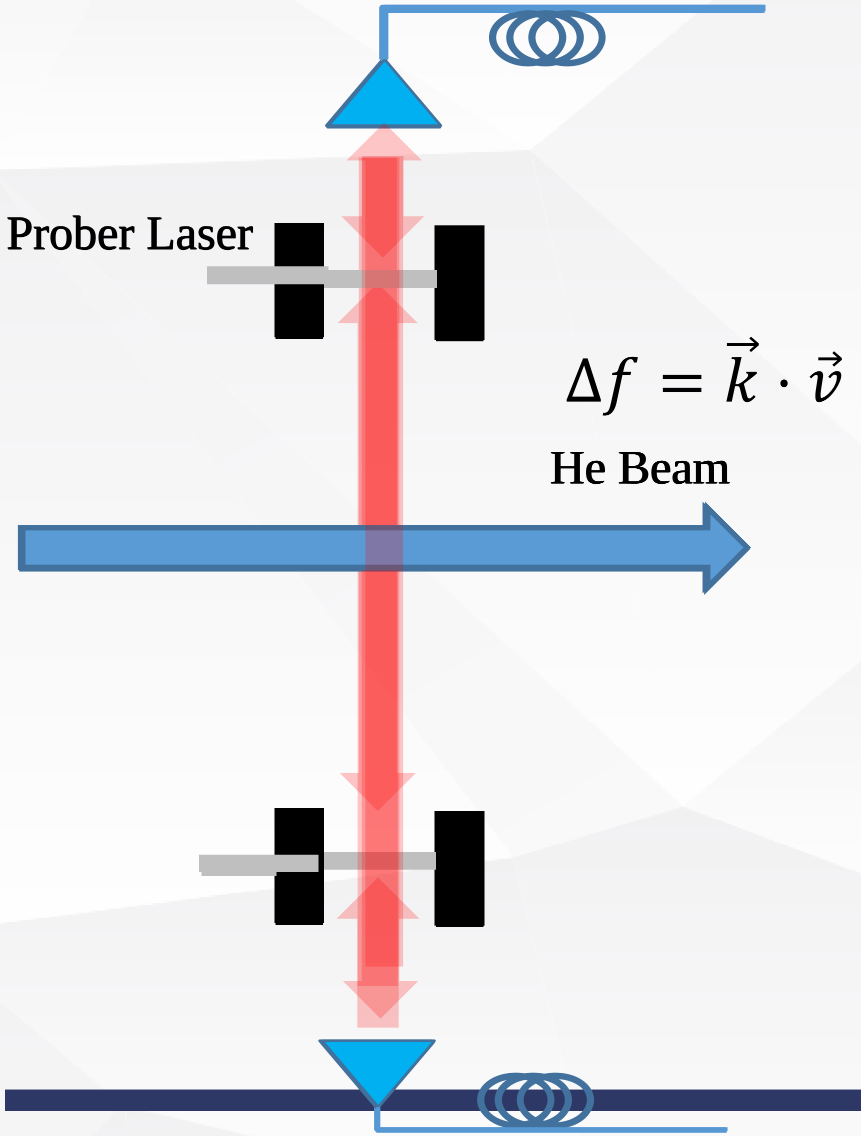
Uncertainty	Correction [kHz]	uncertainty [kHz]	Rel.uncertainty [10^{-12}]
Statistics	-	0.50	1.8
Frequency calibration	-	0.55	2.0
First-Order Doppler	-	1.00	3.6
Line-Profile	-	0.40	1.2
Second-order Doppler	+0.70	0.15	0.5
Laser Power	-	0.10	0.3
Quantum Interference	+0.60	0.10	0.3
Scattering light	-	0.05	0.2
Zeeman effect	-	0.01	0.04
Light-force-induced shift	+0.5	0.8	3
Recoil shift	-42.20	-	
Total	-40.90	1.6	5.0

●Light Force Induce Shift





Systematic effect :Light-Force-Shift



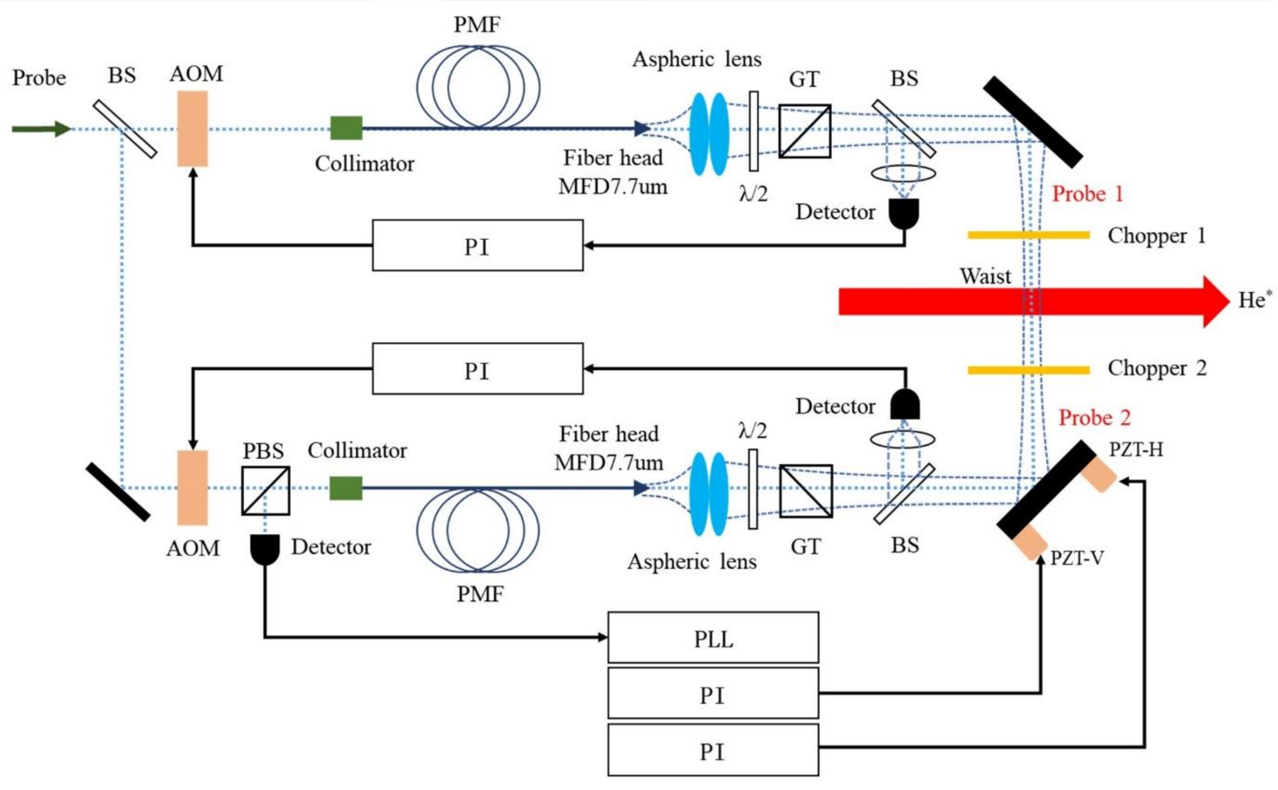
$$\Delta f = \vec{k} \cdot \vec{v}$$

PHYSICAL REVIEW A **107**, 042811 (2023)

