少体原子的精密谱

H_2, He & QED

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May 22, 2018

中国科学技术大学
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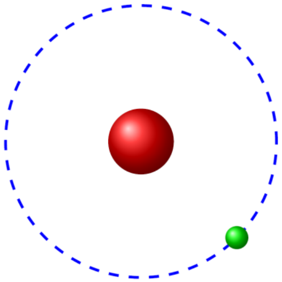
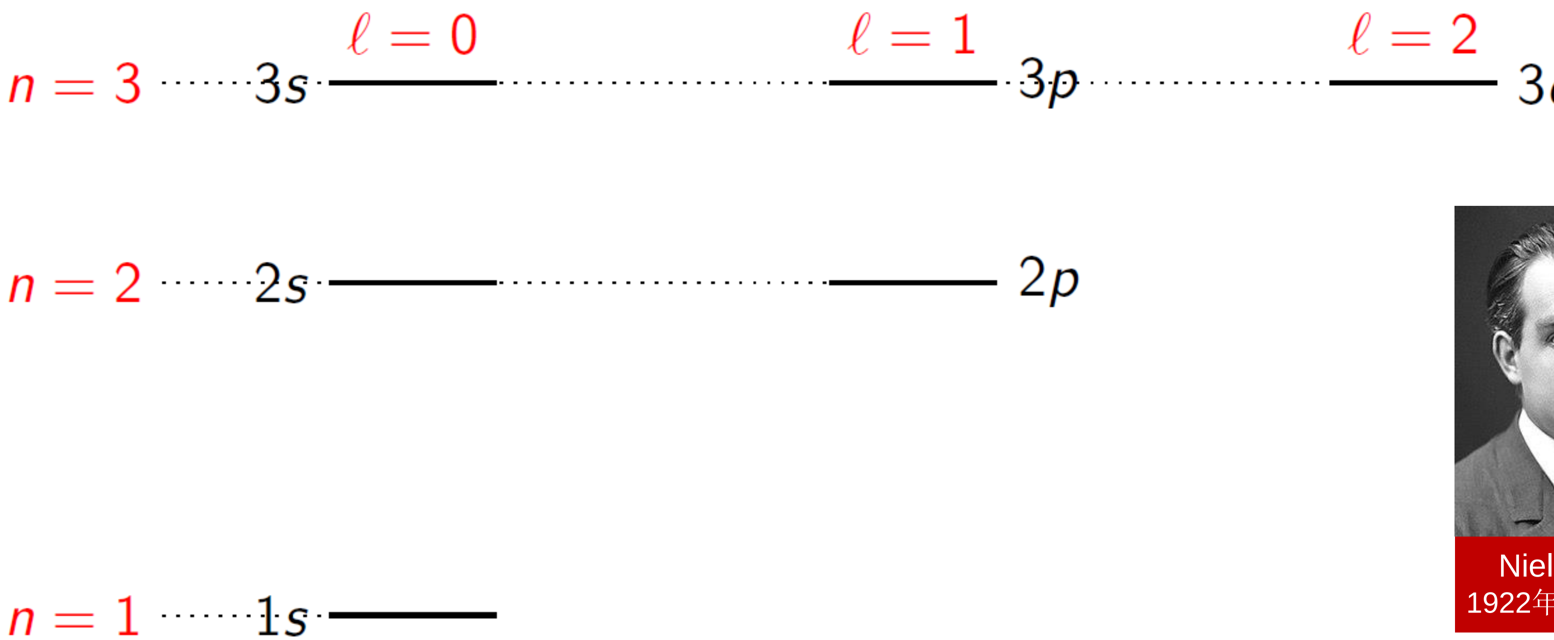
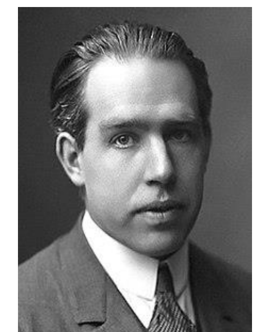
創寰宇學府
育天下英才
嚴濟慈 一九八八年五月 題

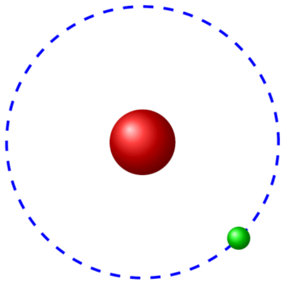


Energy levels of the hydrogen atom





Niels Bohr
1922年诺贝尔奖



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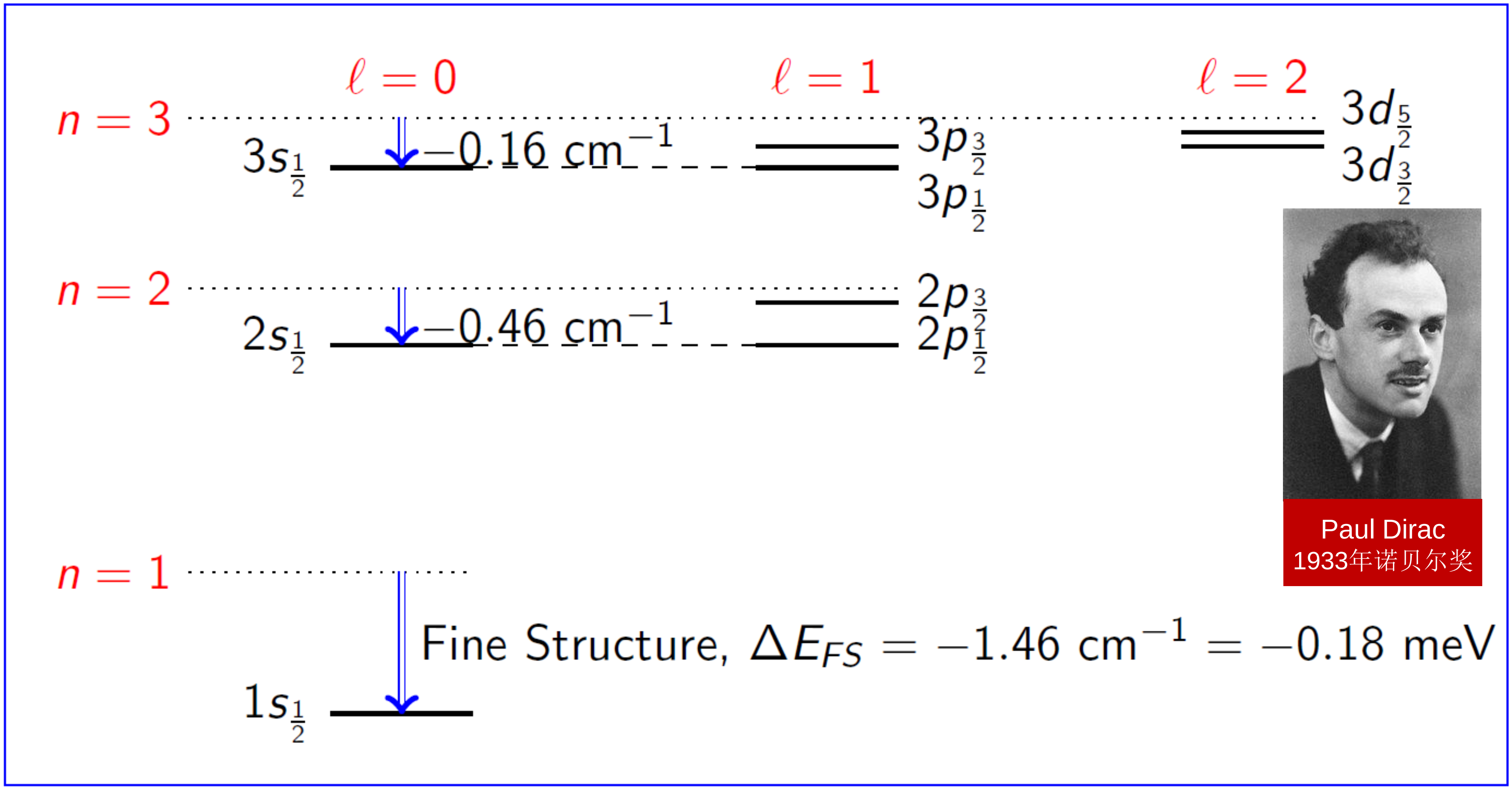
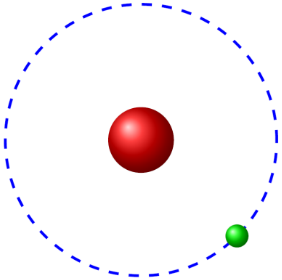


Paul Dirac
1933年诺贝尔奖

Shuiming Hu, smhu@ustc.edu.cn



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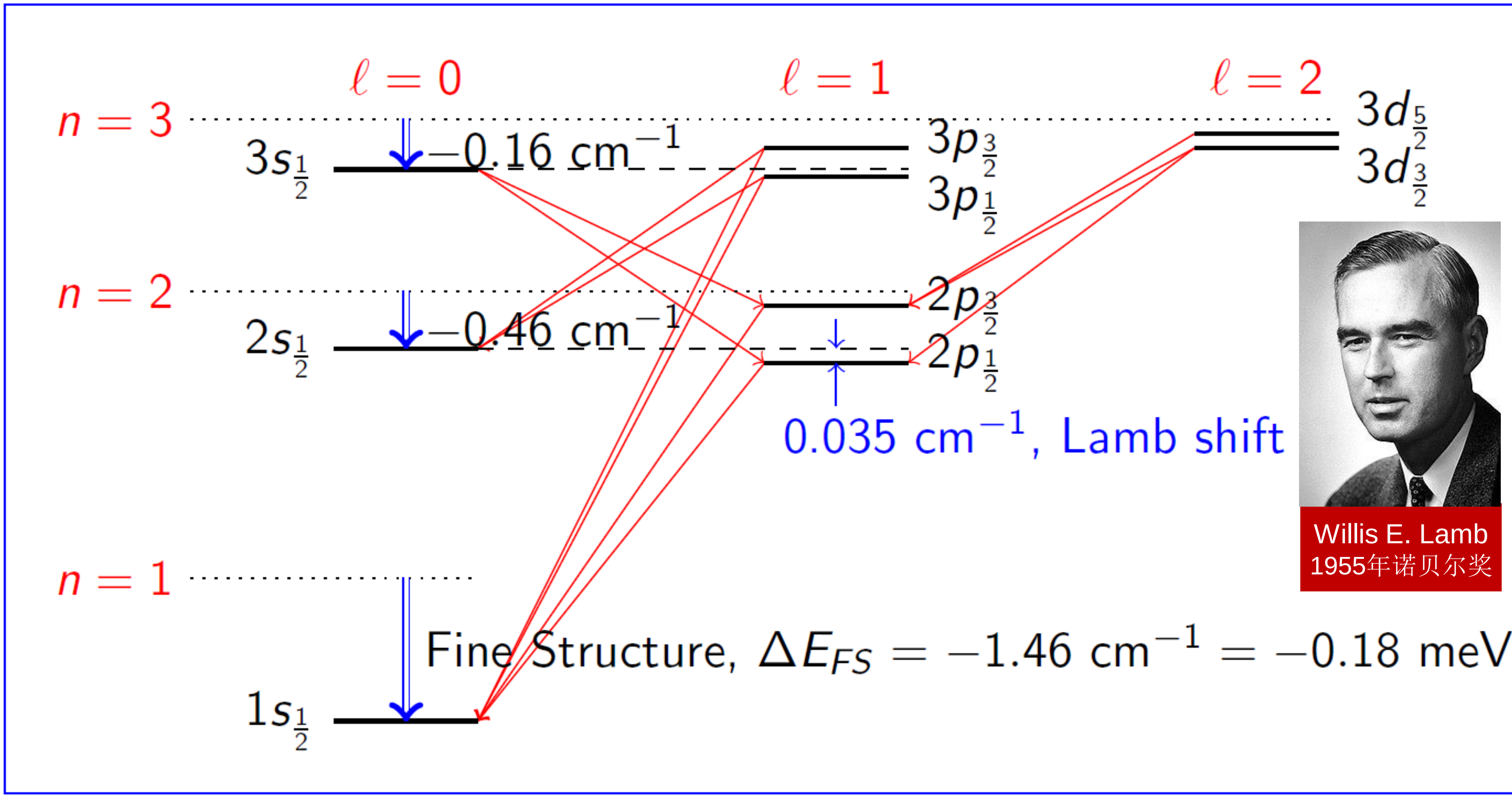
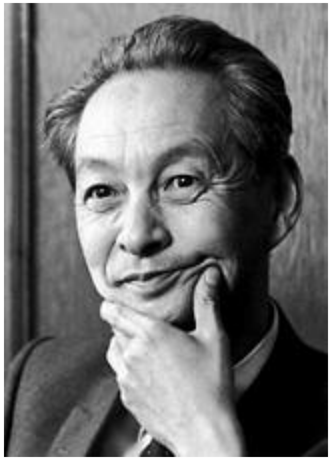


