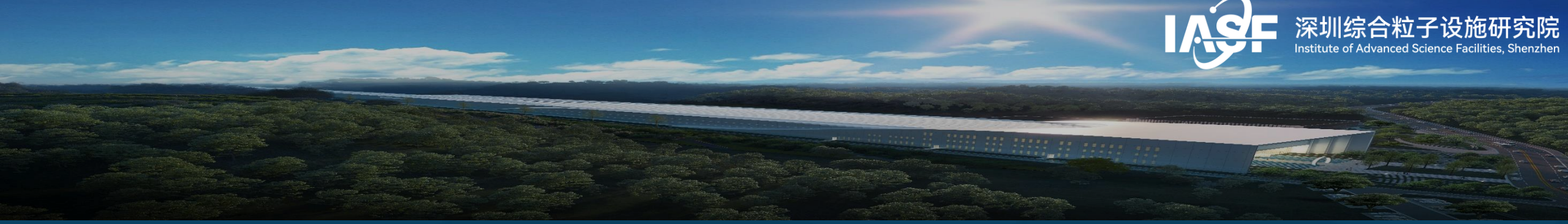

深圳综合粒子设施研究院
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Precision Spectroscopy of Helium Atoms

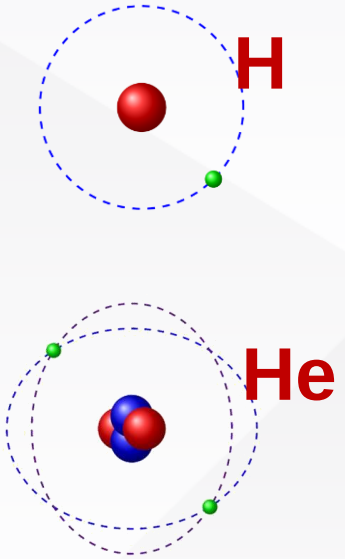
Yu Sun
孙羽

International Conference on Precision Physics of Simple Atomic Systems
ETH Zurich 2024/6/11

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 $R_\infty(r_p)$, α, m_p/m_e
- New Physics?



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

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

Beyer et al., Science 2017

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

Introduction : Simple Atom, Fundamental Physics

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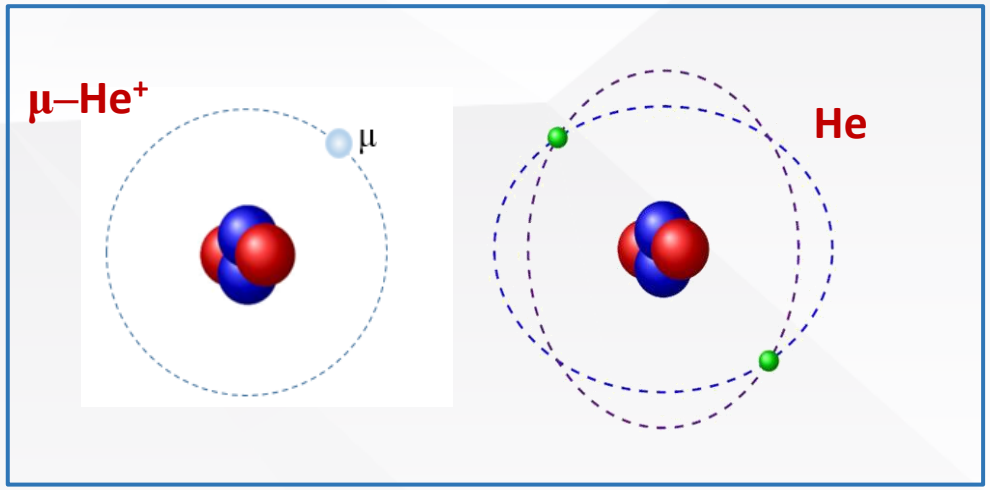
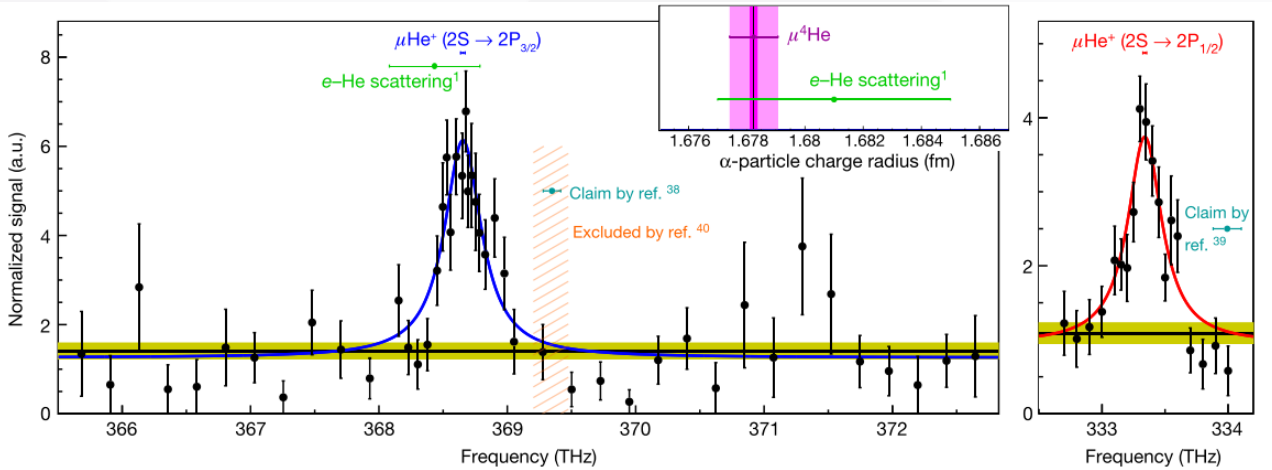
Nuclear Radius of μ-He$^+$



Nature (2021) **589** 527



μ-He$^+$/He

Testing fundamental interactions on the helium atom

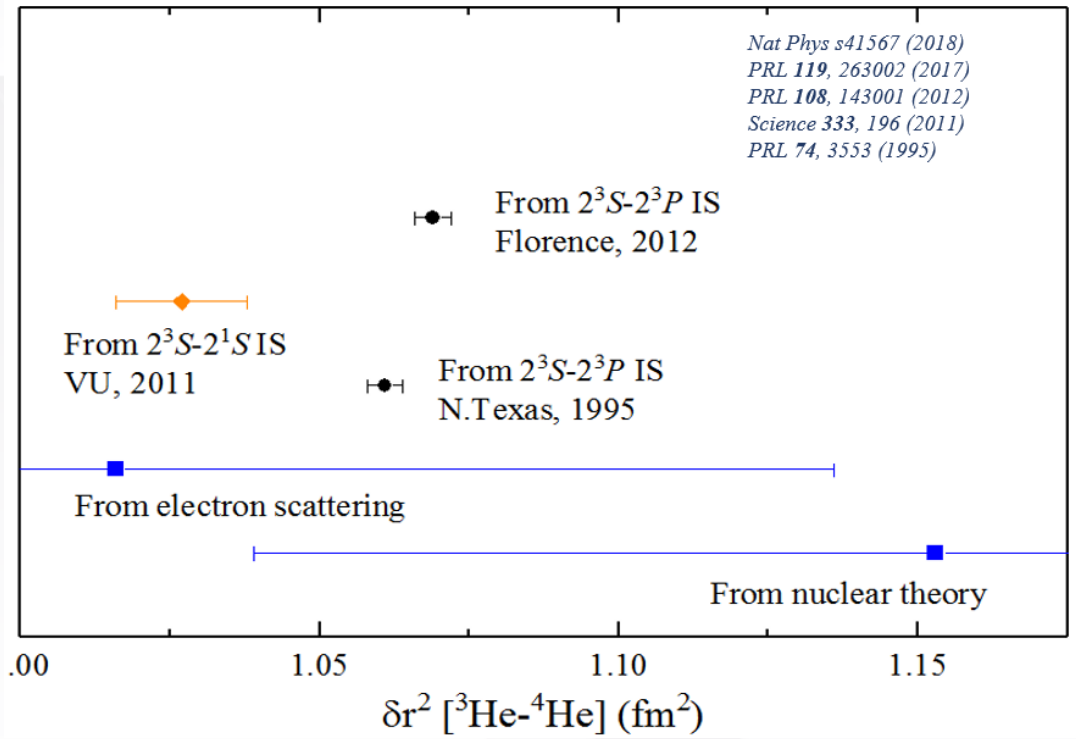
Krzysztof Pachucki,[1] Vojtěch Patkóš,[2] and Vladimir A. Yerokhin[3]

- 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 Squared Nuclear Charge Radius Difference



- $\delta r^2 = r_{He\text{-}3}^2 - r_{He\text{-}4}^2$
- Sufficient to Compare with μ-He^+
- Results from 2S-2P different from 2^1S-2^3S
- Need more independent experiment to verify

Precision Measurement of Helium

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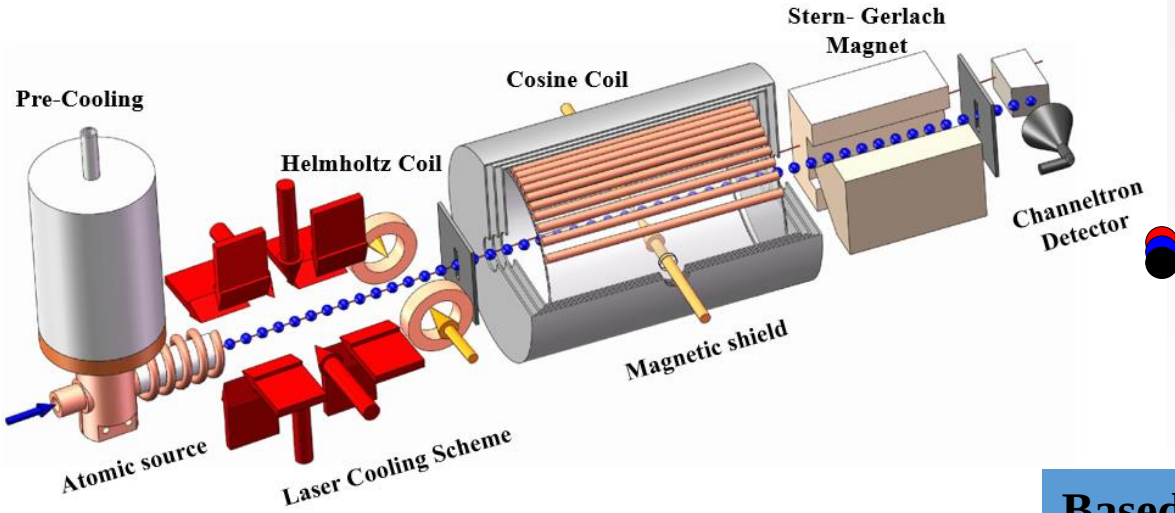
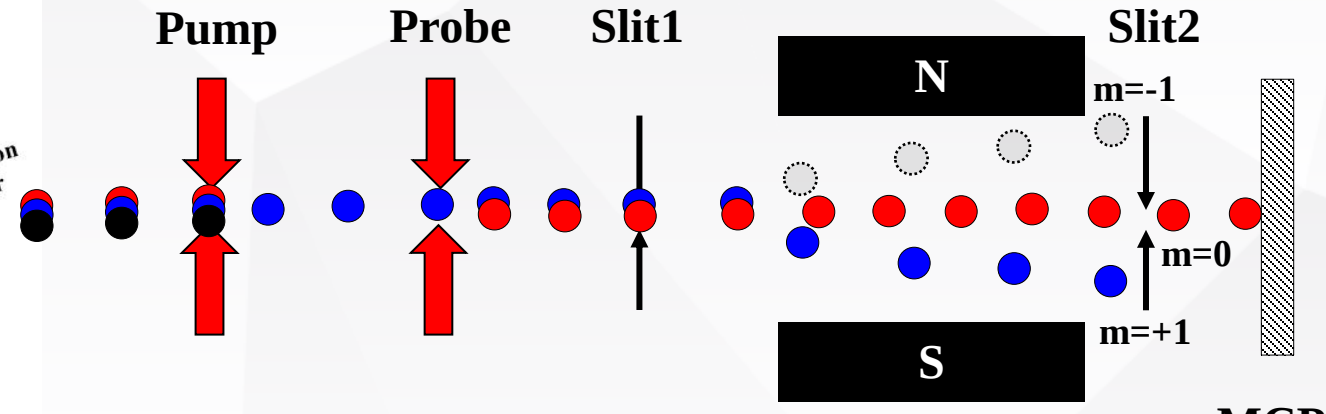
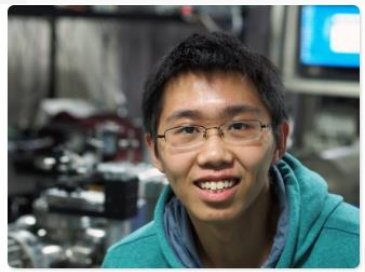
Laser cooling based atomic beam system