Editors' Suggestion

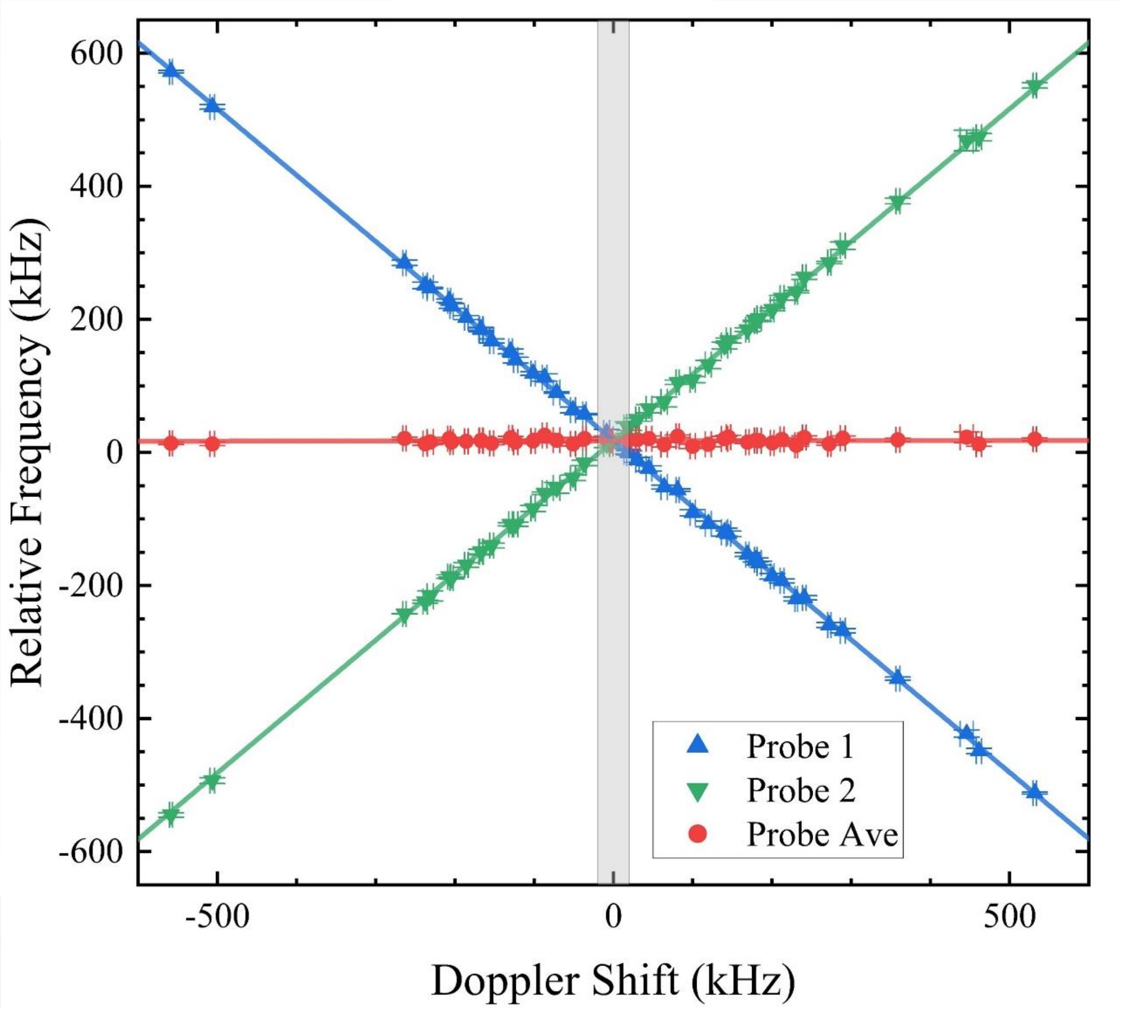
Doppler-free spectroscopy of an atomic beam probed in traveling-wave fields

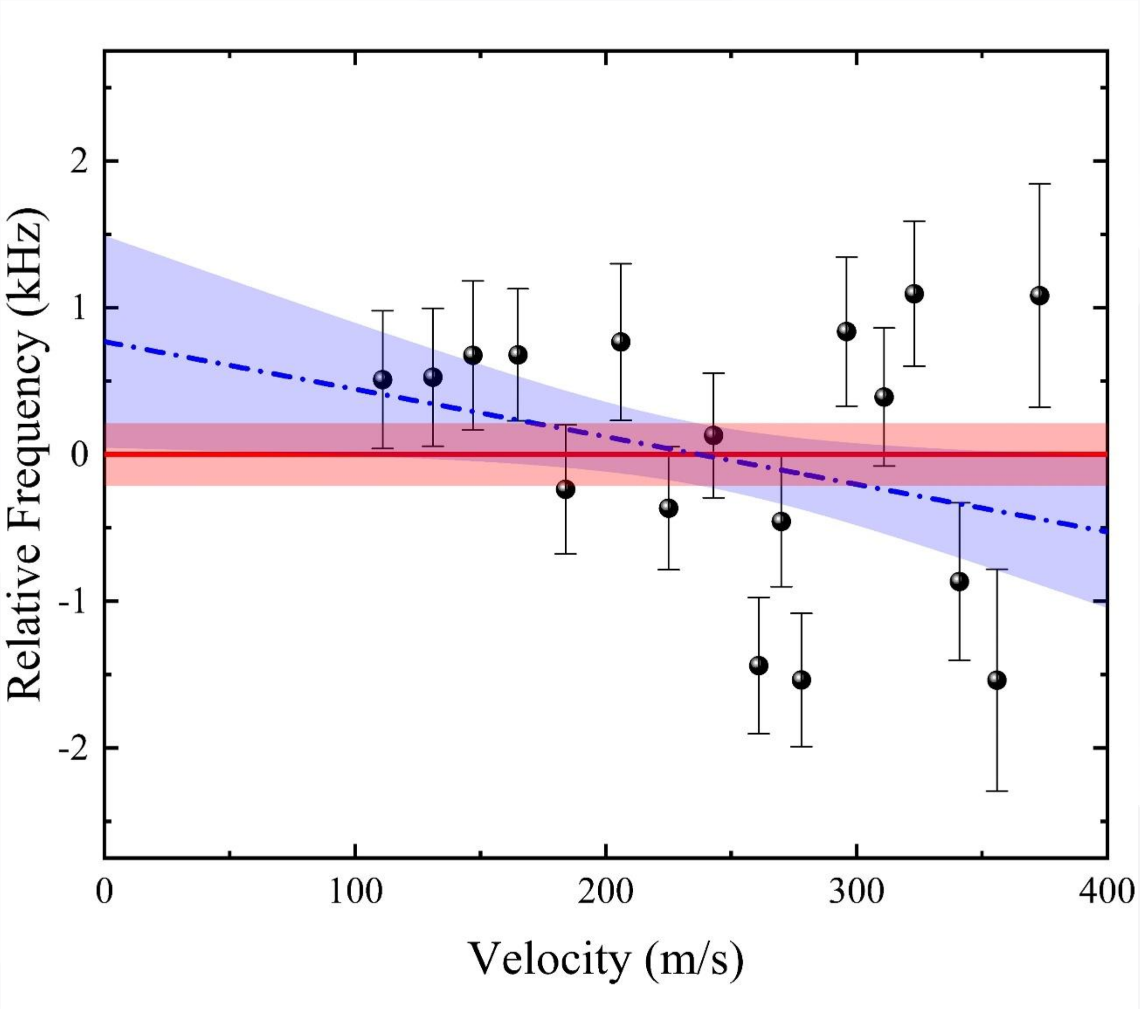
Jin-Lu Wen (温金录),[1] Jia-Dong Tang (唐家栋),[2] Jun-Feng Dong (董俊峰),[1] Xiao-Jiao Du (杜小娇),[3] Shui-Ming Hu (胡水明),[1,2,*] and Y. R. Sun (孙羽)[3,†]