QED: "the jewel of physics"

--- Richard Feynman



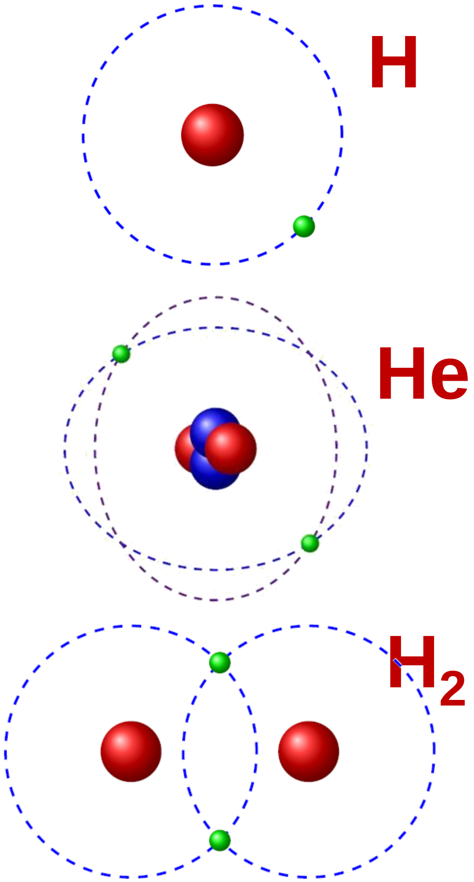
The Nobel Prize in Physics 1965

Sin-Itiro Tomonaga, Julian Schwinger, Richard P. Feynman

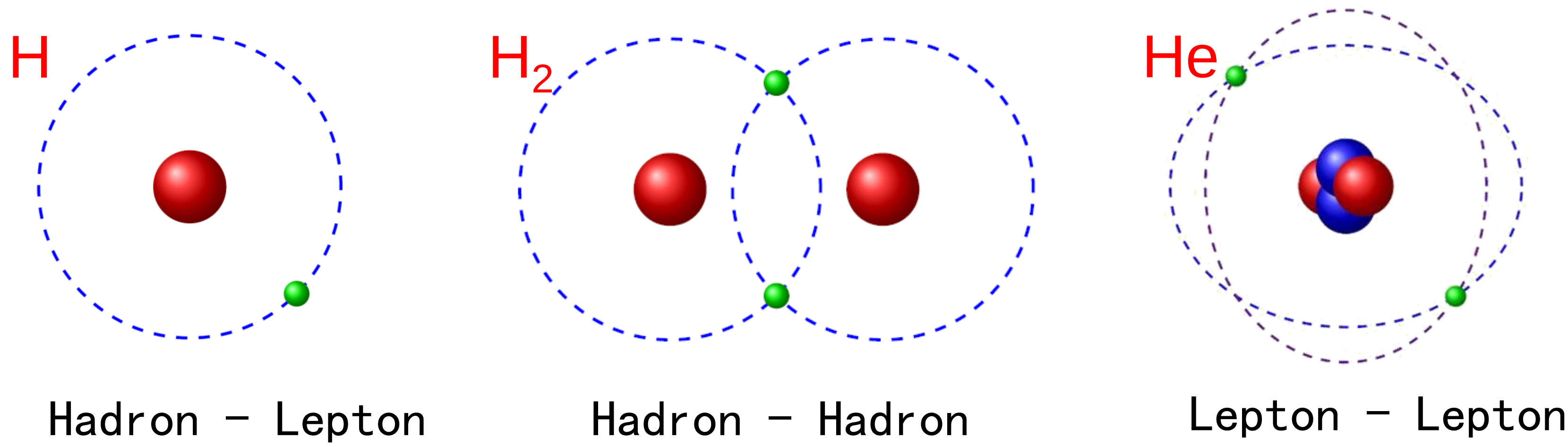
Simplest few-body systems

- 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}

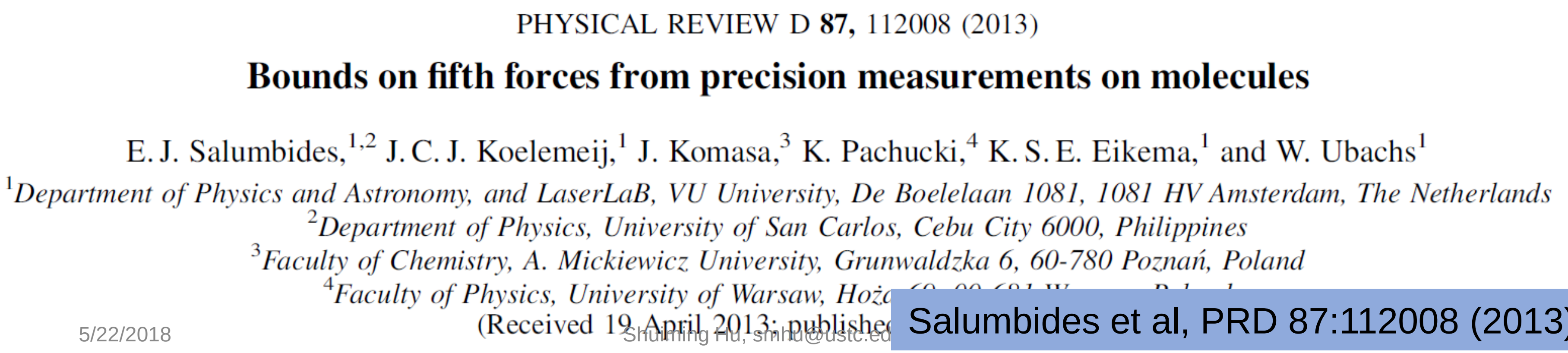
- Test of bound-state QED
- Determination of R_∞ (r_p), α, m_p/m_e
- New Physics?



Search for Physics Beyond the Standard Model in Atoms



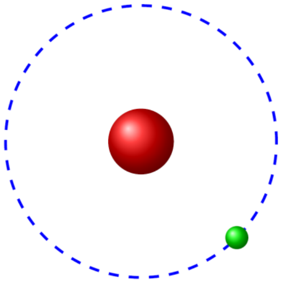
The 5th force??


PHYSICAL REVIEW D **87,** 112008 (2013)

Bounds on fifth forces from precision measurements on molecules

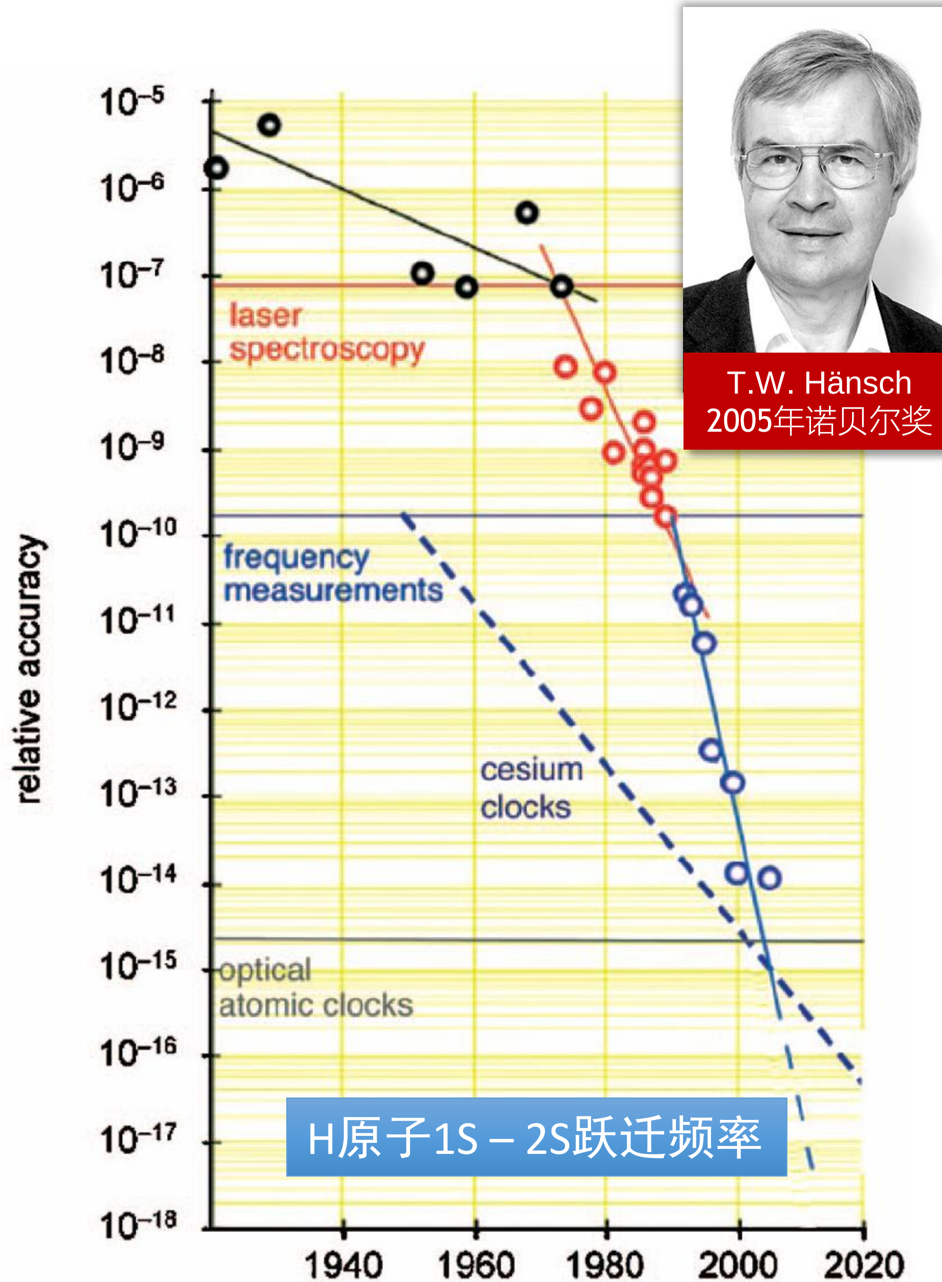
E. J. Salumbides,[1,2] J. C. J. Koelemeij,[1] J. Komasa,[3] K. Pachucki,[4] K. S. E. Eikema,[1] and W. Ubachs[1]
[1]*Department of Physics and Astronomy, and LaserLaB, VU University, De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands*
[2]*Department of Physics, University of San Carlos, Cebu City 6000, Philippines*
[3]*Faculty of Chemistry, A. Mickiewicz University, Grunwaldzka 6, 60-780 Poznań, Poland*
[4]*Faculty of Physics, University of Warsaw, Hoża*
(Received 19 April 2013; published