Front. Phys. China, **4(2)**, 165 (2009)
Physical Review A **91**, 030502(R) (2015)

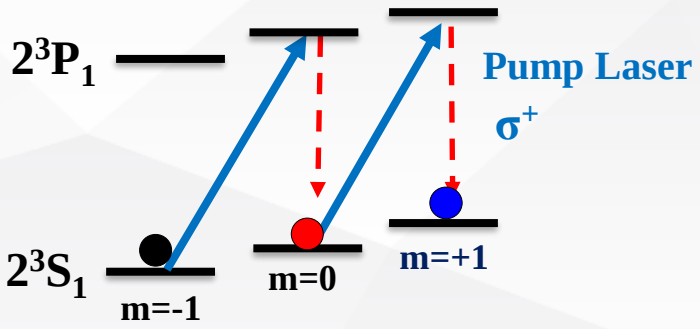


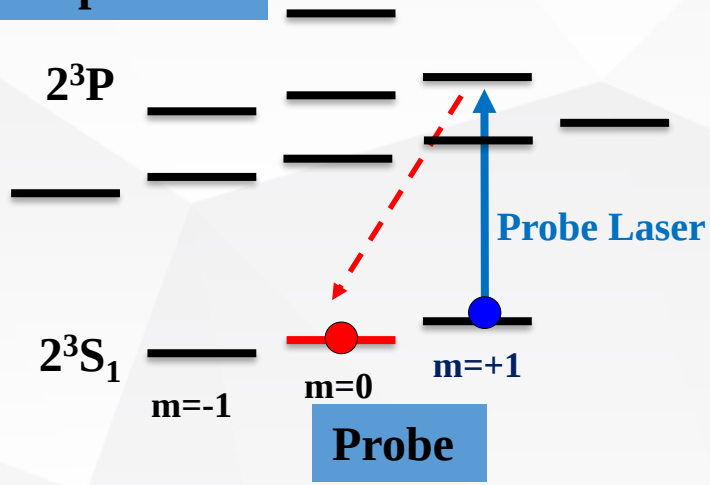




X. Zheng

Based on Optical Pump-Probe





Precision Measurement of Helium

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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
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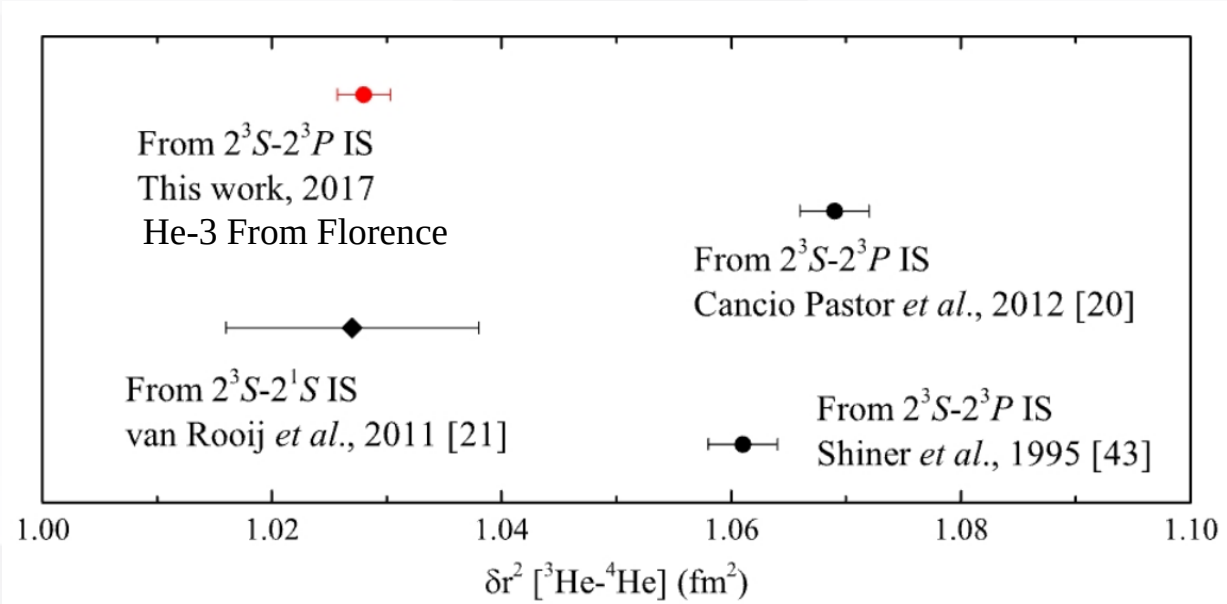
Recoil shift	-42.20	-	
Total	-40.90	1.6	5.0

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



Design New Experiment Method

Systematic effect：

- First Order Doppler Effect
- Light Force shift

氦原子精密谱测量实验研究--2S-2P跃迁测量

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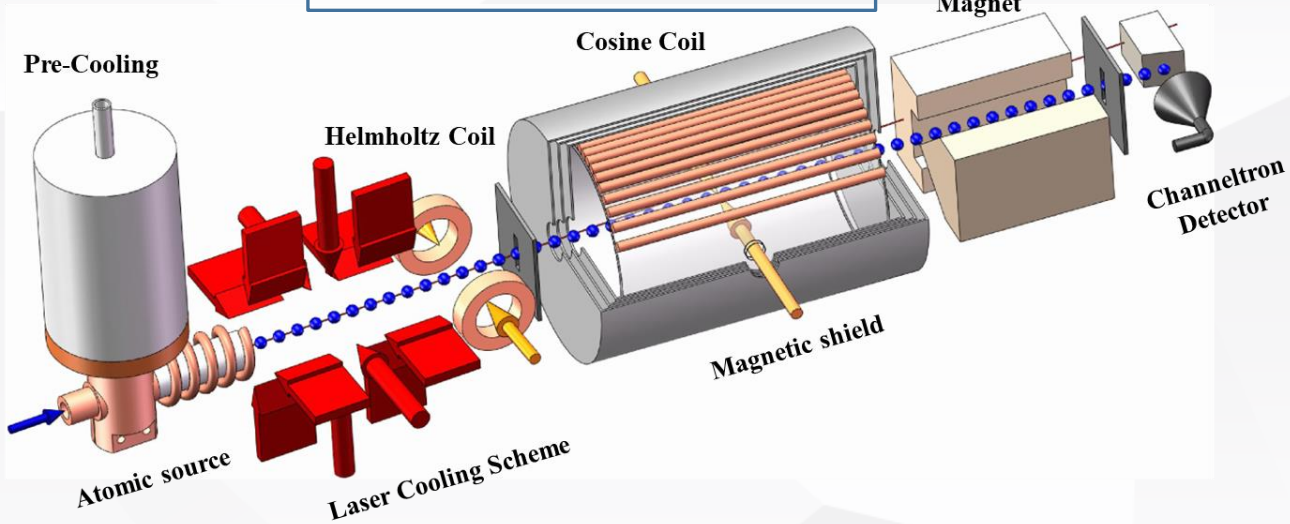
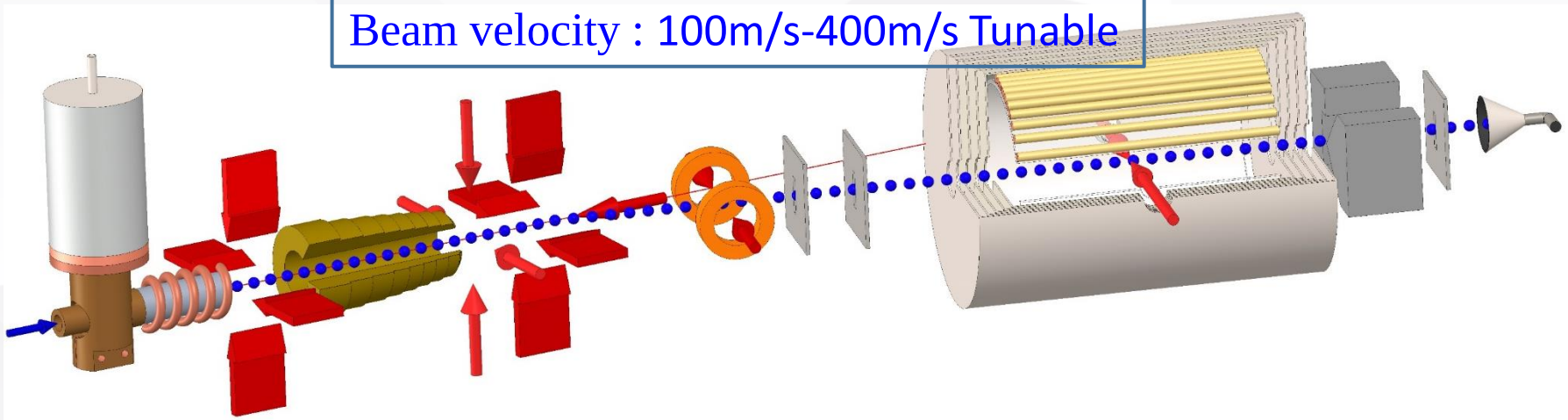
Beam velocity :1000m/s



- Speed Fast
- Transvers velocity large
- Effect of SG Lower

Beam velocity : 100m/s-400m/s Tunable



- Speed Slower
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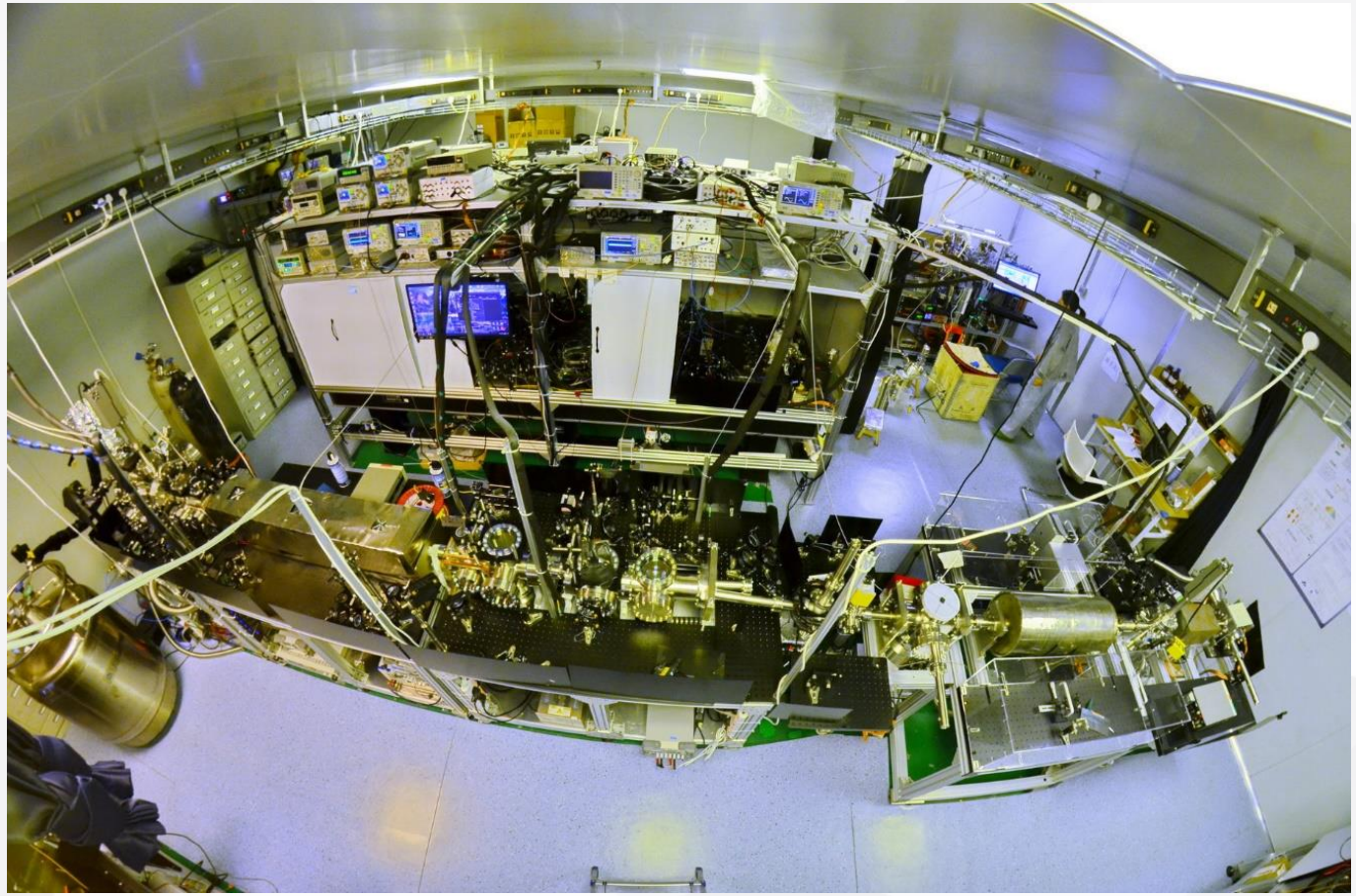
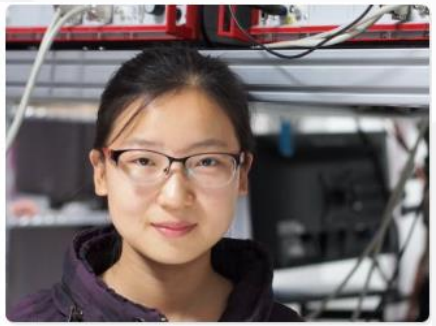
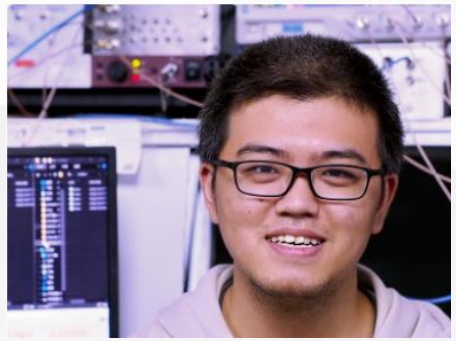
Precision Measurement of Helium