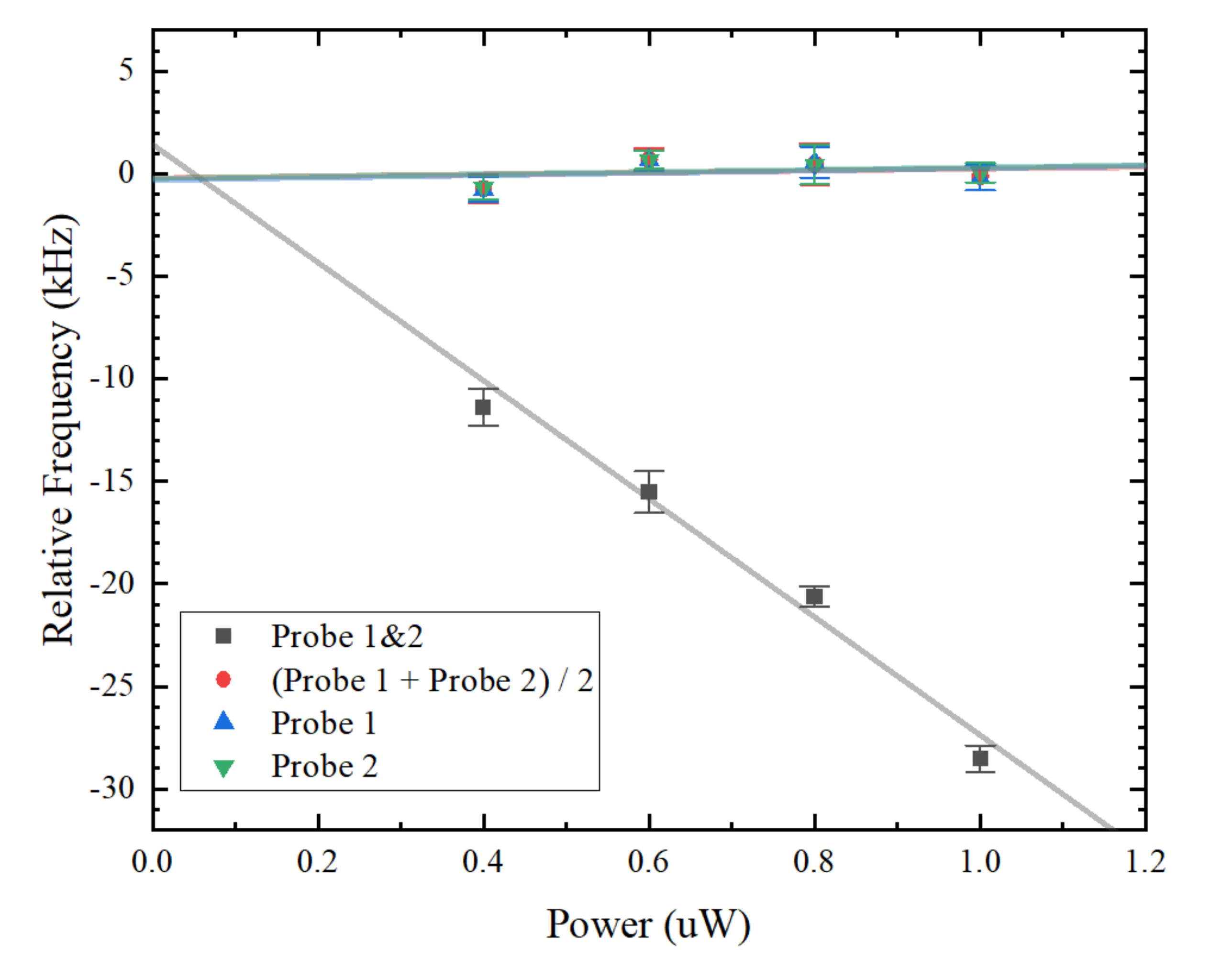
PRA **107**, 042811 (2023)

Systematic effect :Light-Force-Shift



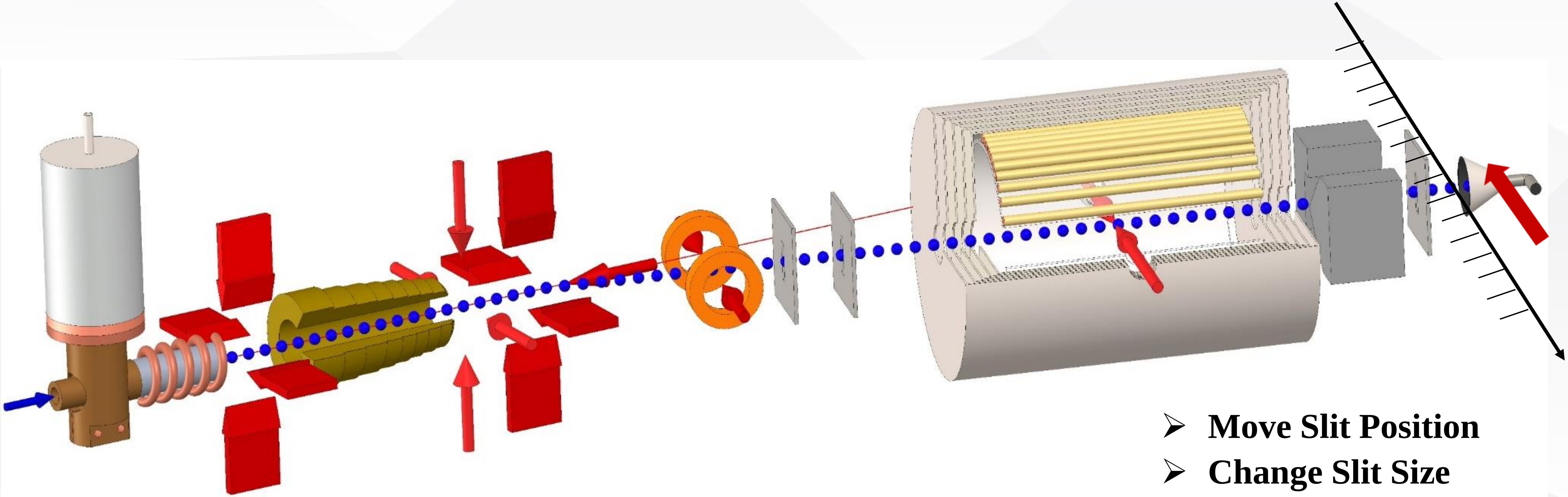


Systematic effect :Light-Force-Shift



- Stand-Wave vs Traveling-Wave
- Estimate Light-Force-Shift
- Consistent with 2017 result
- The derivation is not from Light-Force-Shift

Systematic effect :Geometry effect from the slit



- Move Slit Position
- Change Slit Size

Test Potential Systematic Effect From Stern-Gerlach Exp.