Salumbides et al, PRD 87:112008 (2013)



氢原子精密谱

- 检验量子电动力学（QED）理论
- 测量里德堡常数R_∞
- 发展激光技术：光梳 ➞ 光钟



Simplest few-body systems

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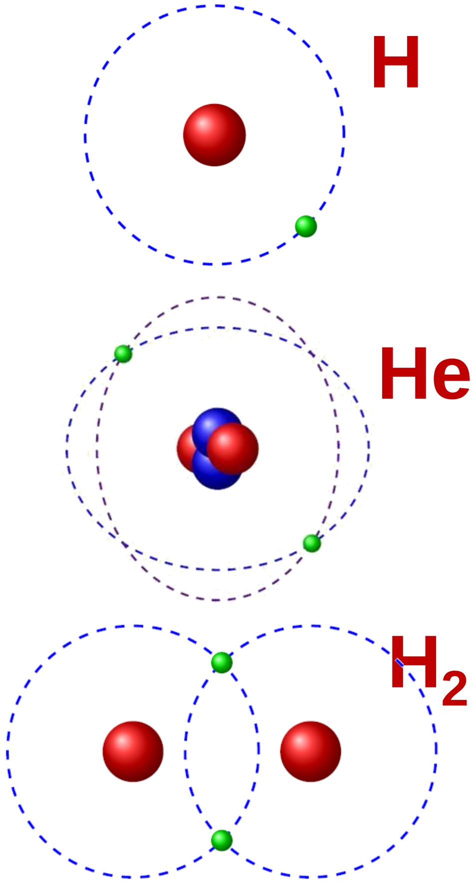


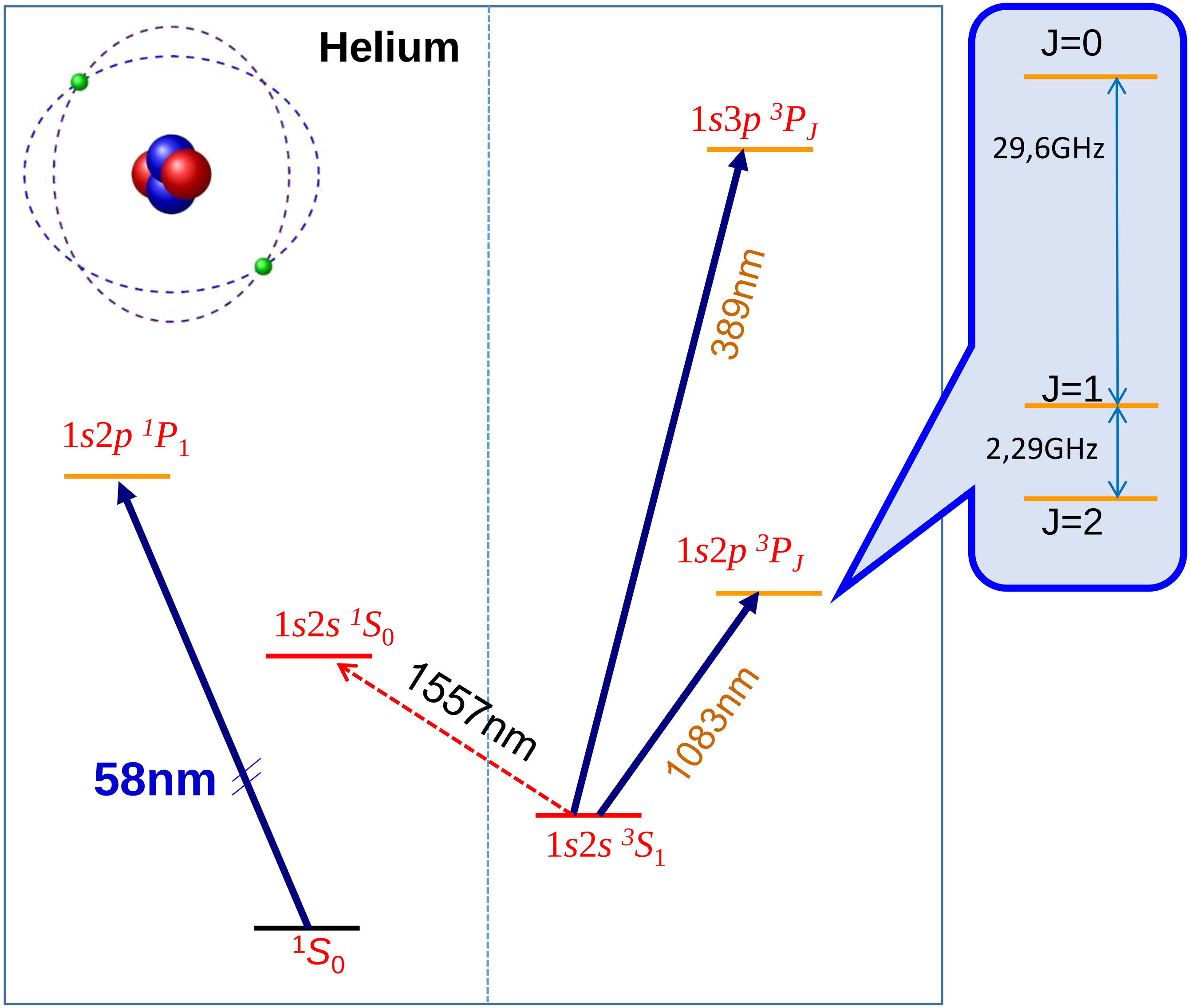
- Test of bound-state QED
- Determination of R_∞ (r_p), α, m_p/m_e
- New Physics?

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

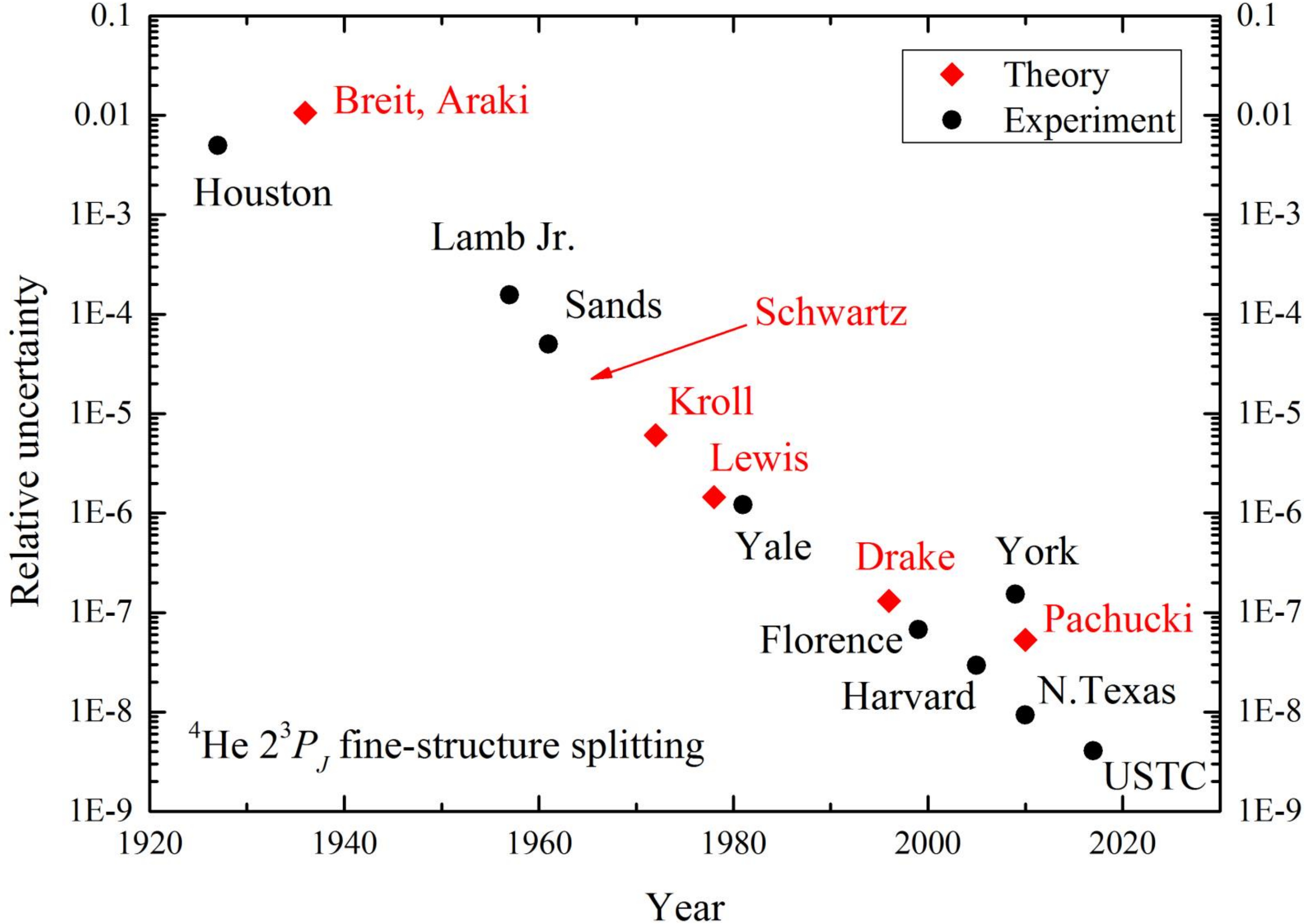
$$X_{20}\alpha^2 + X_{30}\alpha^3 + \cdots$$