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



J.-J. Chen



J.-L.Wen

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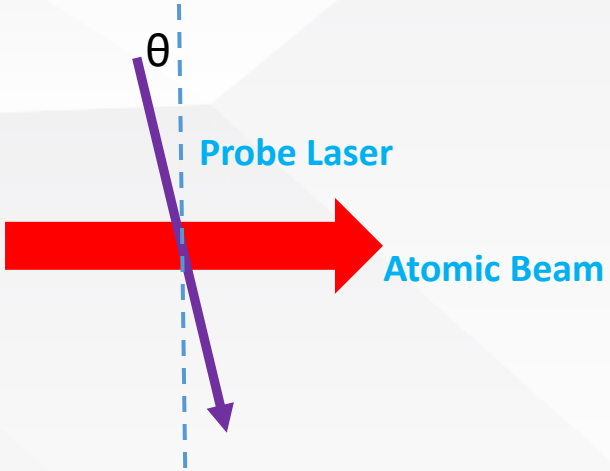
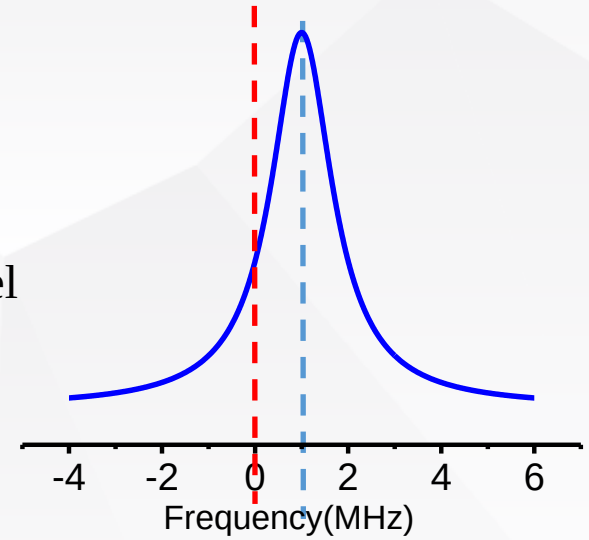
Precision Measurement of Helium

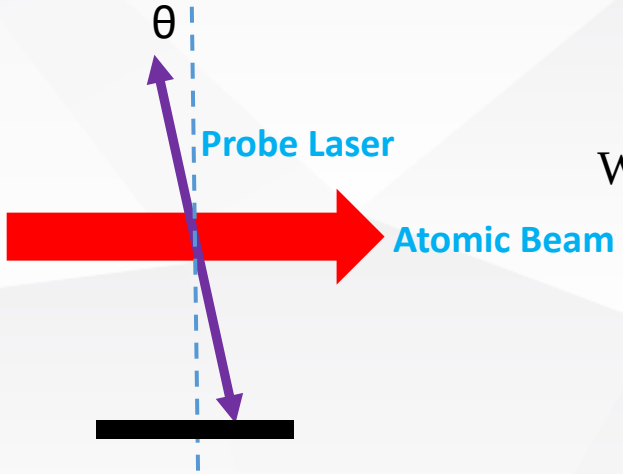
- First Order Doppler



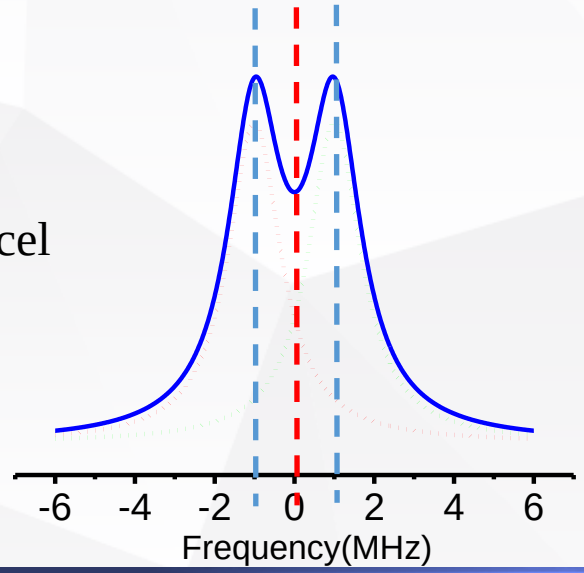
$$\Delta\nu_D = k\nu \cdot \theta$$

No Doppler cancel



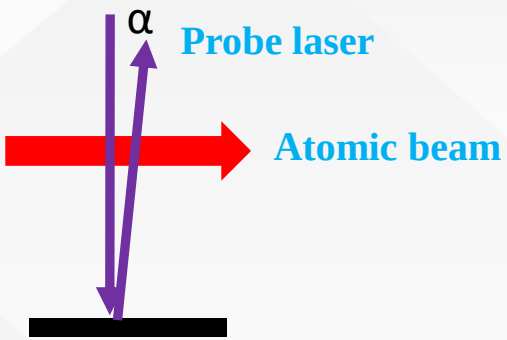


With Doppler cancel



Precision Measurement of Helium

- First Order Doppler

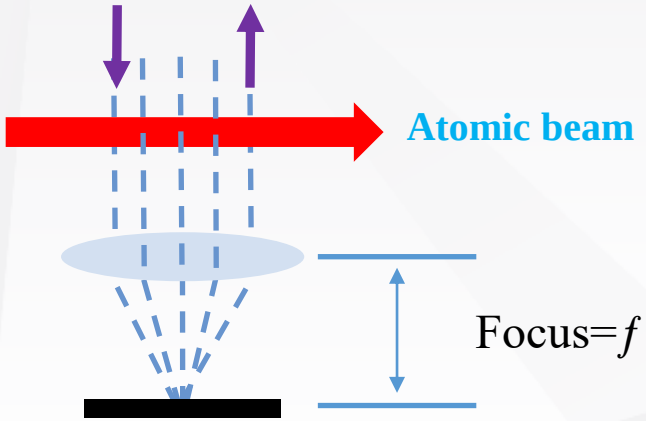


$$\Delta\nu_D \approx \frac{1}{2} k v \cdot \alpha$$

10urad correspond to about 3kHz derivation

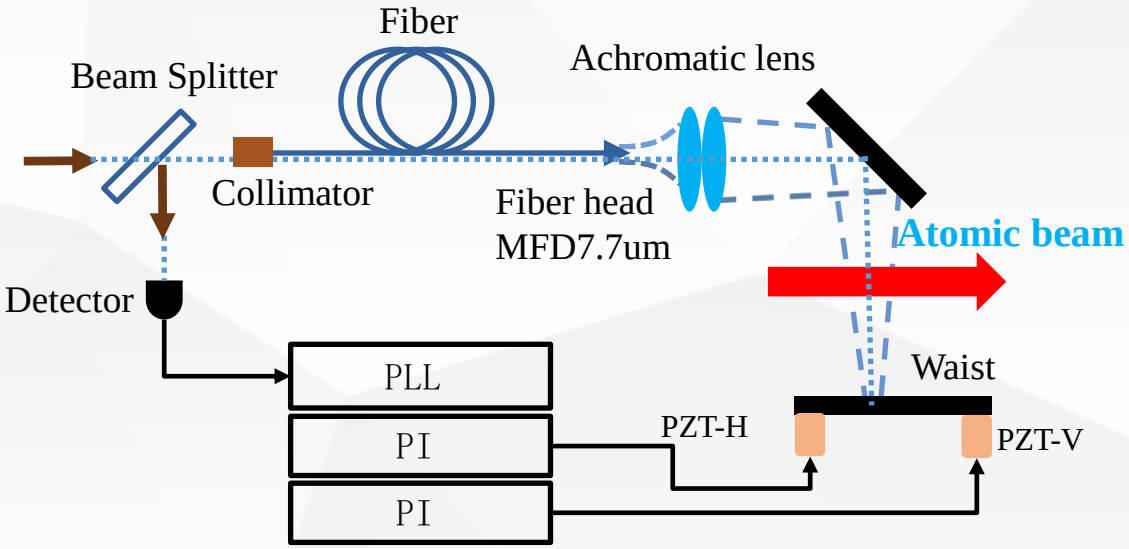
➢ **Cancel Mechanism**

✓ Cat's eye optical method



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

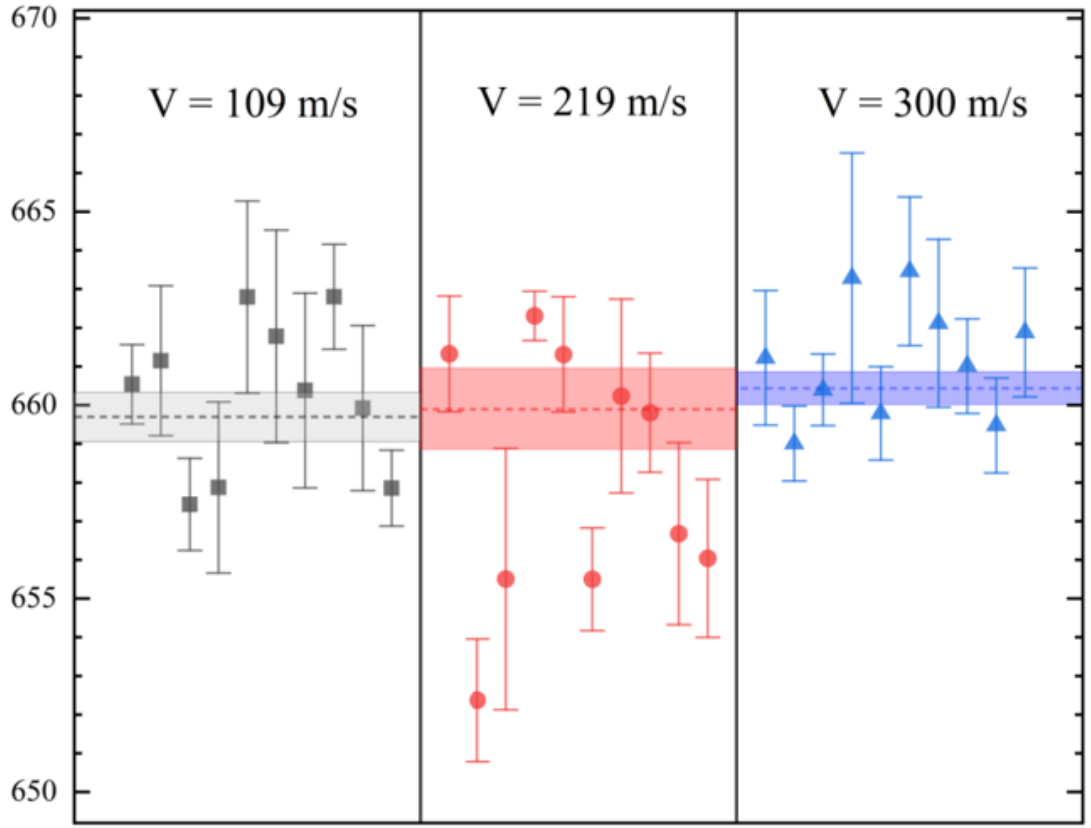
✓ Active Feedback method



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 each other
- The derivation is not from doppler effect