Systematic effect :Geometry effect from the slit

PRL 60 1351 (1988) post-selection

VOLUME 60, NUMBER 14 PHYSICAL REVIEW LETTERS 4 APRIL 1988

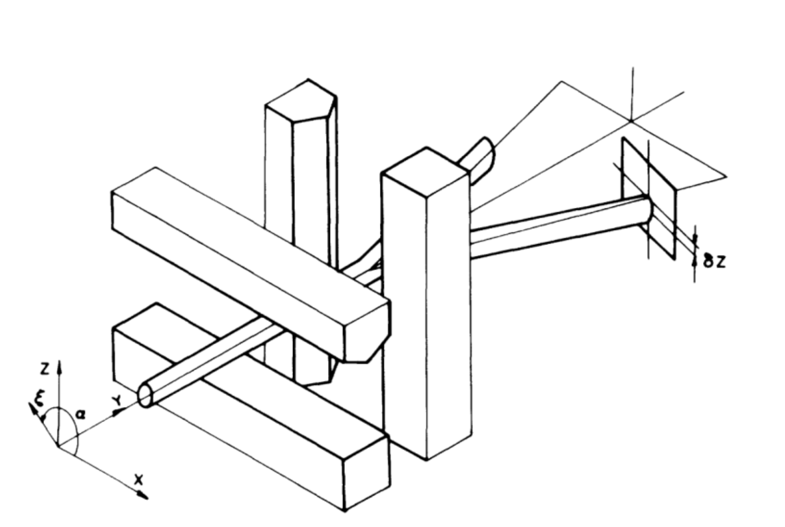
How the Result of a Measurement of a Component of the Spin of a Spin- $\frac{1}{2}$ Particle Can Turn Out to be 100

Yakir Aharonov, David Z. Albert, and Lev Vaidman
Physics Department, University of South Carolina, Columbia, South Carolina 29208, and School of Physics and Astronomy, Tel-Aviv University, Ramat Aviv 69978, Israel

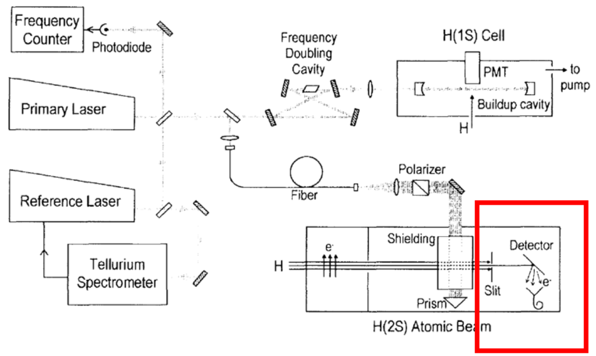
(Received 30 June 1987)

We have found that the usual measuring procedure for preselected and postselected ensembles of quantum systems gives unusual results. Under some natural conditions of weakness of the measurement, its result consistently defines a new kind of value for a quantum variable, which we call the weak value. A description of the measurement of the weak value of a component of a spin for an ensemble of preselected and postselected spin- $\frac{1}{2}$ particles is presented.

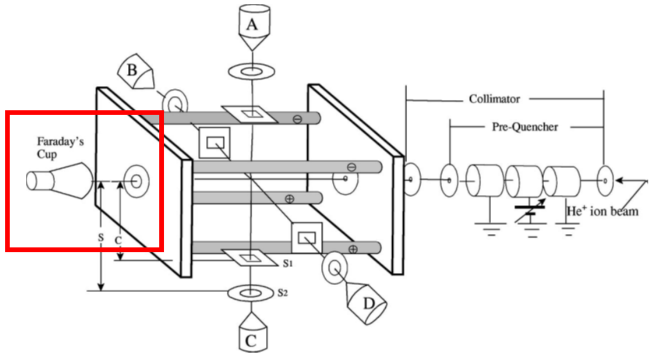
PACS numbers: 03.65.Bz



- H Lamb Shift (included in CODATA for r_p)
- He$^+$ Lamb Shift

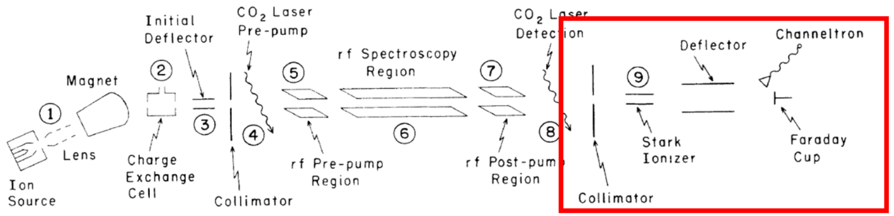


- D. J. Berkeland, et al.
Phys. Rev. Lett. 75.2470 (1995)



- A. van Wijngaarden, et al.
Phys. Rev. A 63.012505 (2000)

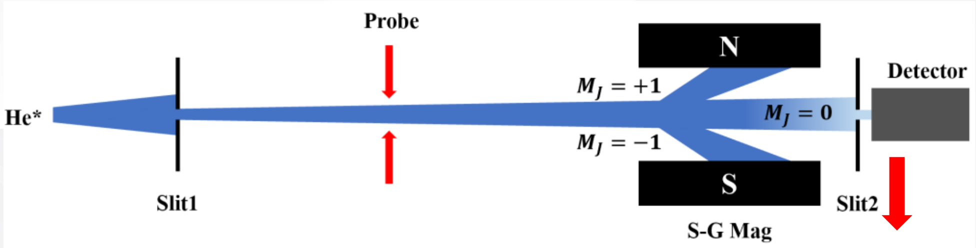
- Rydberg state microwave spectroscopy



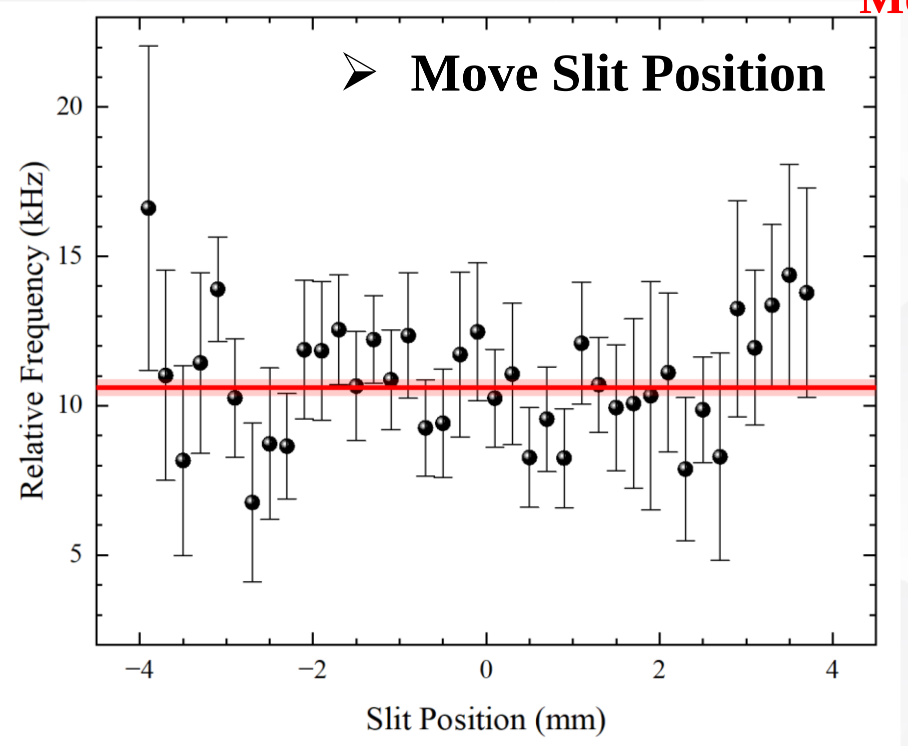
- E. A. Hessels, et al.
Phys. Rev. A 46.2622 (1992)