Beyer et al., Science 2017

Transitions of He



^{4}He 2^3P精细结构分裂



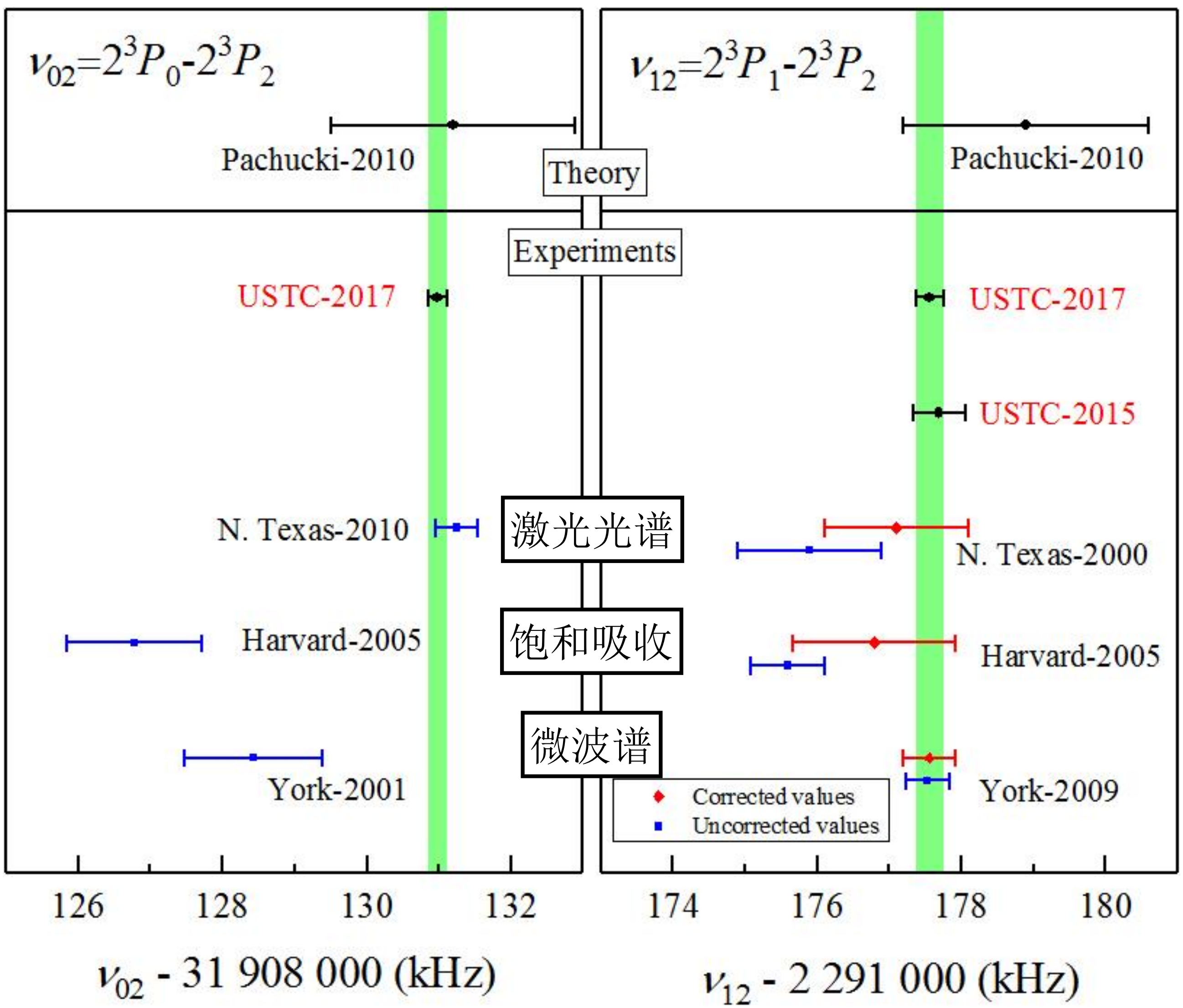
氦原子精细结构能级

$$E_{\rm fs} = E_{\rm fs}^{(4)} + E_{\rm fs}^{(5)} + E_{\rm fs}^{(6)} + E_{\rm fs}^{(7)} + O(\alpha^8)$$

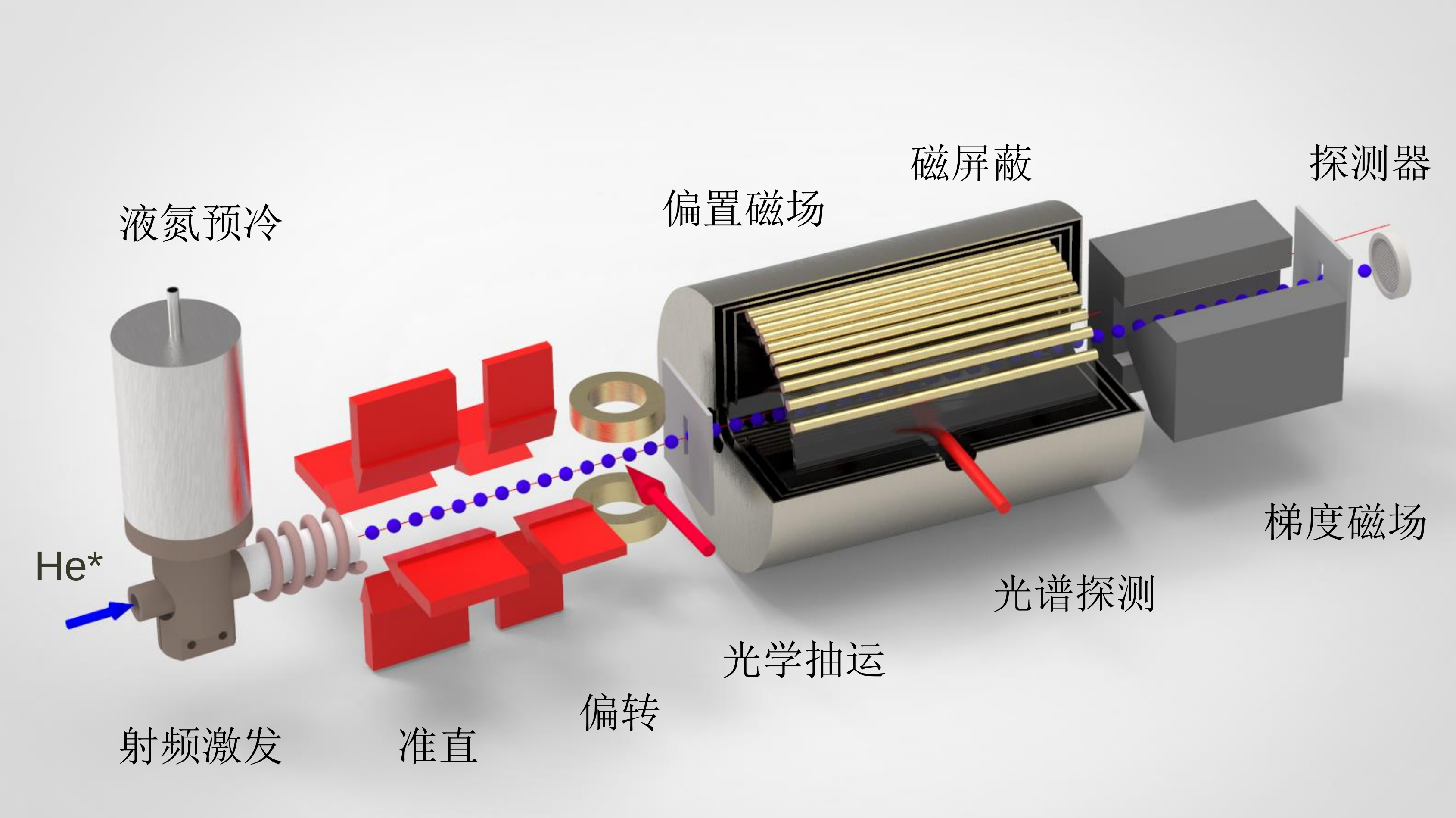
Term	ν_{01}	ν_{12}	ν_{02}
$m\alpha^4(+m/M)$	29 563 765.45	2 320 241.43	
$m\alpha^5(+m/M)$	54 704.04	−22 545.00	
$m\alpha^6$	−1 607.52(2)	−6 506.43	
$m\alpha^6 m/M$	−9.96	9.15	
$m\alpha^7\log(Z\alpha)$	81.43	−5.87	
$m\alpha^7$, nlog	18.86	−14.38	
$m\alpha^8$	±1.7	±1.7	
Total theory	29 616 952.29 ± 1.7	2 291 178.91 ± 1.7	31 908 131.20 ± 1.7
Experiment	29 616 951.66(70)[a]	2 291 177.53(35)[d]	31 908 131.25(30)[f]
	29 616 952.7(10)[b]	2 291 175.59(51)[a]	31 908 126.78(94)[a]
	29 616 950.9(9)[c]	2 291 175.9(10)[e]	

Krzysztof Pachucki and Vladimir A. Yerokhin
Journal of Physics:Conference Series **264**(2011) 012007