Uncertainty Budget of 2S-2P transition frequency Measurement

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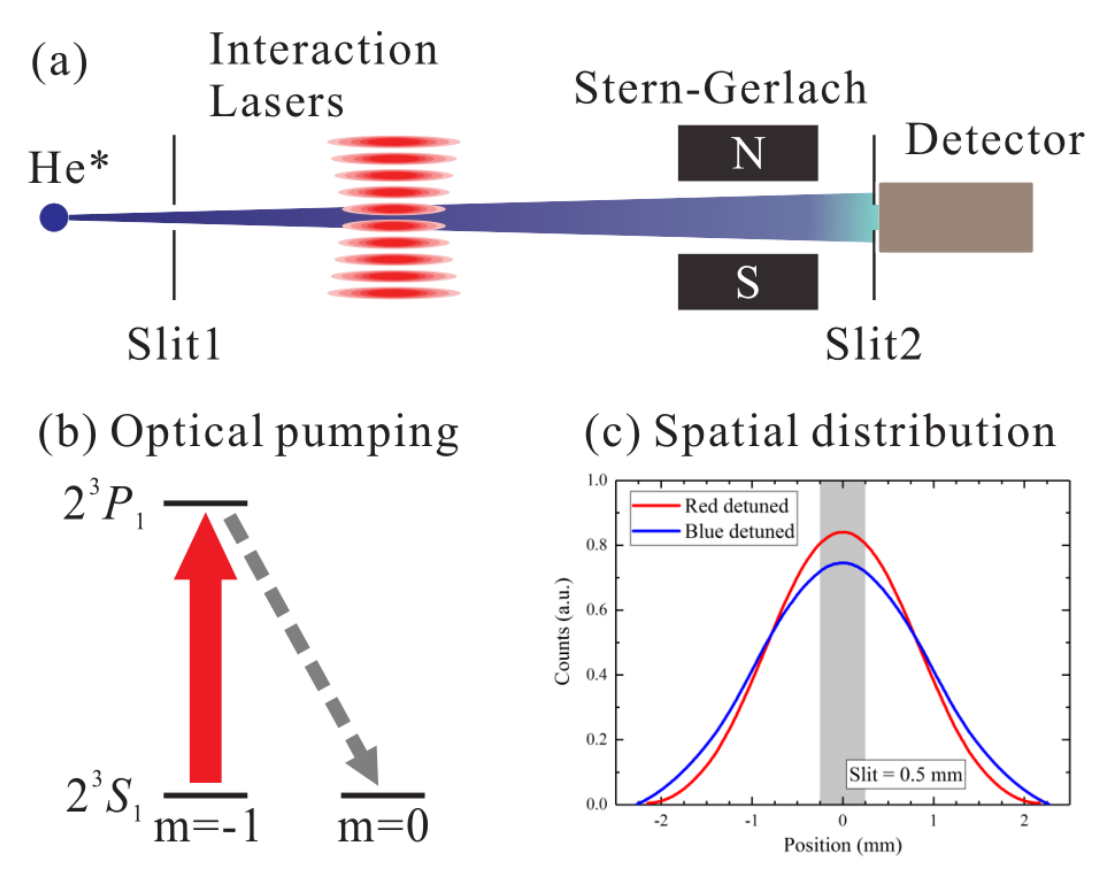
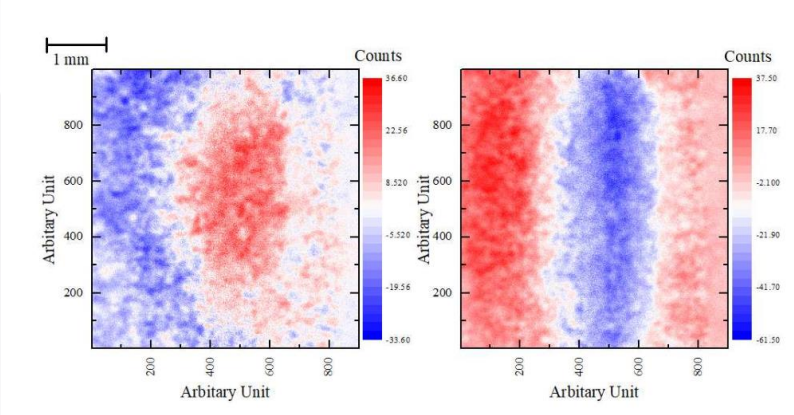
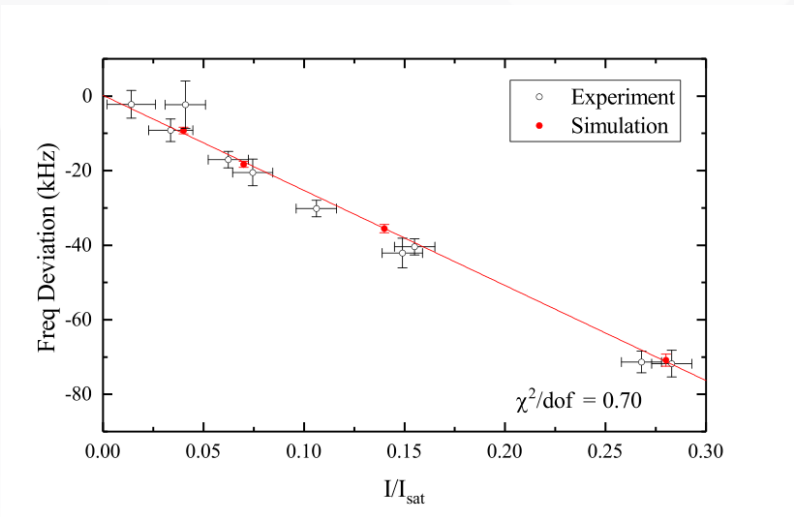
Light-force-induced shift	+0.5	0.8	3
Recoil shift	-42.20	-	
Total	-40.90	1.6	5.0

Light Force Induce Shift







Precision Measurement of Helium

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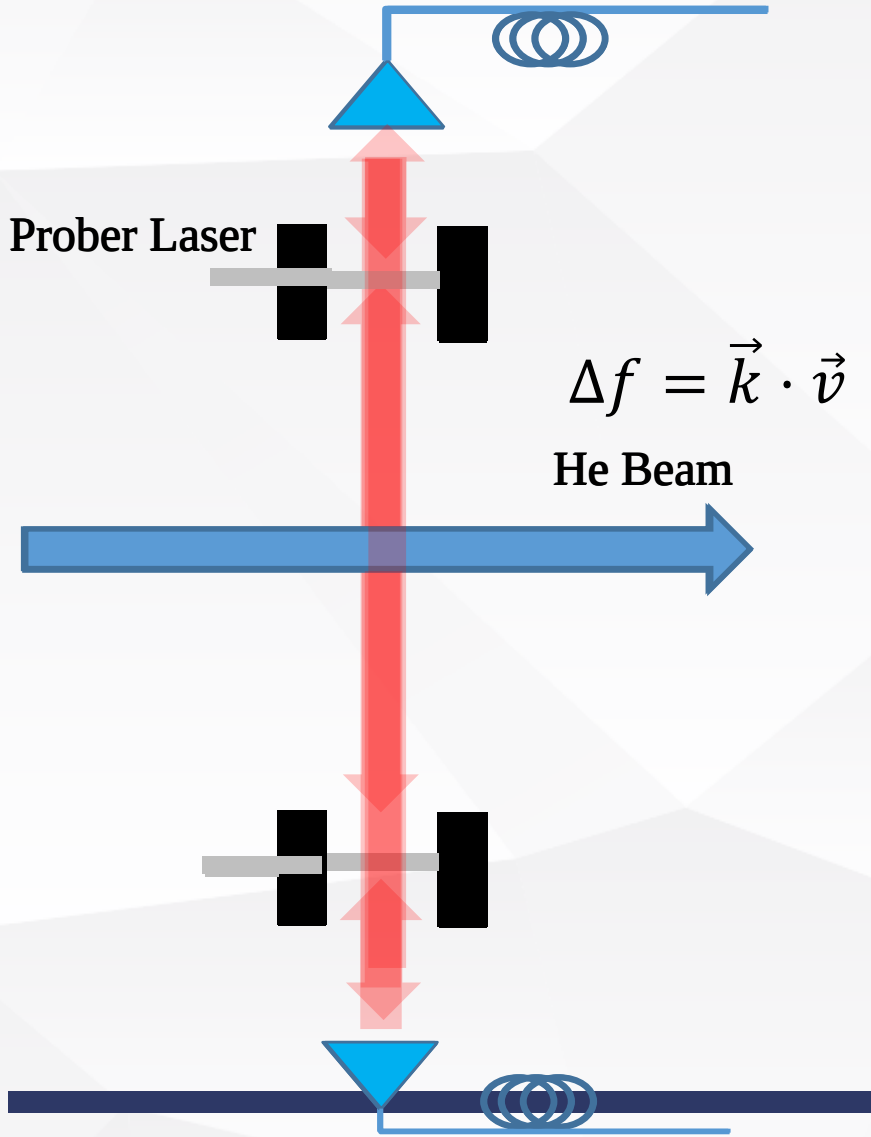
Institute of Advanced Science Facilities, Shenzhen

Systematic effect :Light-Force-Shift

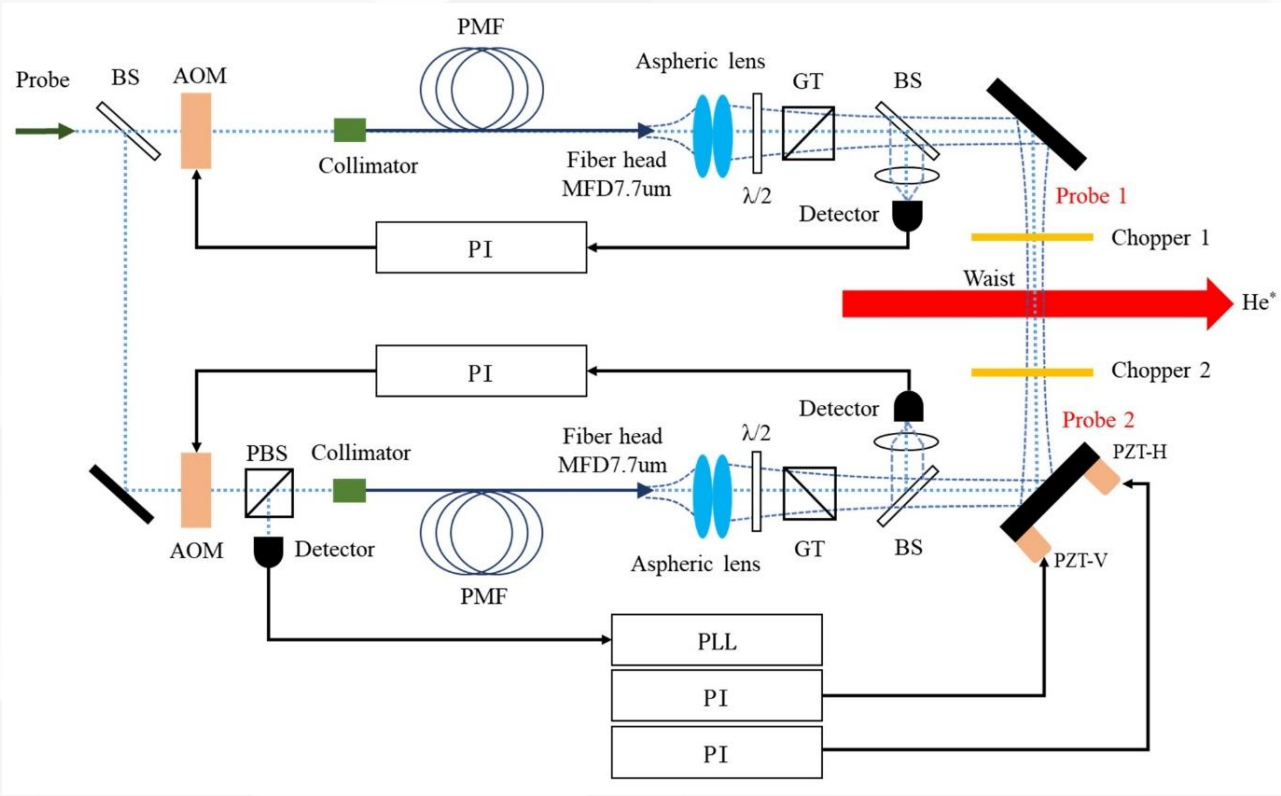


PHYSICAL REVIEW A **107**, 042811 (2023)