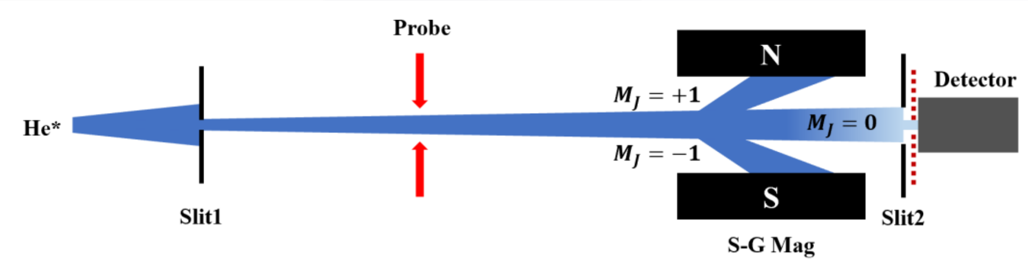
- ➢ Applied in quantum information, quantum metrology
- ➢ Find also existed in precision measurement

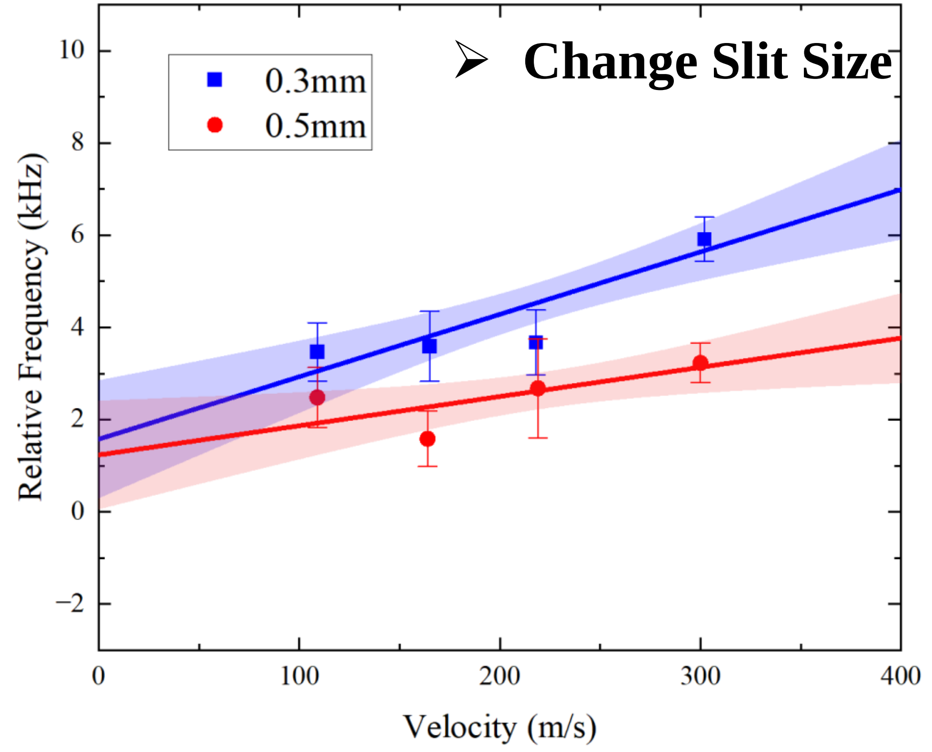
Systematic effect :Geometry effect from the slit