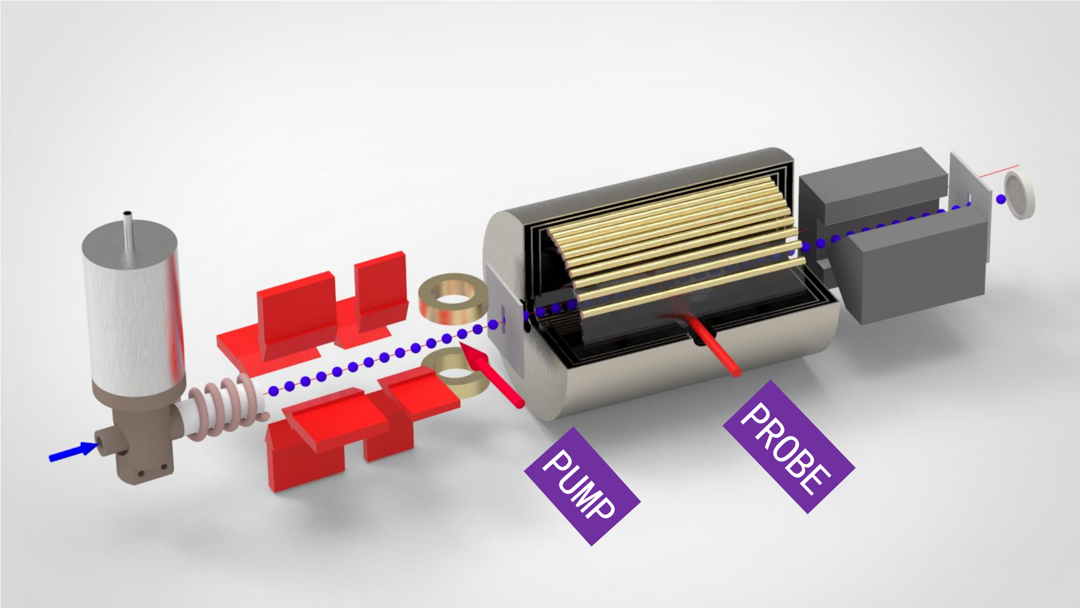
氦-4原子 (1s2p) 2^3P 精细结构能级间隔

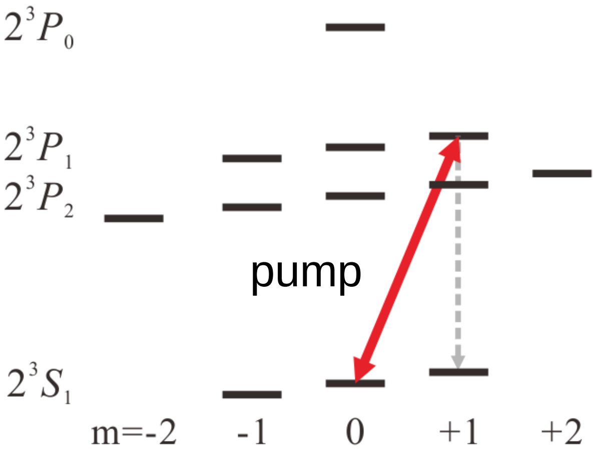


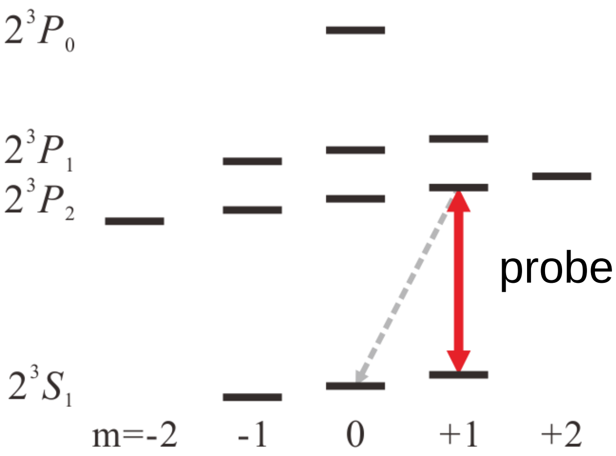
实验装置与原理



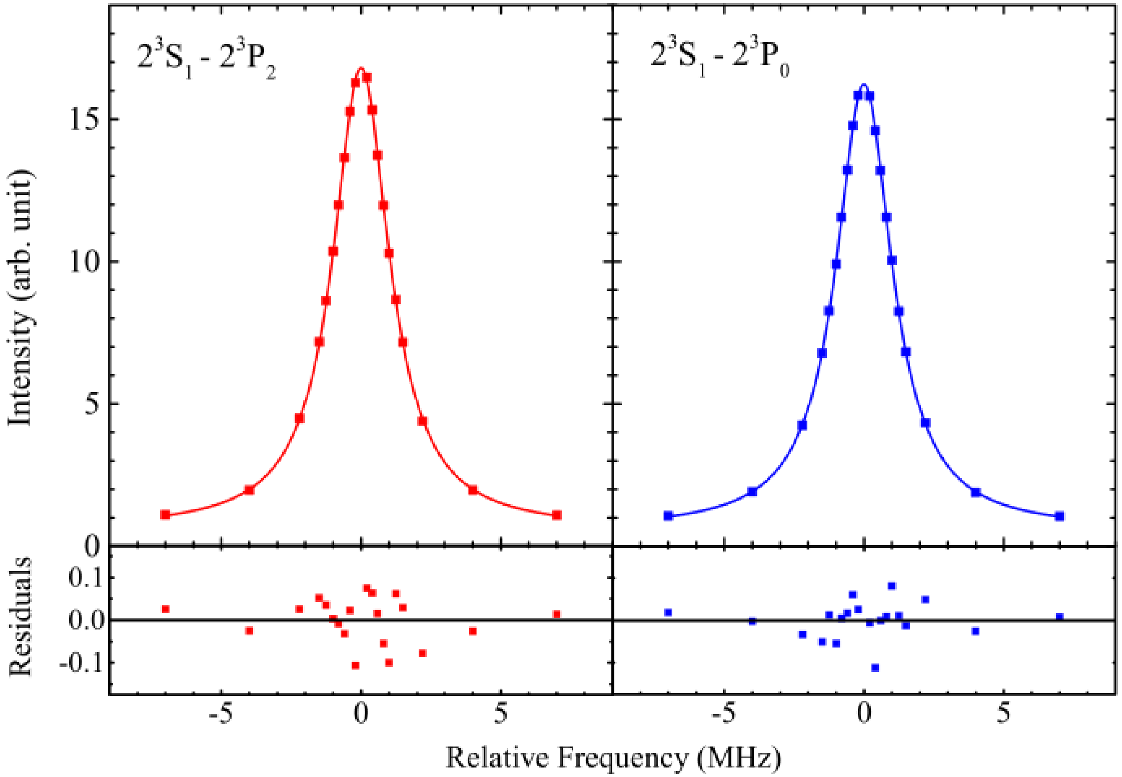
实验装置与原理


PUMP
PROBE


2^3P_0
2^3P_1
2^3P_2
pump
2^3S_1
m=-2
-1
0
+1
+2

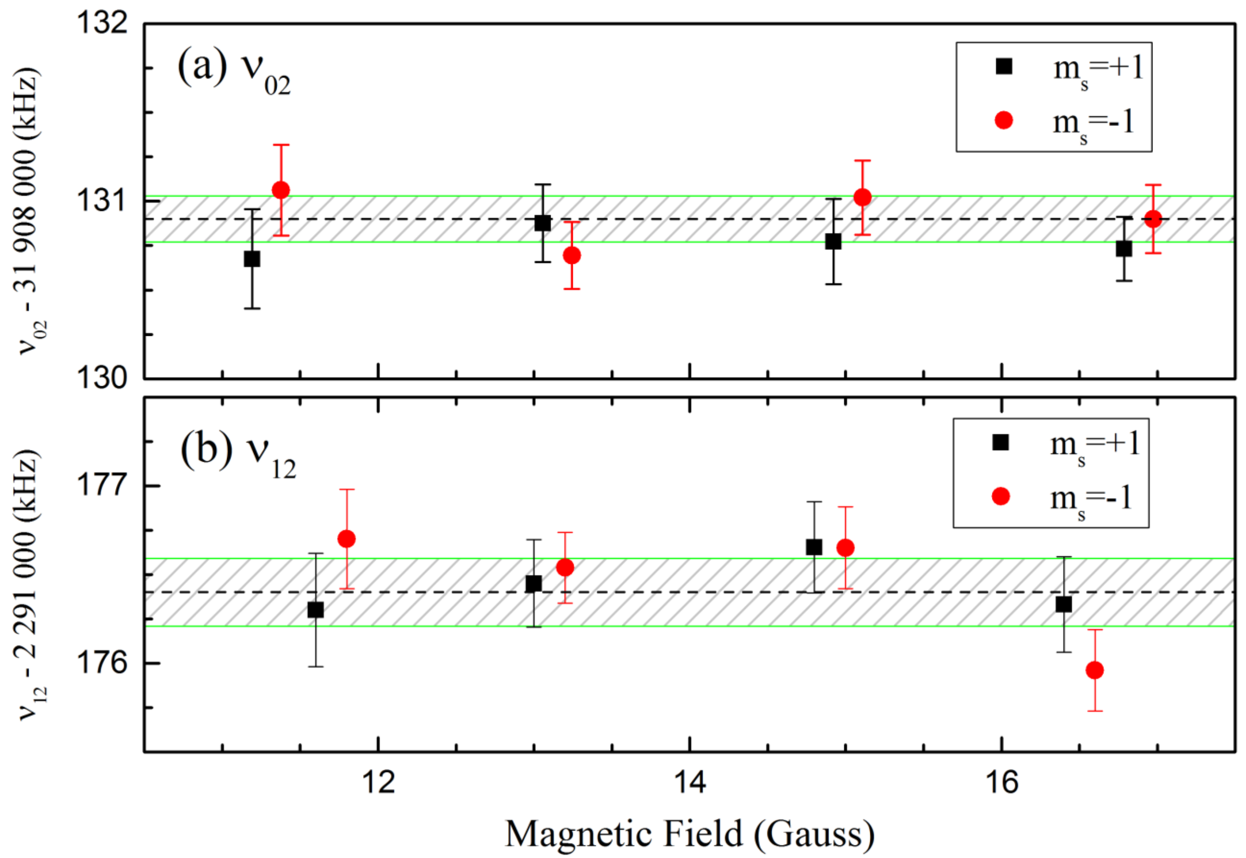

2^3P_0
2^3P_1
2^3P_2
probe
2^3S_1
m=-2
-1
0
+1
+2

实验方法



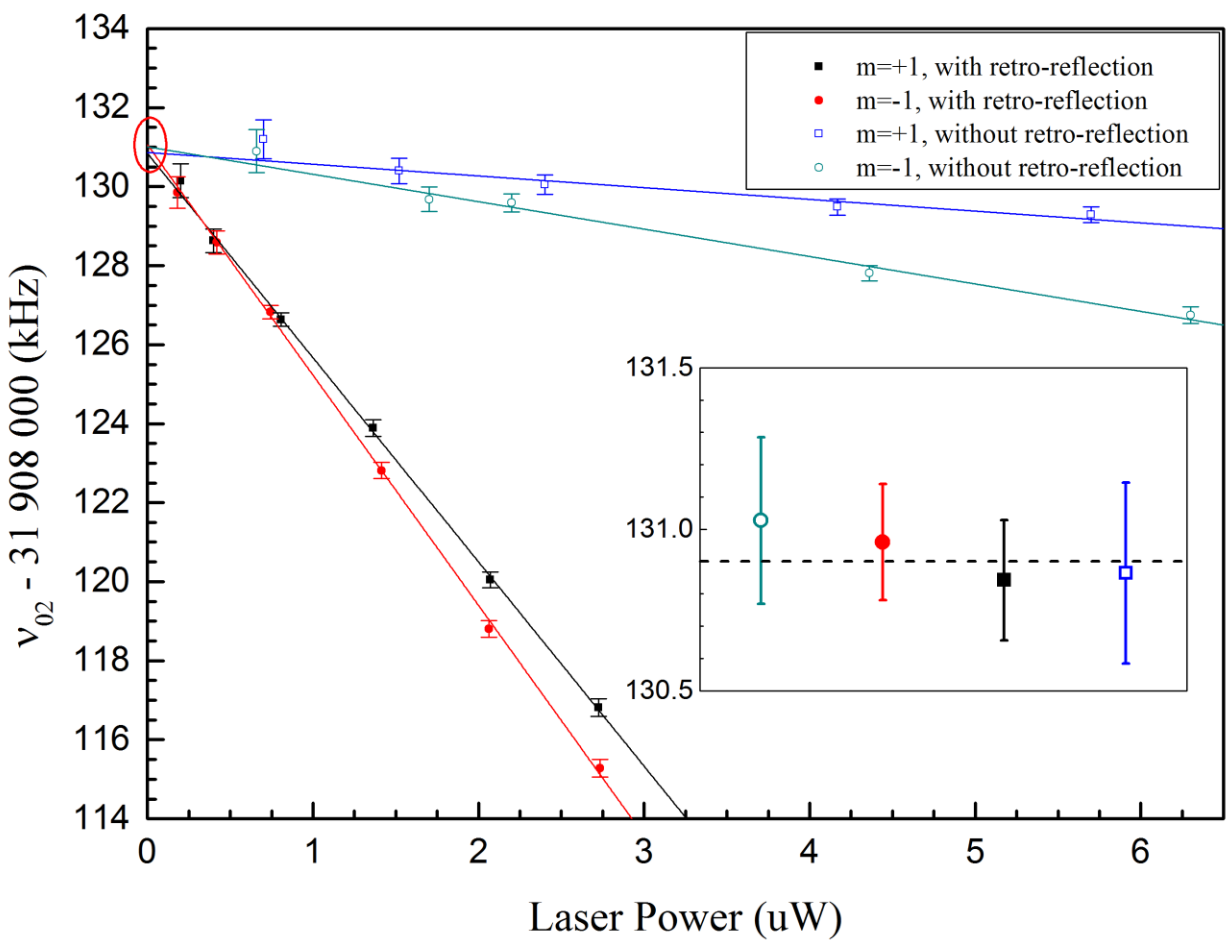
- 光学抽运：
  制备单量子态
- 光谱探测：
  快速切换探测激光
- 拟合光谱：
  中心频率间隔