Editors' Suggestion

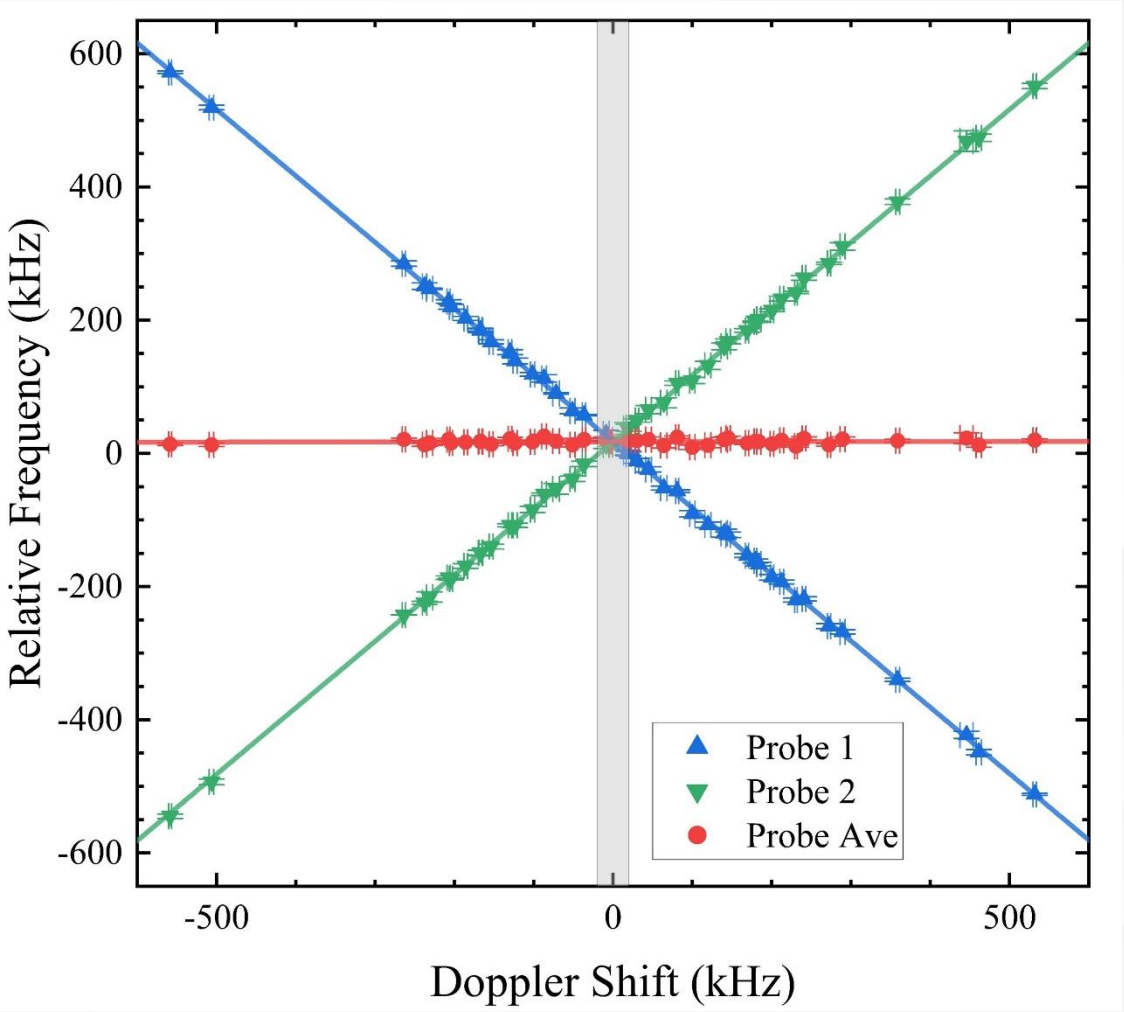
Doppler-free spectroscopy of an atomic beam probed in traveling-wave fields

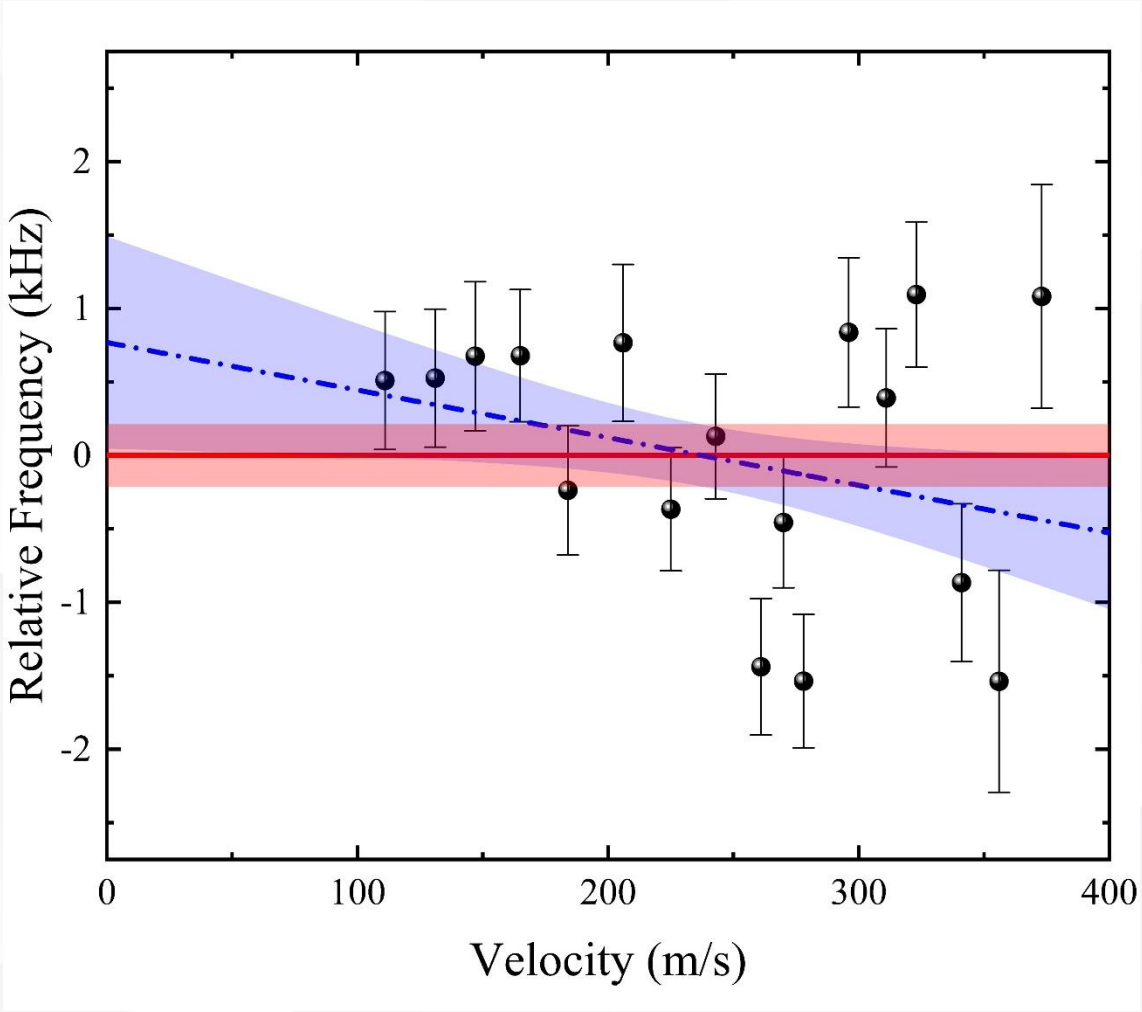
Jin-Lu Wen (温金录),[1] Jia-Dong Tang (唐家栋),[2] Jun-Feng Dong (董俊峰),[1] Xiao-Jiao Du (杜小娇),[3] Shui-Ming Hu (胡水明),[1,2,*] and Y. R. Sun (孙羽)[3,†]



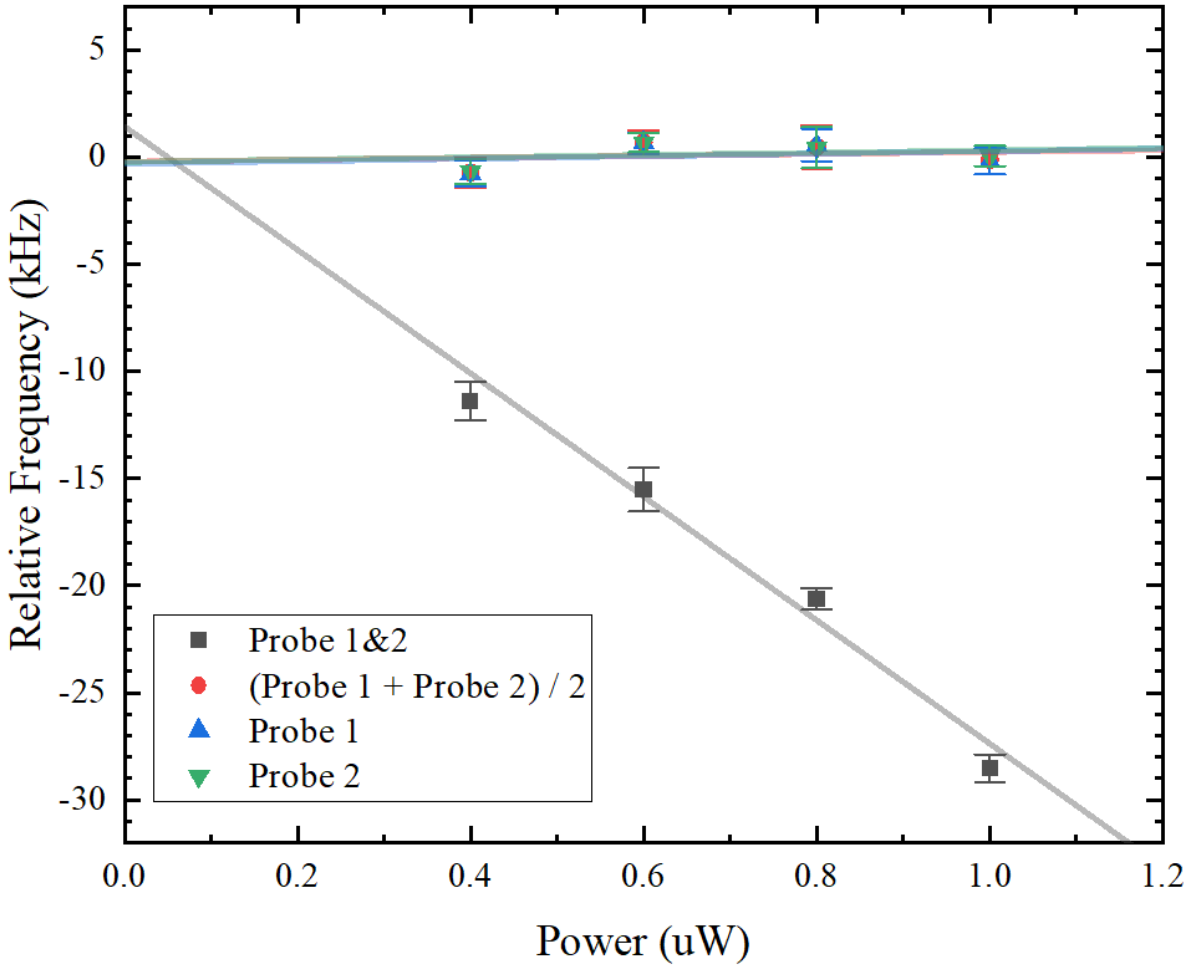
PRA **107**, 042811 (2023)

Systematic effect :Light-Force-Shift





Systematic effect :Light-Force-Shift



- Stand-Wave vs Traveling-Wave
- Estimate Light-Force-Shift
- The derivation is not from Light-Force-Shift