Move Slit Position

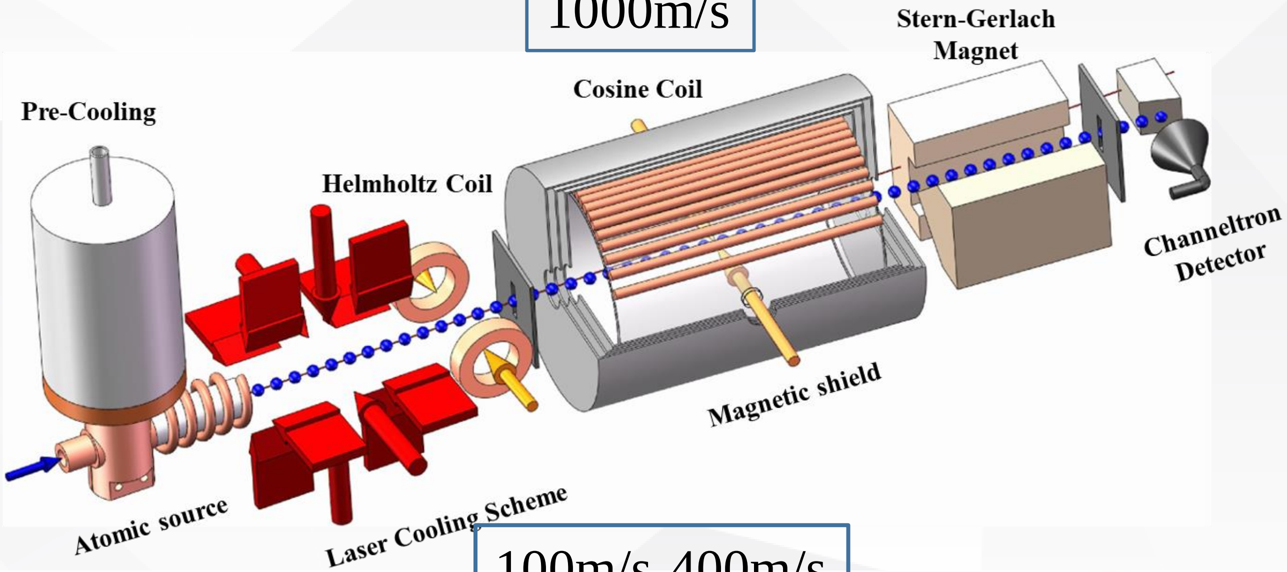






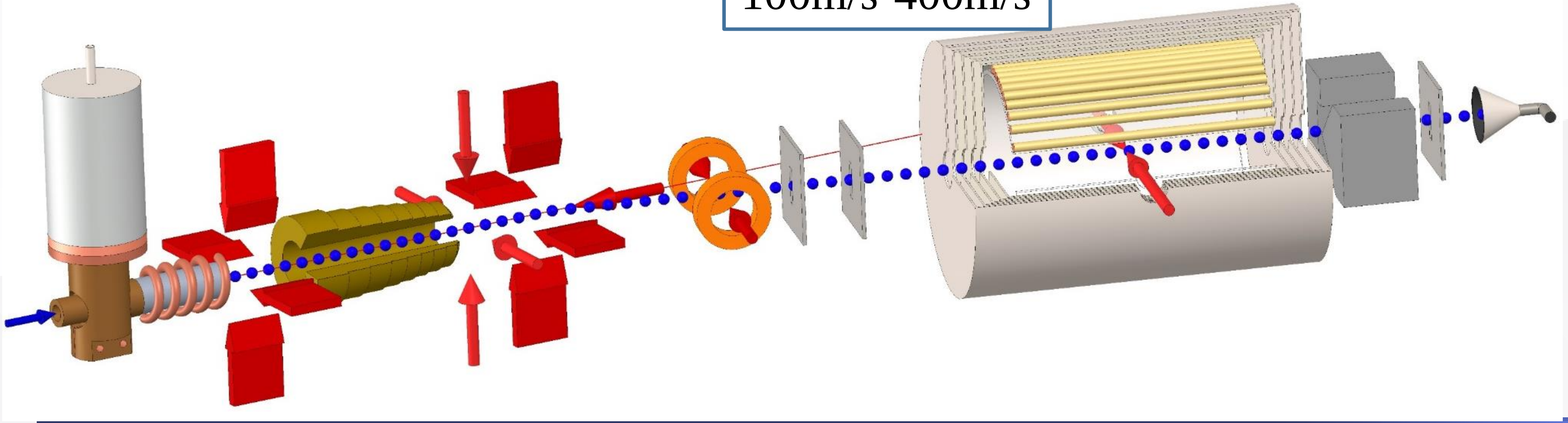
Remove Slit Restrictions？

1000m/s



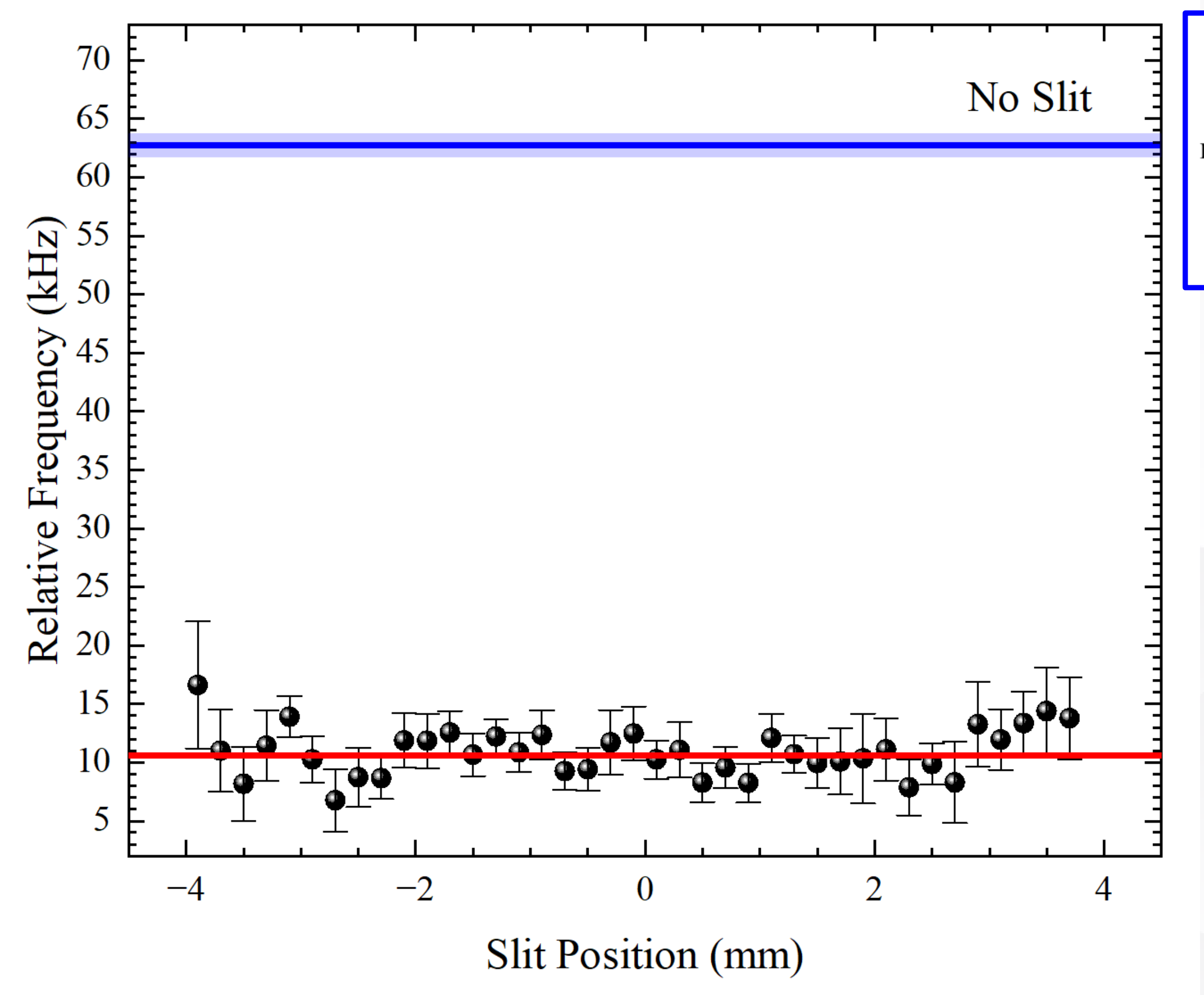
- Speed Faster
- Transvers velocity larger
- Effect of SG Lower
- The Slit can not be removed

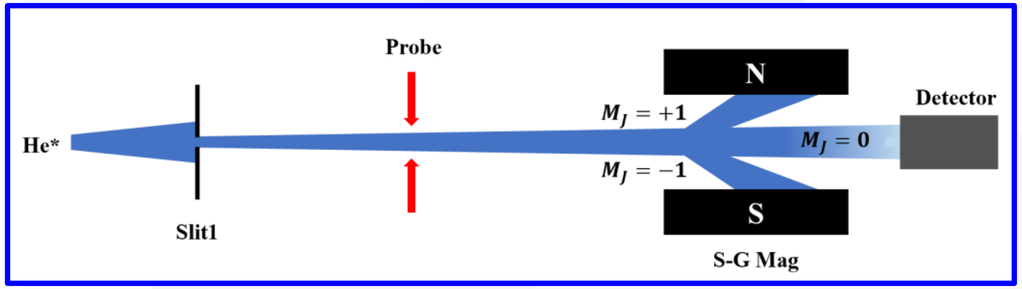
100m/s-400m/s



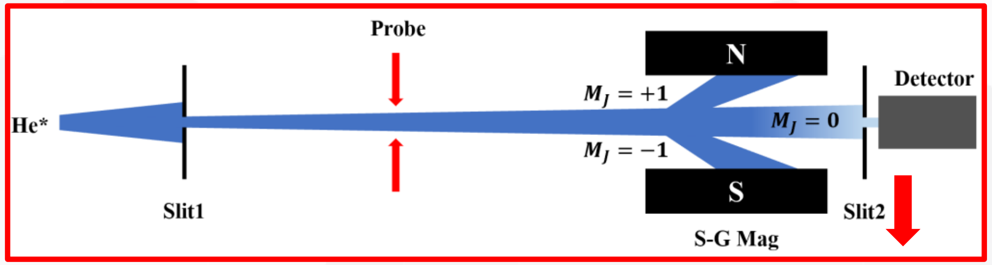
- Speed Slower
- Transvers velocity lower
- Effect of SG Higher
- The Slit can be removed