系统误差检查 － 磁场



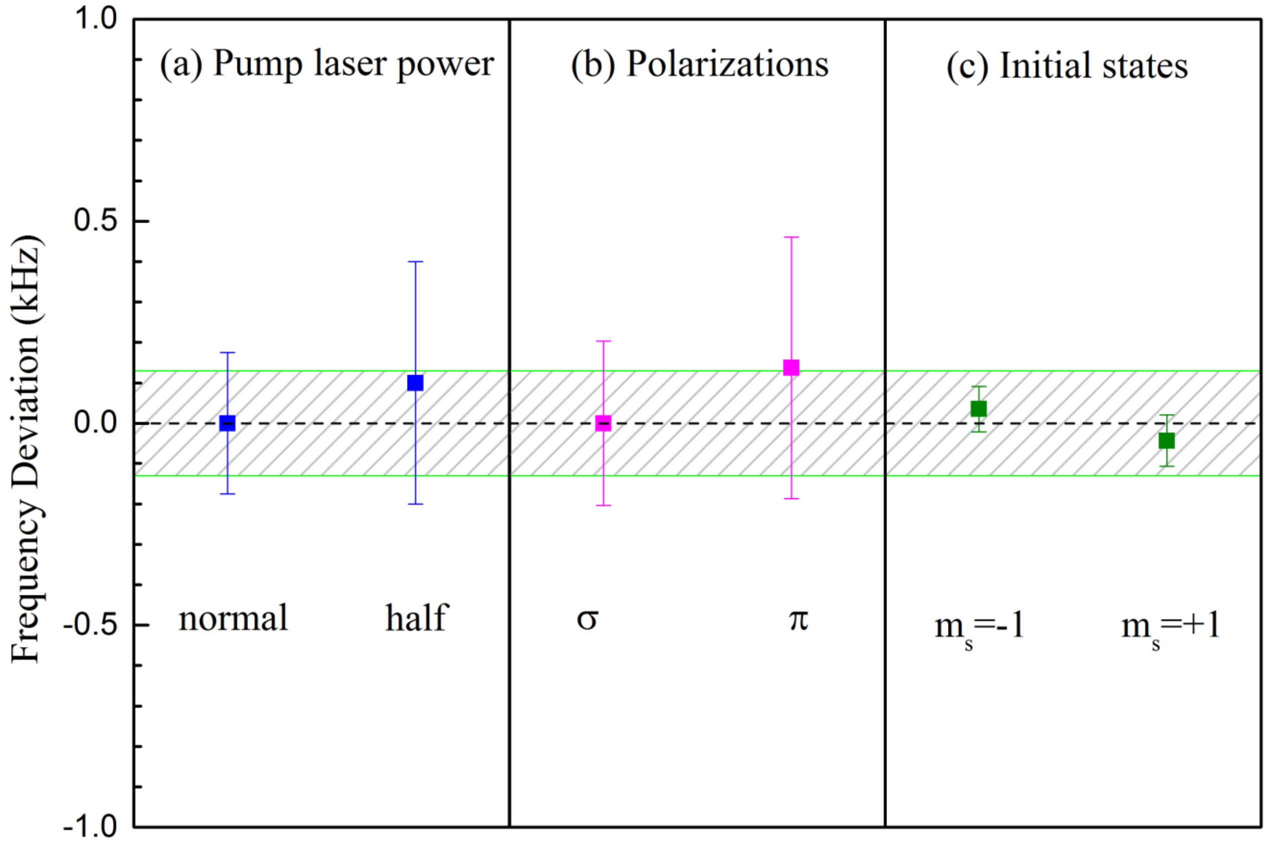
(a) ν02
ms=+1
ms=-1
132
131
130
ν02 - 31 908 000 (kHz)
(b) ν12
ms=+1
ms=-1
177
176
ν12 - 2 291 000 (kHz)
12
14
16
Magnetic Field (Gauss)

系统误差检查 - 激光功率



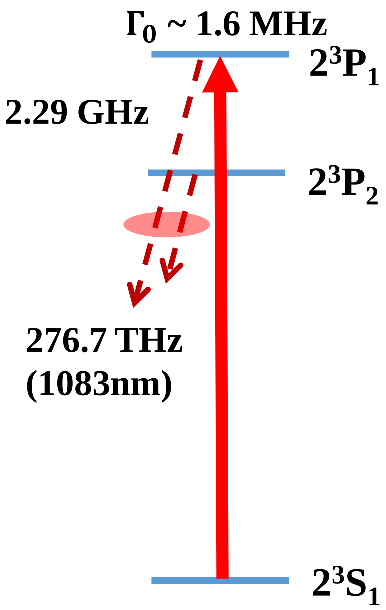
m=+1, with retro-reflection
m=-1, with retro-reflection
m=+1, without retro-reflection
m=-1, without retro-reflection
134
132
130
128
126
124
122
120
118
116
114
ν02 - 31 908 000 (kHz)
0
1
2
3
4
5
6
Laser Power (uW)
131.5
131.0
130.5

系统误差检查 － 其他



(a) Pump laser power
(b) Polarizations
(c) Initial states
Frequency Deviation (kHz)
1.0
0.5
0.0
-0.5
-1.0
normal
half
σ
π
m_s=-1
m_s=+1

量子干涉效应



- 干涉效应来自于临近的能级
- 即使激光功率外推到零也仍然存在

$$\frac{interval}{\Gamma_0} = \frac{2\,291\,MHz}{1.6\,MHz} \approx 1400$$

$$shift \approx \frac{1.6\,MHz}{1400} \approx 1.1\,kHz$$

经验估算

- 计算修正**1.21(10) kHz** 对于2^3P_1-2^3P_2 测量.

M. Horbatsch, E. A. Hessels, *Phys. Rev. A* **82**, 052519 (2010)

A. Marsman, M. Horbatsch, E. A. Hessels, *Phys. Rev. A* **91**, 062506 (2015)

测量不确定度

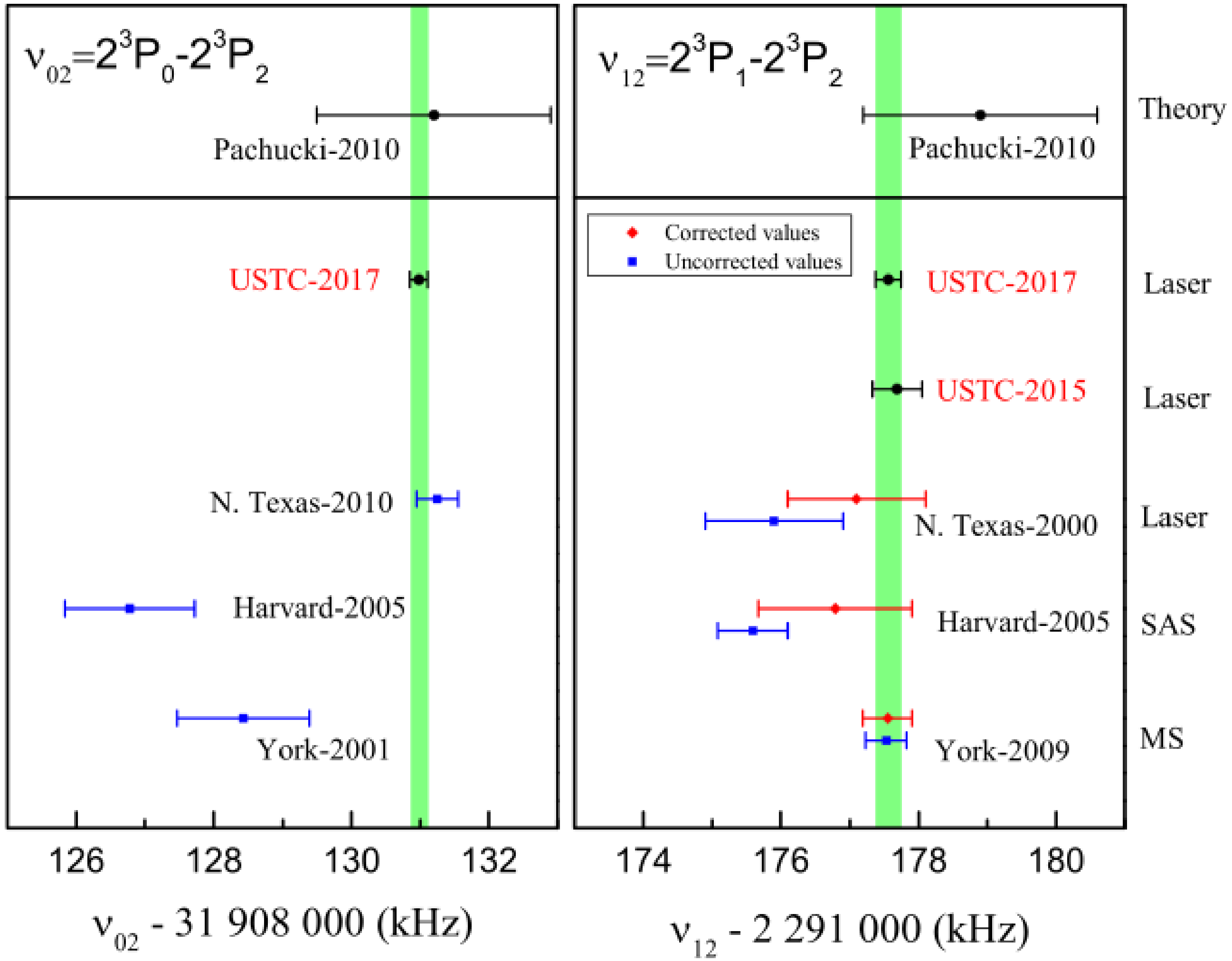
测量不确定度表 (kHz)