Uncertainty Budget of 2S-2P transition frequency Measurement

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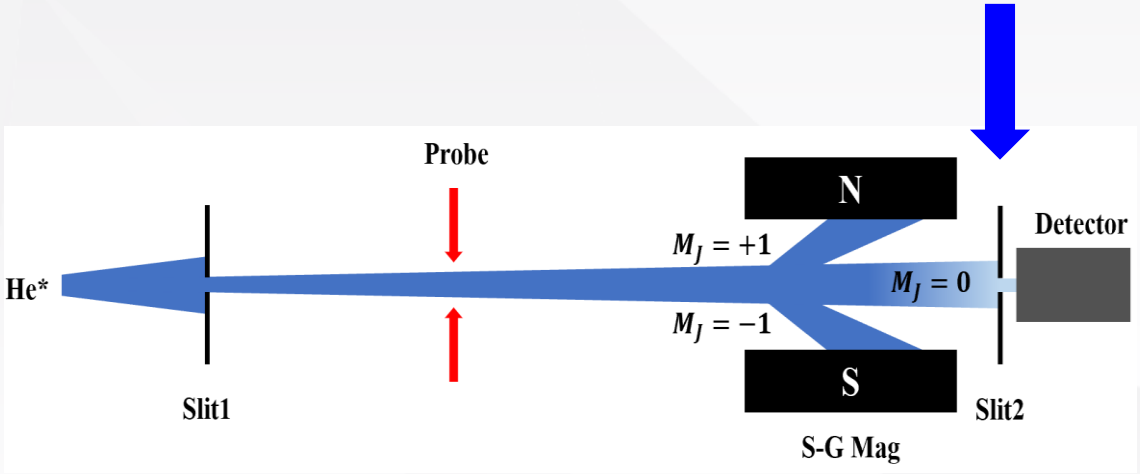
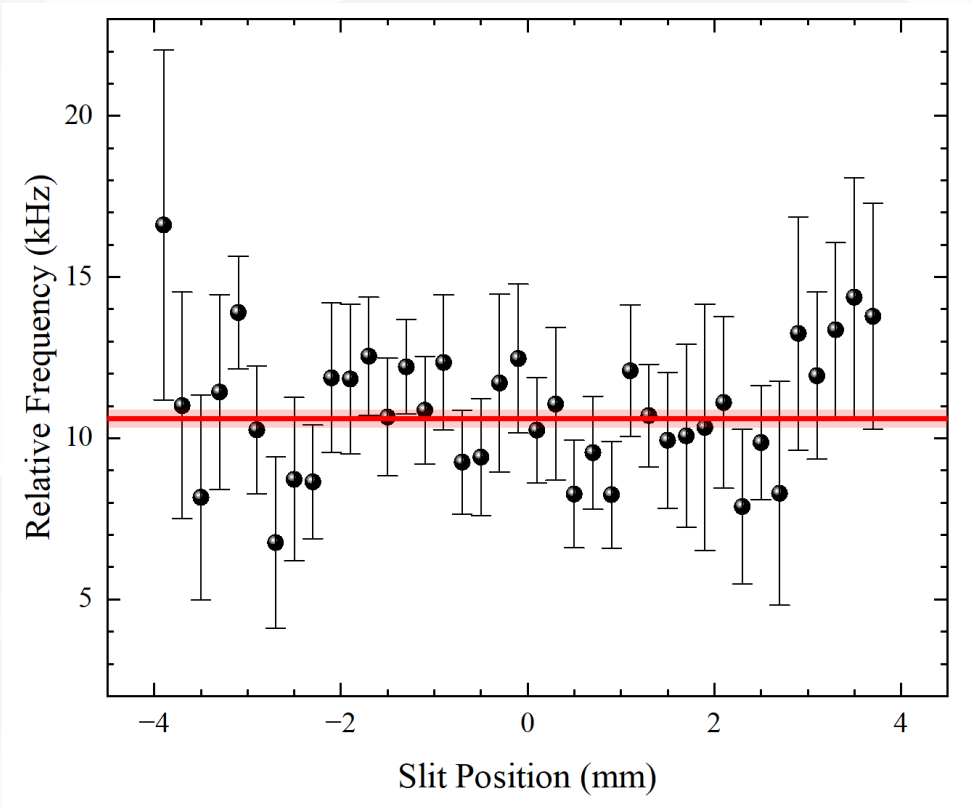
Total	-40.90	1.6	5.0

Systematic effect :Geometry effect from the slit



Move Slit Position

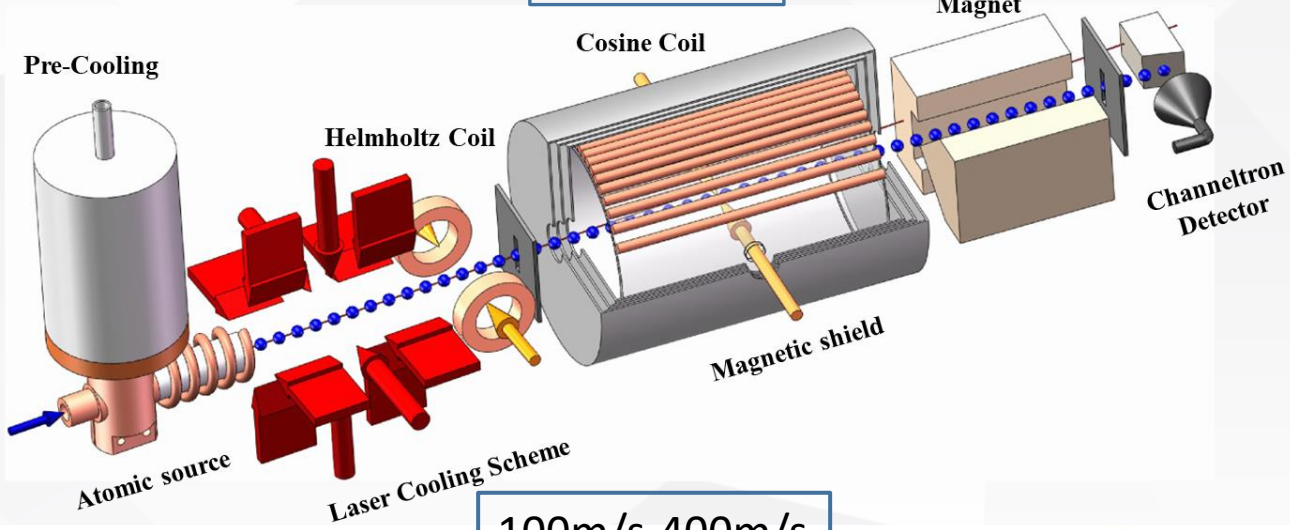
➢ **Move Slit Position**



Precision Measurement of Helium

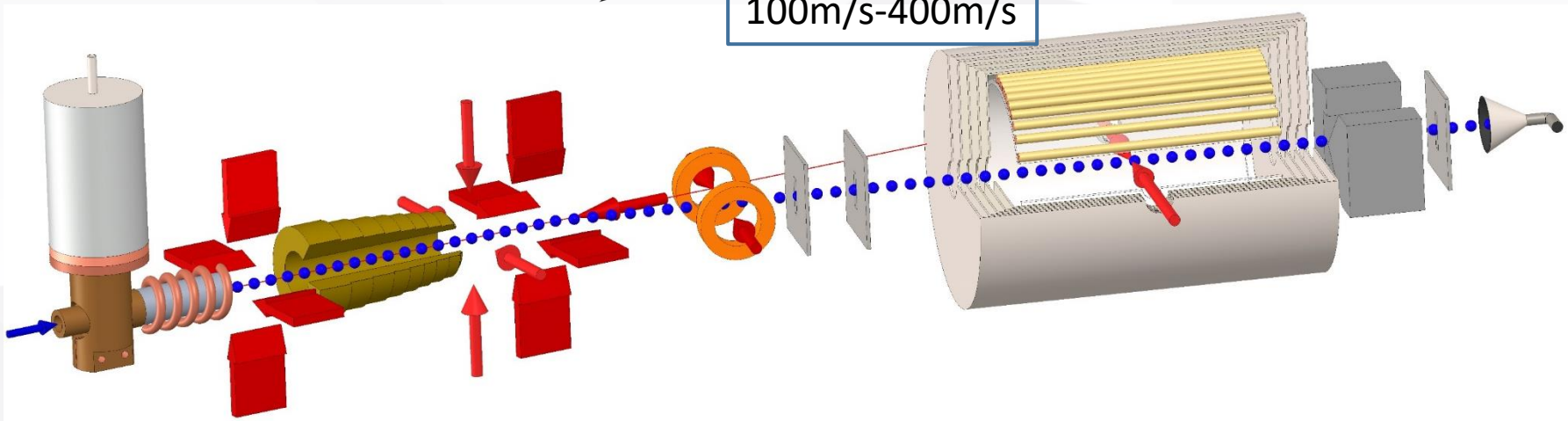
Remove Slit ？

1000m/s



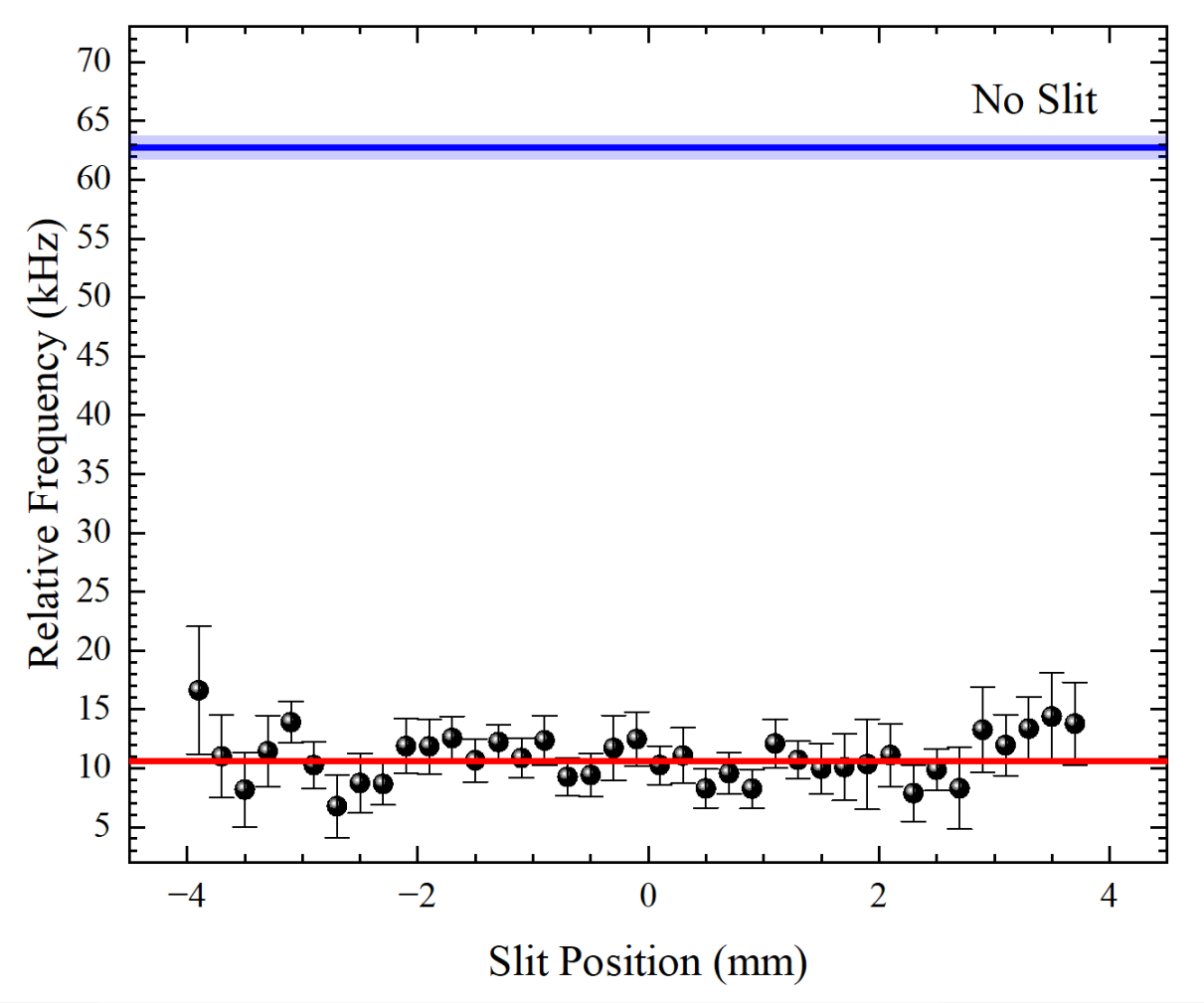
- Speed Fast
- Transvers velocity large
- Effect of SG Lower
- The Slit can not be removed

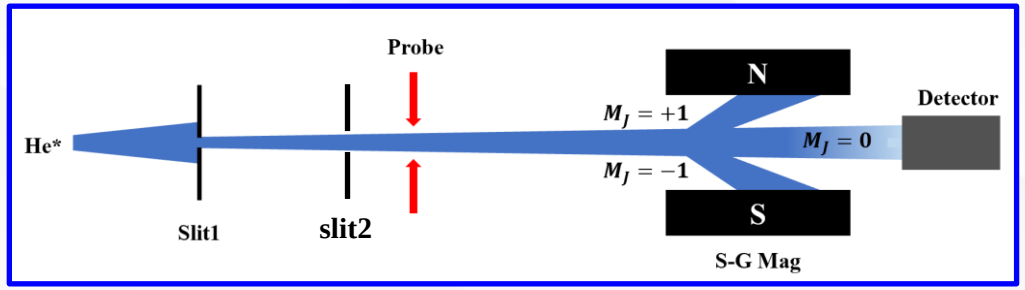
100m/s-400m/s



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

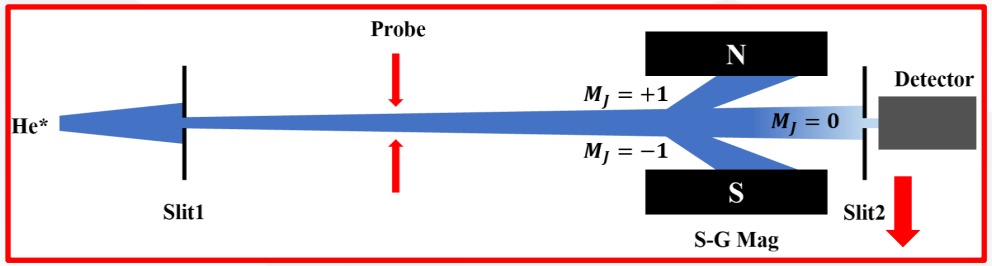
Systematic effect :Geometry effect from the slid