Systematic effect :Geometry effect from the slid





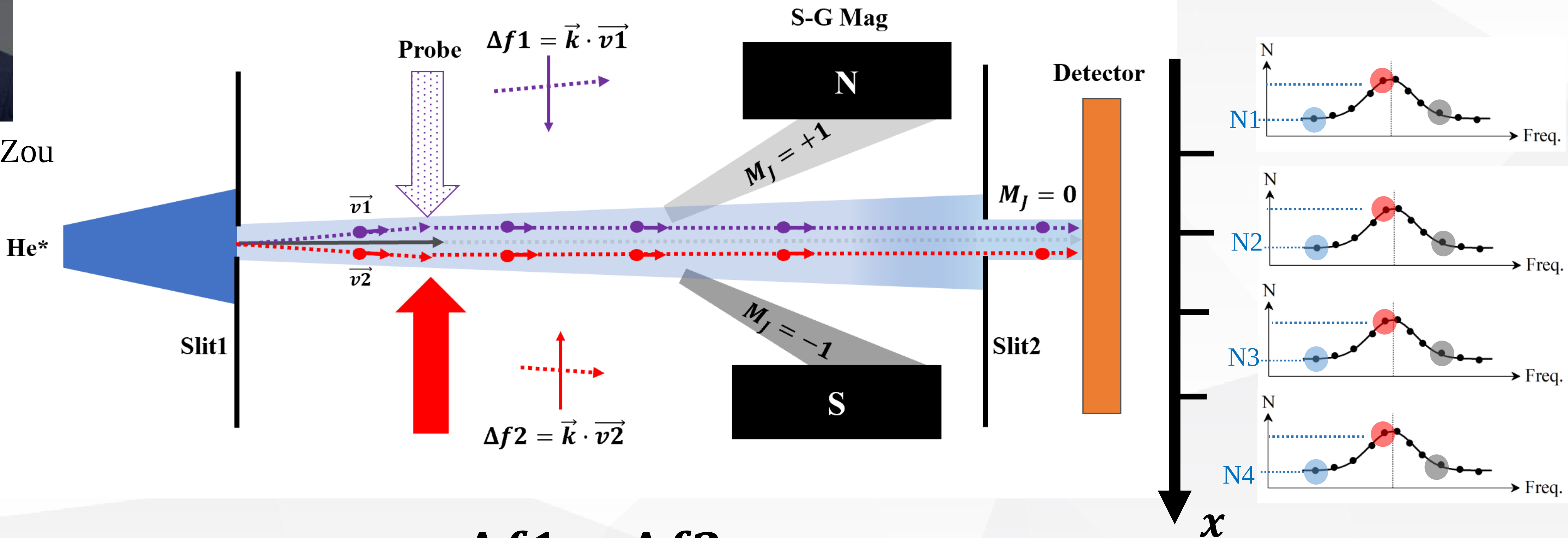
- Move Slit—Different position give same result
- With and Without slit have big difference