误差来源	ν_{02}	$\Delta\nu(1\sigma)$	ν_{12}	$\Delta\nu(1\sigma)$
统计	31 908 130.90	0.06	2 291 176.35	0.08
磁场塞曼效应		0.06		0.09
探测激光功率		0.06		0.06
一阶多普勒		0.03		0.03
杂散光影响		0.02		0.02
激光偏振		0.03		0.08
初始量子态		0.04		0.04
量子干涉效应	+0.08	0.03	+1.21	0.10
不确定度	31 908 130.98	0.13	2 291 177.56	0.19

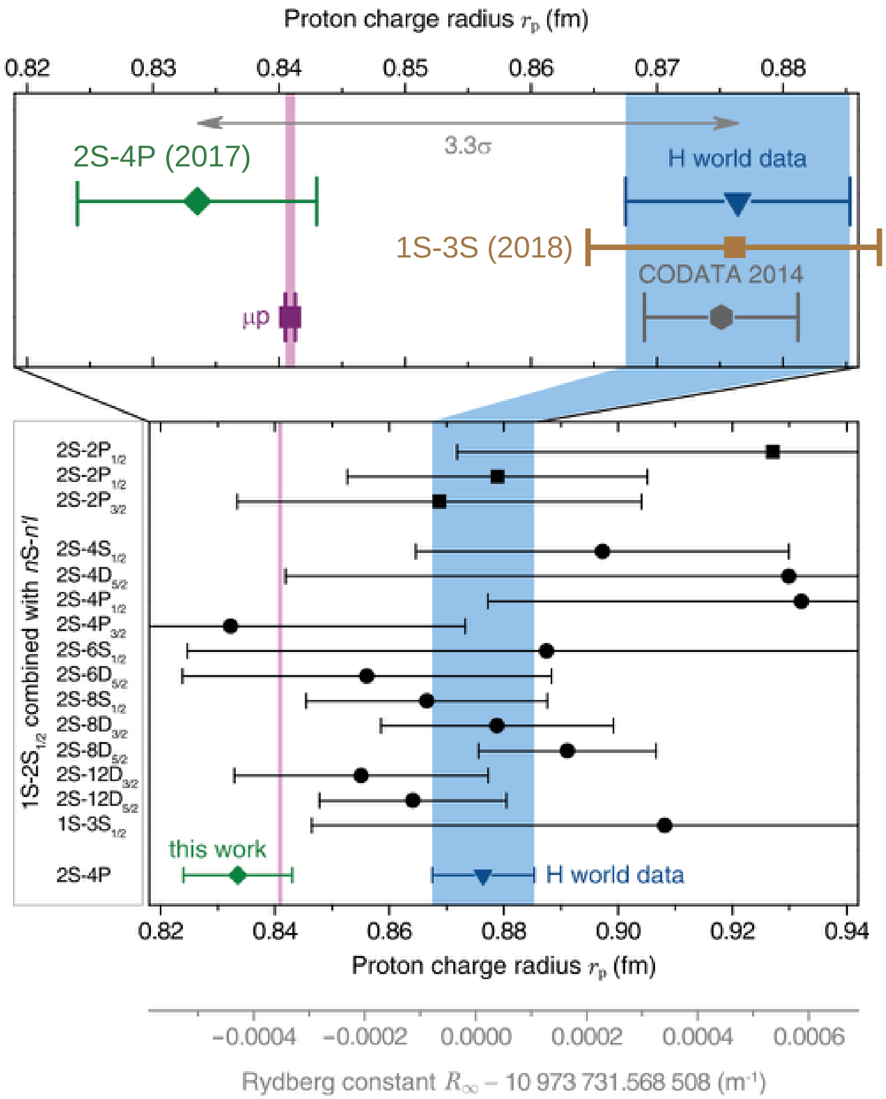
Physical Review A **91**, 030502(R) (2015)
Physical Review Letters **118**,063001 (2017)

- 检验束缚态QED：验证$m\alpha^7$阶修正
- 测定精细结构常数α：至2 ppb（实验）

G.-P. Feng, *et al.*, PRA 2015
X. Zheng, *et al.*, PRL 2017



“质子半径之谜”



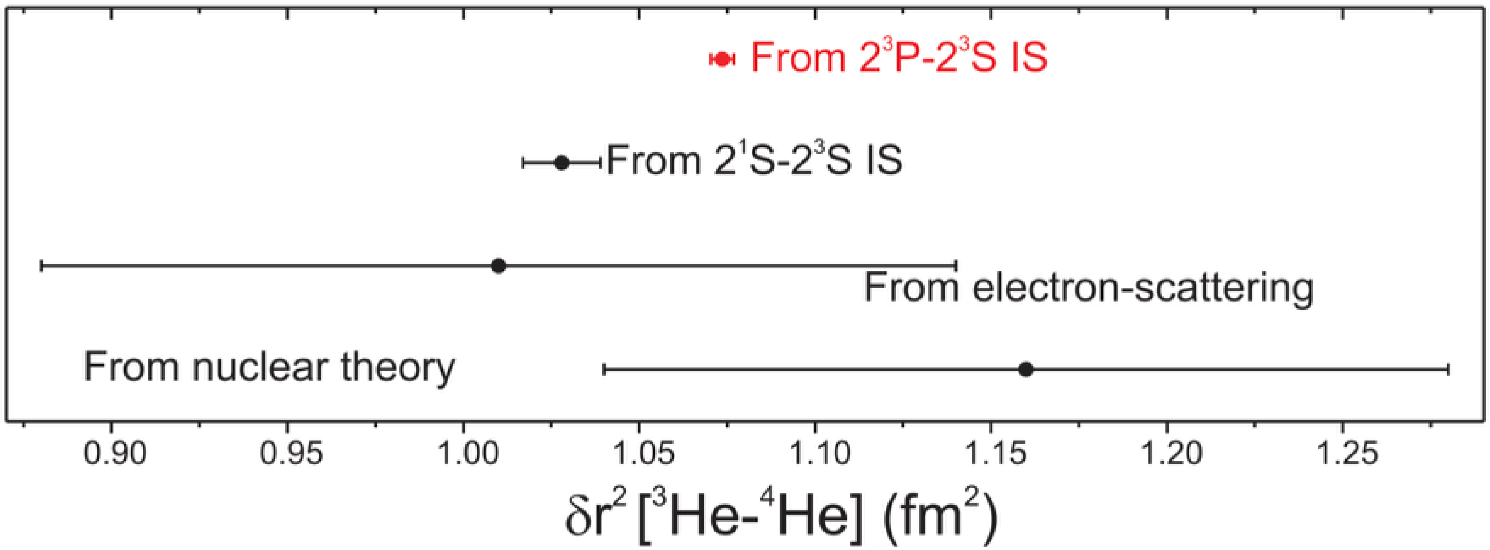
μH, μD, H(2S-4P)

Proton size puzzle!

CODATA, H(1S-3S)

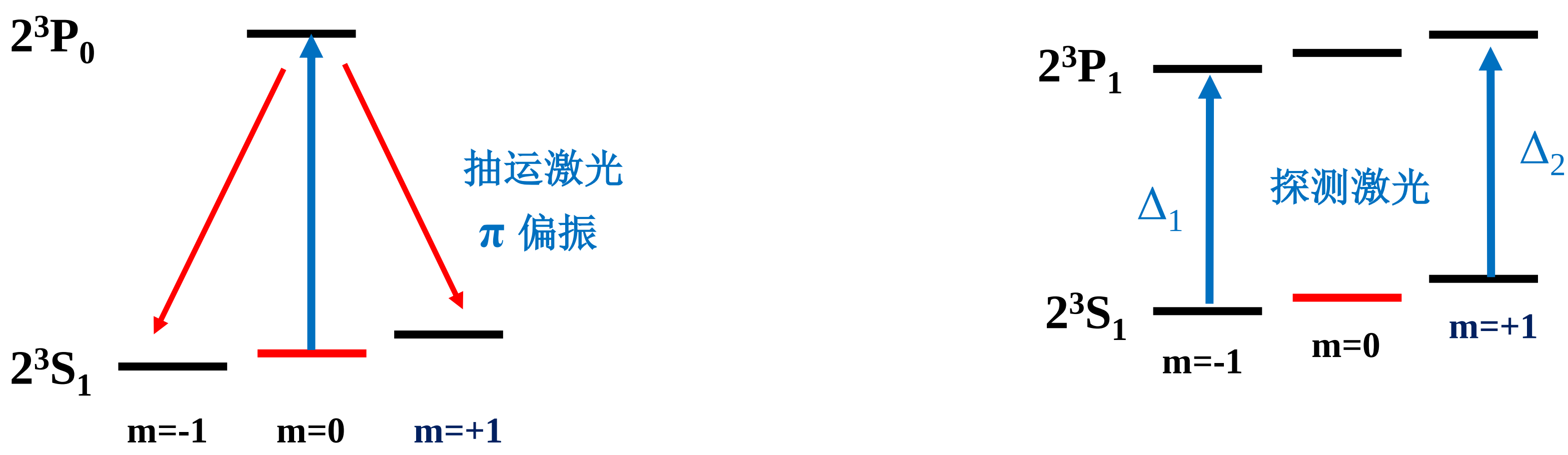
Nature **466**, 213 (2010)
Science **339**, 417 (2013)
Science **353**, 669 (2016)
Science **358**, 79 (2017)
PRL **120**, 183001 (2018)

“He同位素半径之谜”



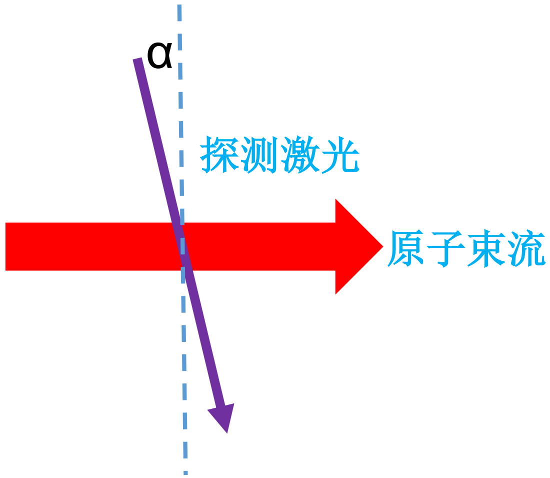
PRL **74**, 3553 (1995)
Science **333**, 196 (2011)
PRL **108**, 143001 (2012)