Remove Slit

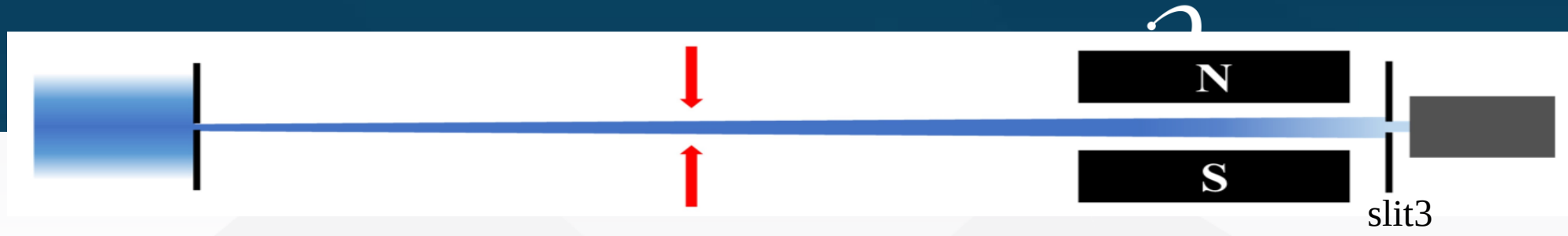
- **Move Slit—Different position give same result**
- **With and Without slit have big difference**



Move Slit Position

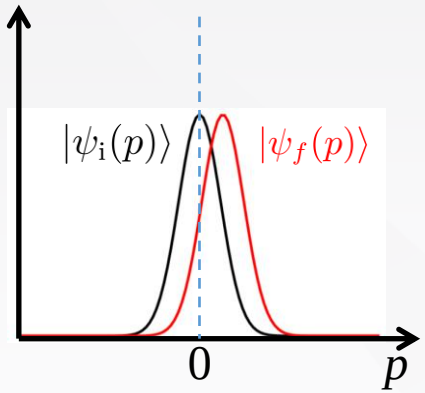
C.-L Zou

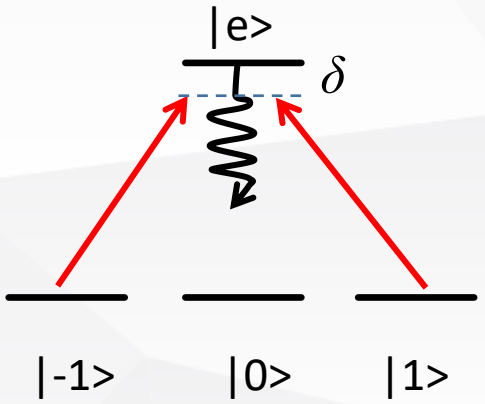
Y.-N. Lv



Initial State:

$$|\psi_i\rangle = |\pm 1\rangle \otimes |\psi_i(p)\rangle$$





Coupling:

$$H = \delta\sigma_{ee} + \left(g_a e^{i\vec{k}\cdot\vec{r}} a^{+} \otimes \sigma_{\pm 1,e}^{-} + h.c.\right) + \sum_k \left[\Delta_k b_k^{\dagger} b_k + \left(g_b e^{i\vec{k_b}\cdot\vec{r}} b_k^{+} \otimes \sigma_{0e}^{-} + h.c.\right)\right]$$

$$At\ time\ t: |\psi_f\rangle$$

$$|\psi_f\rangle = e^{-i\int_0^t H(\tau)d\tau}|\psi_i\rangle$$

The number of atoms finally obtained by slit3

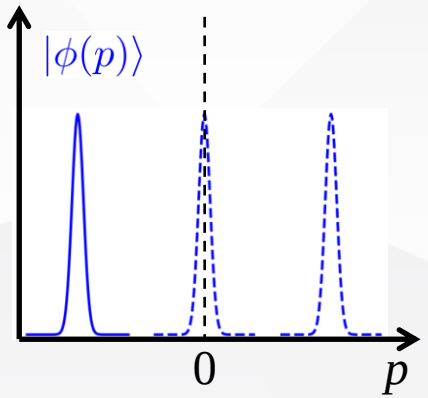
$$N(\delta) \propto |\langle\phi(p)|U_{SE}\langle e|O(\delta)|\pm 1\rangle|\psi_i(p)\rangle|^2$$

Post-selction(WM):

$$\langle\phi \mid \psi_f\rangle = \left\langle\phi\left|e^{-i\int_0^t H(\tau)d\tau}\right|\psi_i\right\rangle$$

State of Post-selction

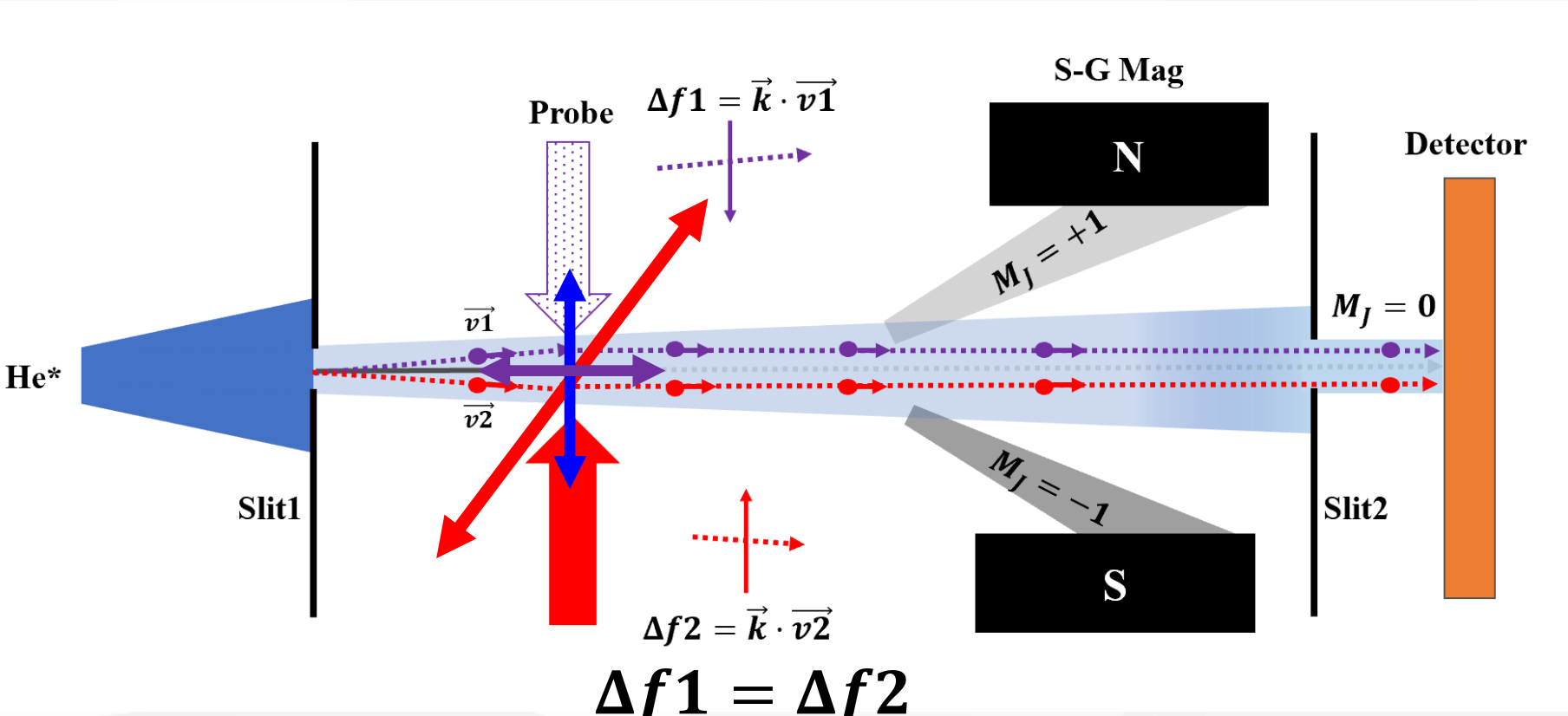
$$|\phi\rangle = |\phi(p)\rangle \otimes |0\rangle$$



Different positions correspond to different distributions

Precision Measurement of Helium

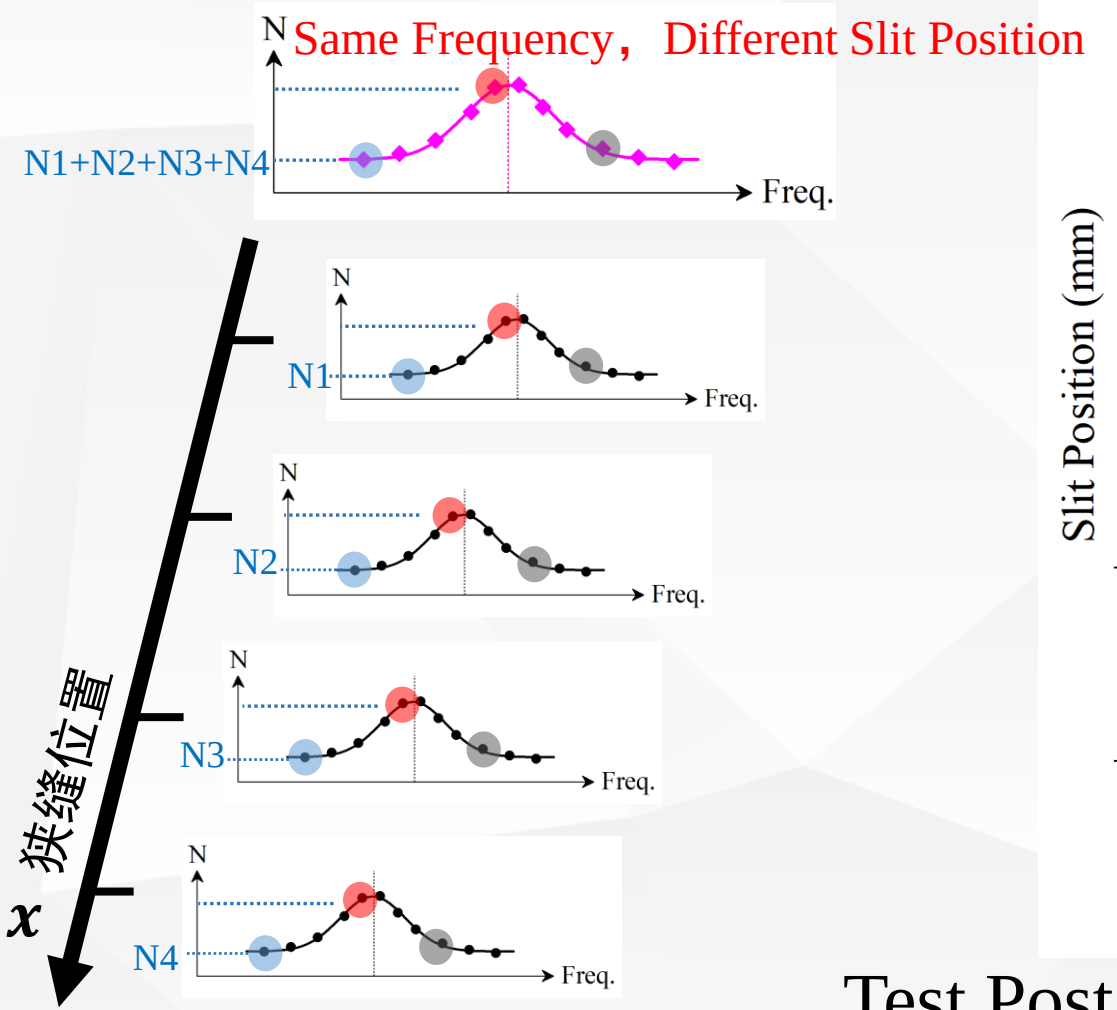
Systematic effect :Geometry effect from the slid=> Post Selection