Move Slit Position

Systematic effect :Geometry effect from the slit=> Post Selection

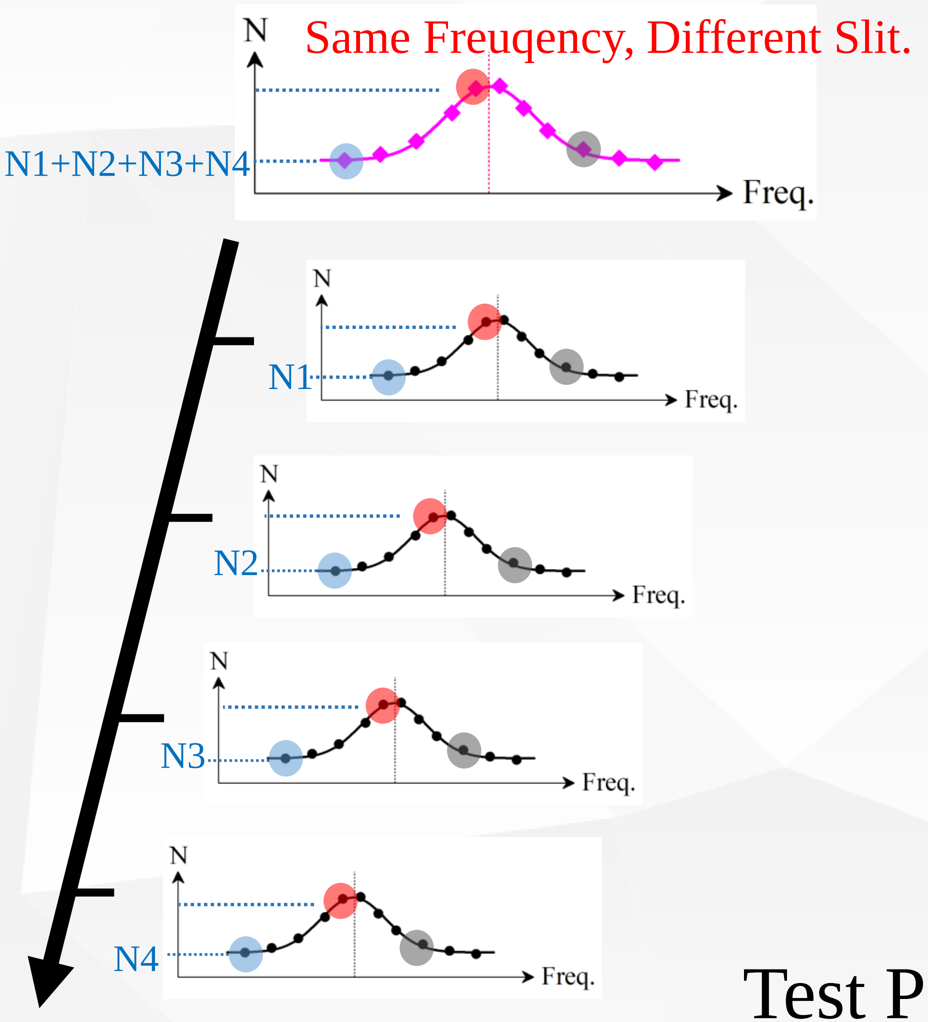
Chang-Ling Zou

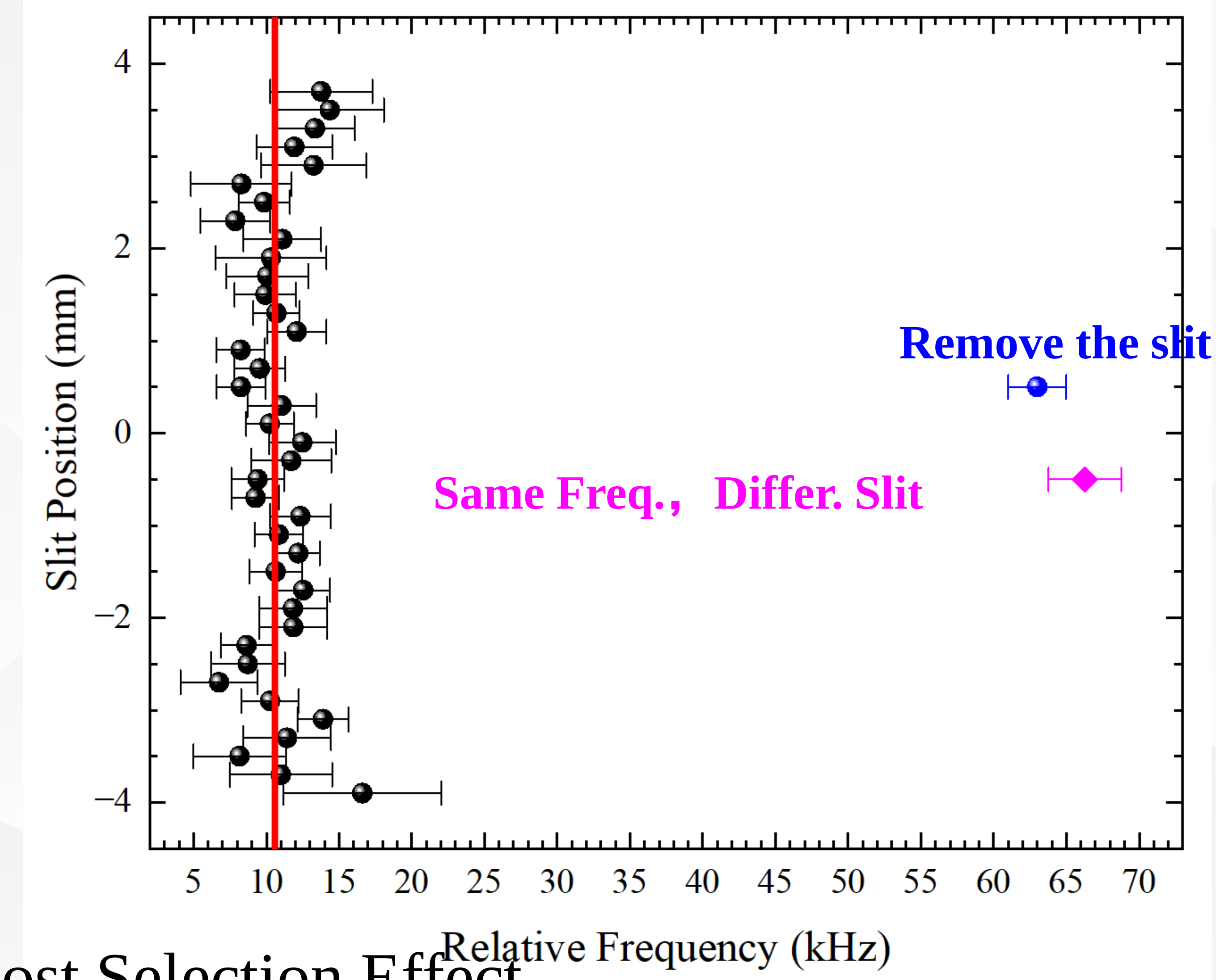


$$\Delta f1 = \Delta f2$$

- ☐ The slit selects atoms with a certain Doppler shift
- ☐ Two Retro-reflect laser feel the same shift

Systematic effect :Post Selection





Test Post Selection Effect

Systematic effect :Post Selection

This Work: $f(2^3S_1 - 2^3P_0) = 276\ 764\ 094\ 712.73\ (86)\ kHz$

Δf(1σ)	X. Zheng	This work
Statistics	0.45	0.22
1st Doppler	1.1	0.82
2nd Doppler	0.15	0.01
Frequency calibration	0.55	0.05
Line profile	0.3	
Quantum interference	0.1	0.1
Zeeman effect	0.01	0.01
Laser power	0.1	0.1
Light-force shift	0.8	
Total	1.6	0.86

Jia-Dong Tang

For X.Zheng2017: +55.4(1.3) kHz

Conclusion

More than 3σ deviation still exists

2^1S-2^3S Result：

--Magic wavelength，Eliminate AC

Ordinary Helium Result ：

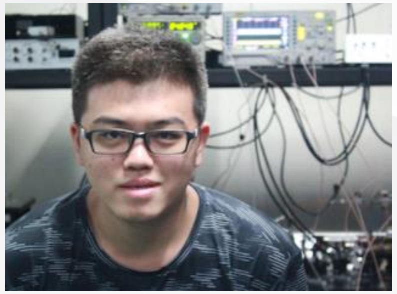
--2^3S-2^3P and 2^1S-2^3S now consistent

μ-He$^+$ compare with He ：

--2^1S-2^3S 3.6std

--Our combined with He-3 about 3 std

--New Physics? Need Confirmed



Jin-Lu Wen

Team Members

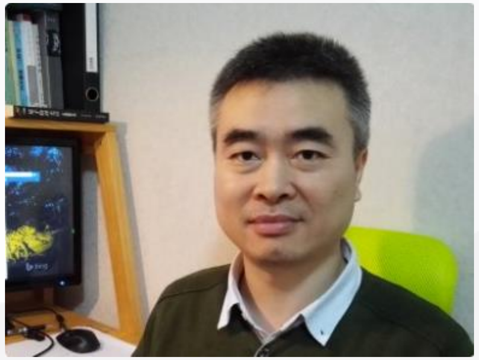
Institute of Advanced Science Facilities (深圳综合粒子设施研究院)

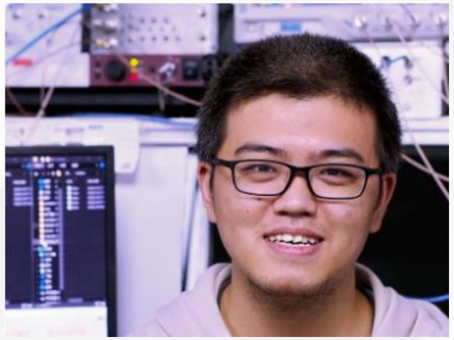

Prof. Sun Yu


Du Xiao-Jiao

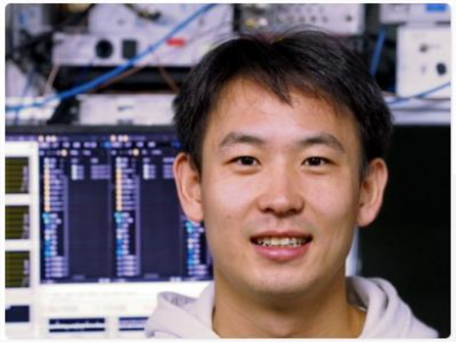

Wei Long

University of Science and Technology of China


Prof. Hu Shui-Ming


Wen Jin-Lu


Tang Jia-Dong


Dong Jun-Feng

第八届原子分子精密谱研讨会 | 首页 | 会议信息 | 日程安排 | 交通住宿 | 注册登记

重要通知

摘要投稿将于第二轮通知开放。本次会议除口头报告外，另设墙报展示，并设立优秀墙报奖若干。

会议简介

由中国物理学会原子与分子物理专业委员会主办、中国科学技术大学、深圳综合粒子设施研究院和南方科技大学光明高等研究院联合承办的第八届原子分子精密谱研讨会将于2024年4月19日至4月22日在广东省深圳市召开。会议将以“探索原子分子精密谱研究中的重要科学问题、发展相关的理论方法以及实验手段、促进相关实验和理论的紧密结合、促进学科交叉”为宗旨，努力为大家提供讨论问题、交流信息的机会和平台。

此次会议诚邀从事原子分子精密谱研究的国内外专家学者参加，展示原子与分子物理领域中的最新成果，分析当前国际研究前沿和热点，交流原子与分子物理研究领域及相关交叉学科的最新动态，促进原子分子精密谱研究的发展。

文档下载

- 第一轮通知
- 注册表
- 摘要模板

会议主题

1. 原子分子精密谱实验；
2. 原子分子精密谱理论与计算方法；
3. 原子分子精密谱应用；
4. 原子分子物理与原子核物理交叉问题；
5. 原子分子物理新技术和新方法。

地方组织委员会

胡水明	陈　帅	吴国荣
刘进军	孙　羽	刘安雯
程存峰	张寒辉	王　进
谈　艳	魏小雅	陈金枚

2024 April 19th to April 22th
at Shenzhen Guangming

The 8th Chinese Conference on Precision spectroscopy of atomic systems

Web-Site： cpsas.ustc.edu.cn

Acknowledgement

USTC

Shui-ming Hu
Zheng-Tian Lu
Wei Jiang

Xin Zheng
Jiao-Jiao Chen

NIM

Zhan-Jun Fang
Fei Meng

NTS

Hai-Feng Jiang

University of Warsaw
K. Pachuchi

UNB (CA)
Zong-Chao Yan

Funding:

Thank You !!!