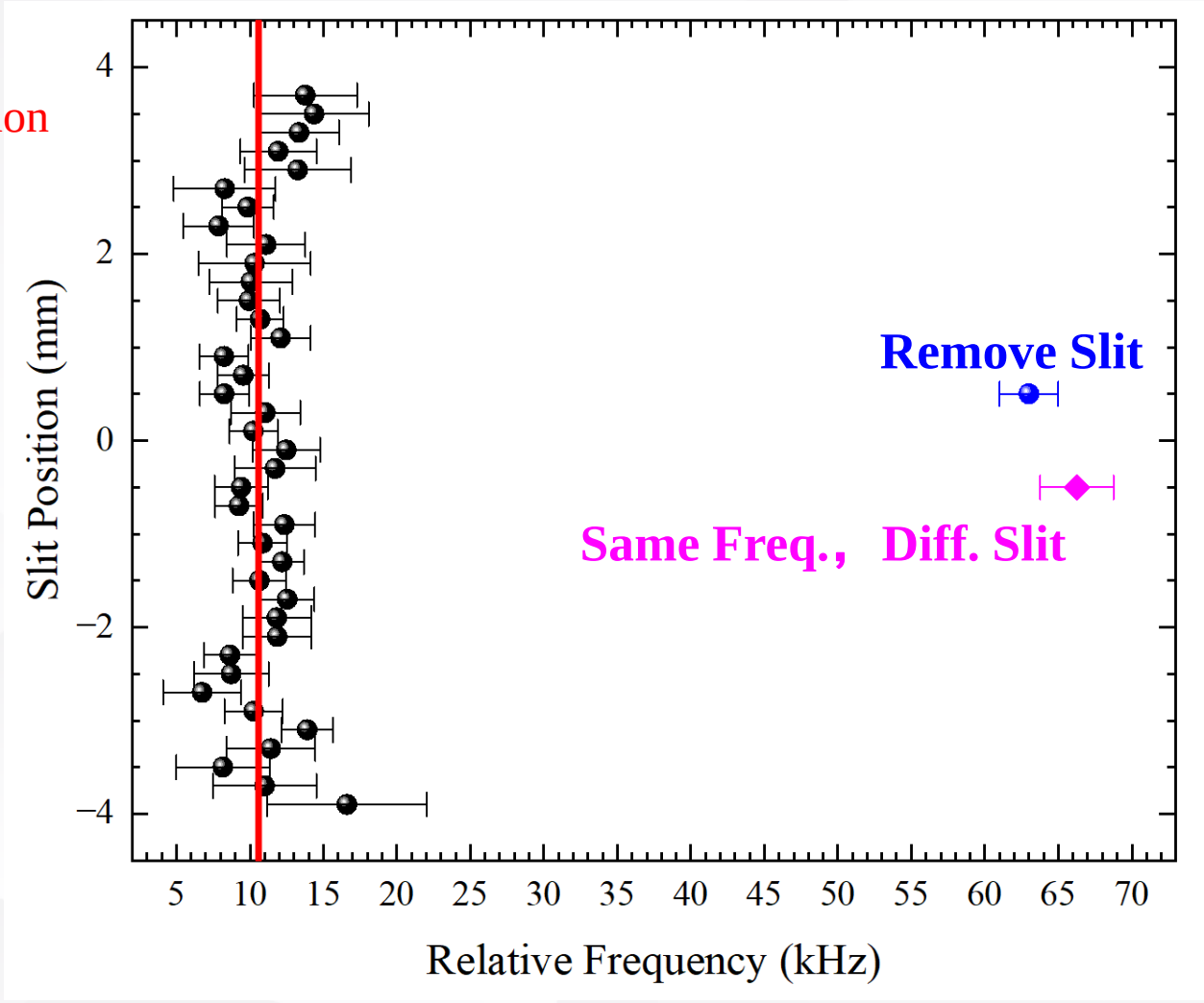


$$\Delta f1 = \Delta f2$$

- The slit selects atoms with a certain Doppler shift
- The two retro-reflection lasers experience the same shift
- Standing Wave or Traveling Wave all the Same
- Move Position of the slit does not change

Systematic effect :Post Selection



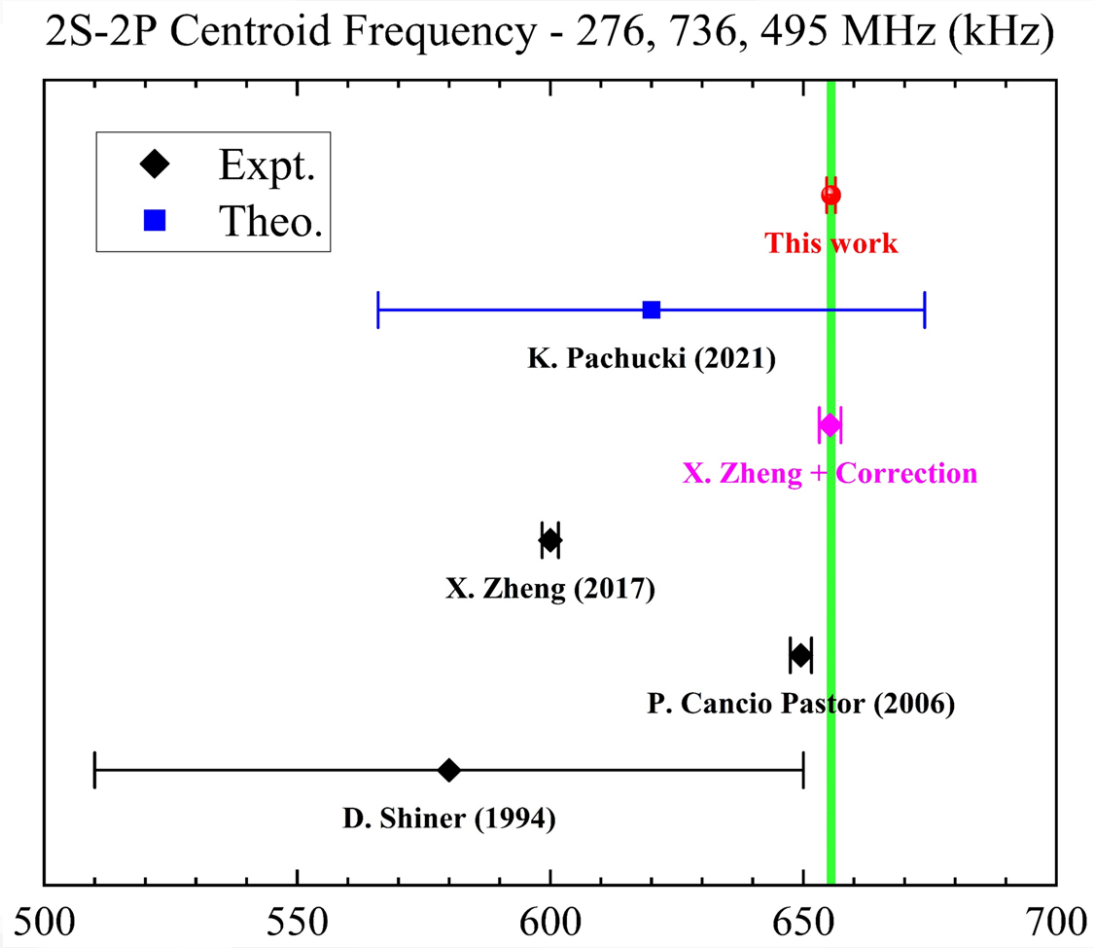


Test Post Selection Effect

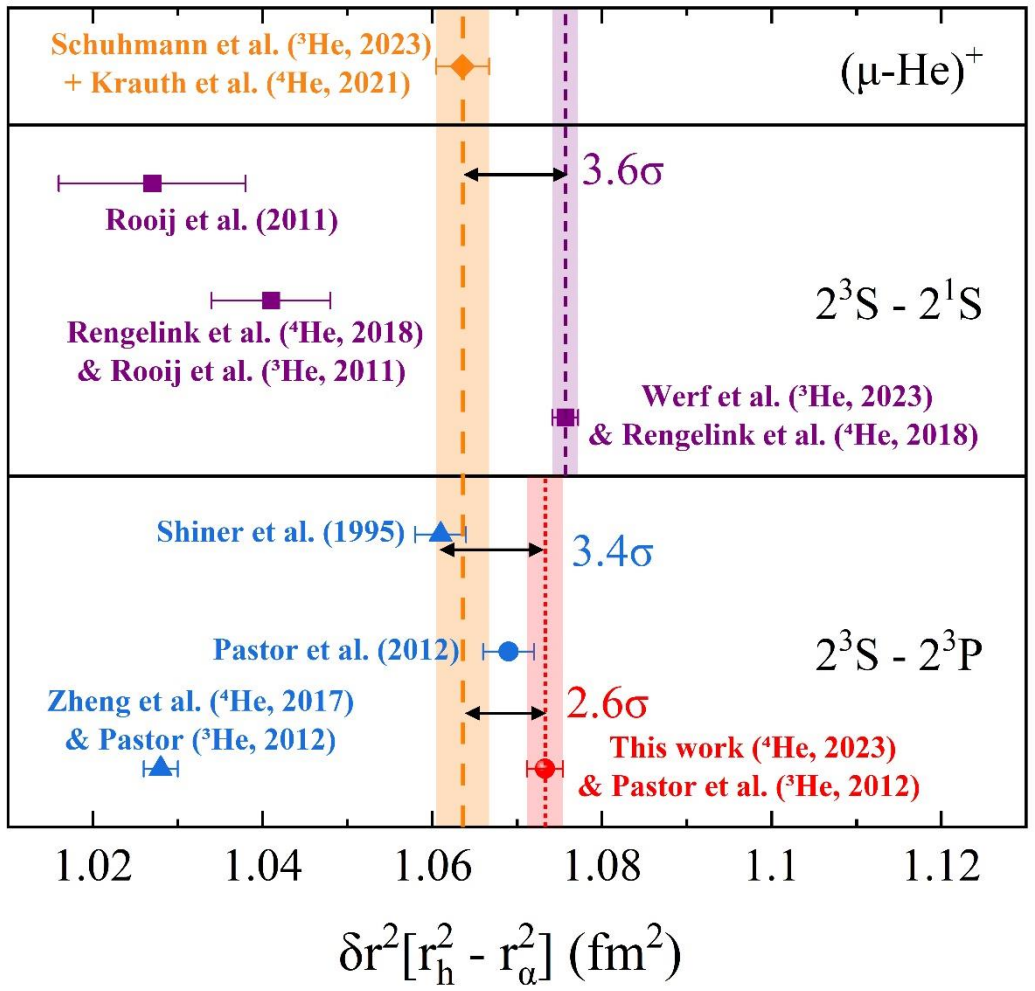
Uncertainty Budget

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

	X. Zheng		This work	
	Correction	Error (1σ)	Correction	Error (1σ)
Statistics		0.45		0.22
1st Doppler		1.1		0.82
2nd Doppler	+ 0.70	0.15		0.01
Frequency calibration		0.55		0.06
Quantum interference	+ 0.08	0.03	+ 0.05	0.02
Zeeman effect		0.01		0.01
Laser power		0.1		0.20
Line profile		0.3		
Recoil shift	- 42.5		- 42.48	
Post-selection shift	+ 55.3	1.5		
Light-force shift	+ 0.5	0.8		
Total		2.1		0.86



Conclusion



Latest 2^1S-2^3S result [arXiv:2306.02333v1]

Latest μ-He^+result [arXiv:2305.11679v2]

--Deviation 3.6 times standard deviation

Ordinary Helium atomic spectrum：

--Three independent experiments were consistent

--Shiner-95 3.4 times standard deviation

μ-He^+ compare with He：

--μ-H and H

--New Physics？

Jin-Lu Wen

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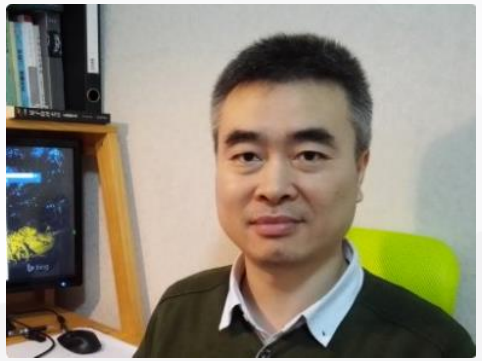
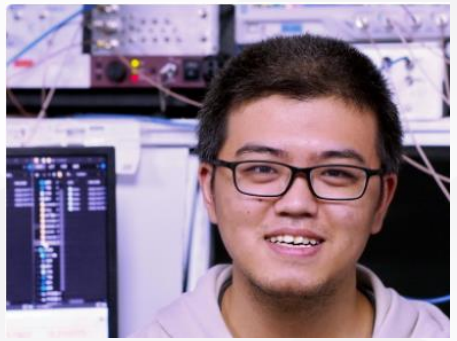


Prof. Hu Shui-Ming



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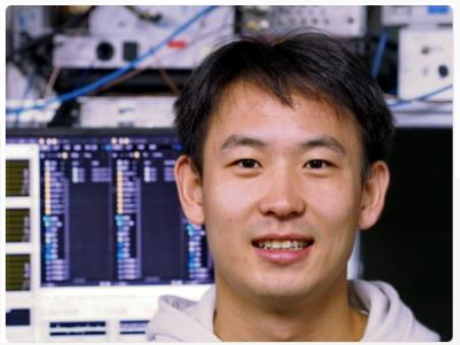
Tang Jia-Dong



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