4He原子2^3S_1-2^3P_1跃迁绝对频率测定方法



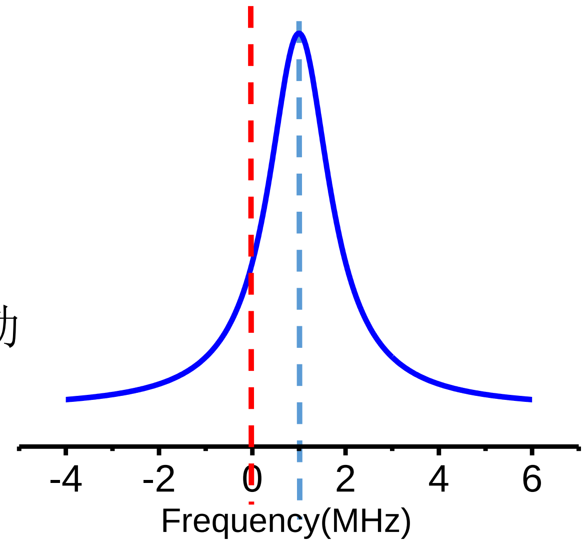
- $\Delta_1 = f_{center} + \Delta_{ZS\_I} + \Delta_{ZS\_II}$
- $\Delta_2 = f_{center} - \Delta_{ZS\_I} + \Delta_{ZS\_II}$
- $f_{center} = (\Delta_1 + \Delta_2)/2 - \Delta_{ZS\_II}$

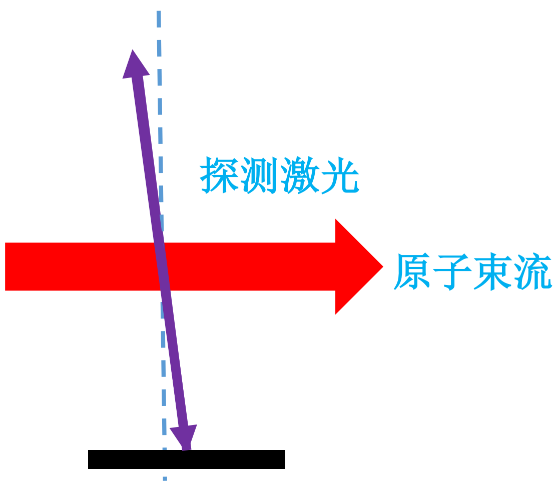
一阶多普勒效应



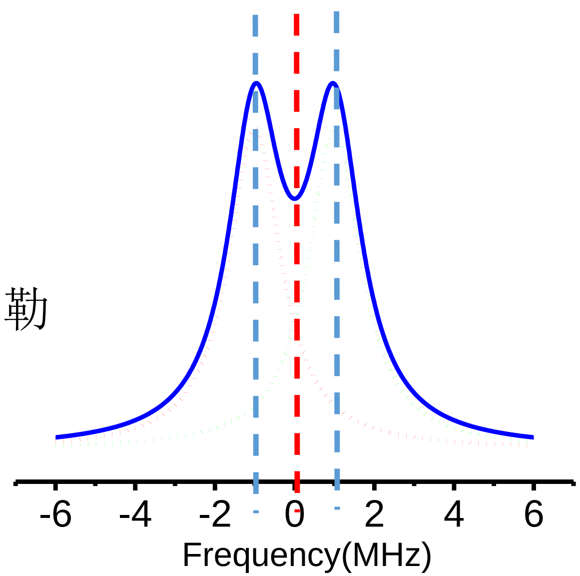
$$\Delta\nu_D \approx kv \cdot \alpha$$

残余一阶多普勒

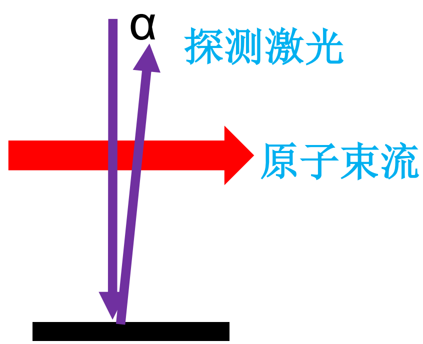




抵消一阶多普勒



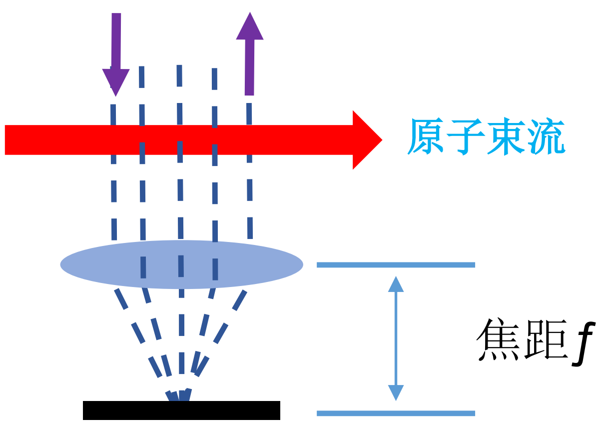
抑制一阶多普勒效应



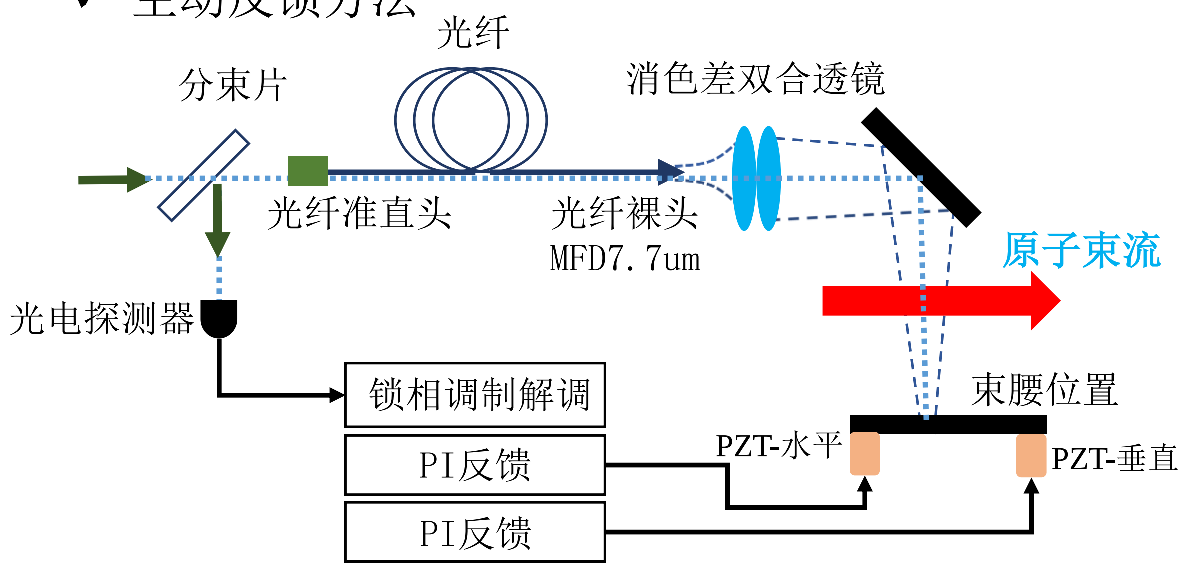
$$\Delta\nu_D \approx \frac{1}{2}kv \cdot \alpha$$

10urad偏差对应于4kHz多普勒位移

- ➢ **抵消机制**
  - ✓ Cat's eye光学方法



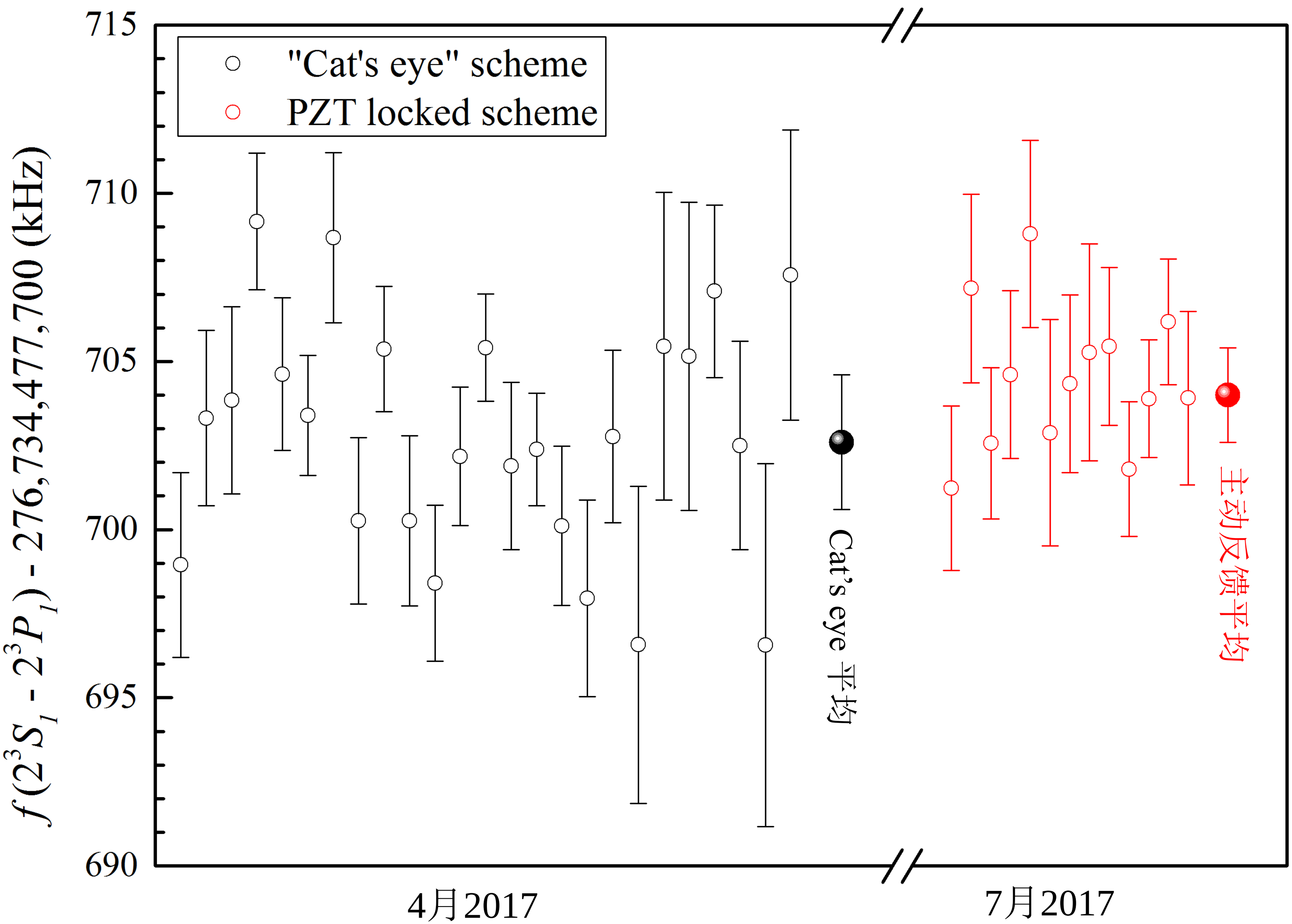
- ✓ 主动反馈方法



Phys. Rev. Lett. **92**,023001 (2004)
Can. J. Phys. **83**,301 (2005)
Phys. Rev. Lett. **105**,123001 (2010)

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

抑制一阶多普勒效应

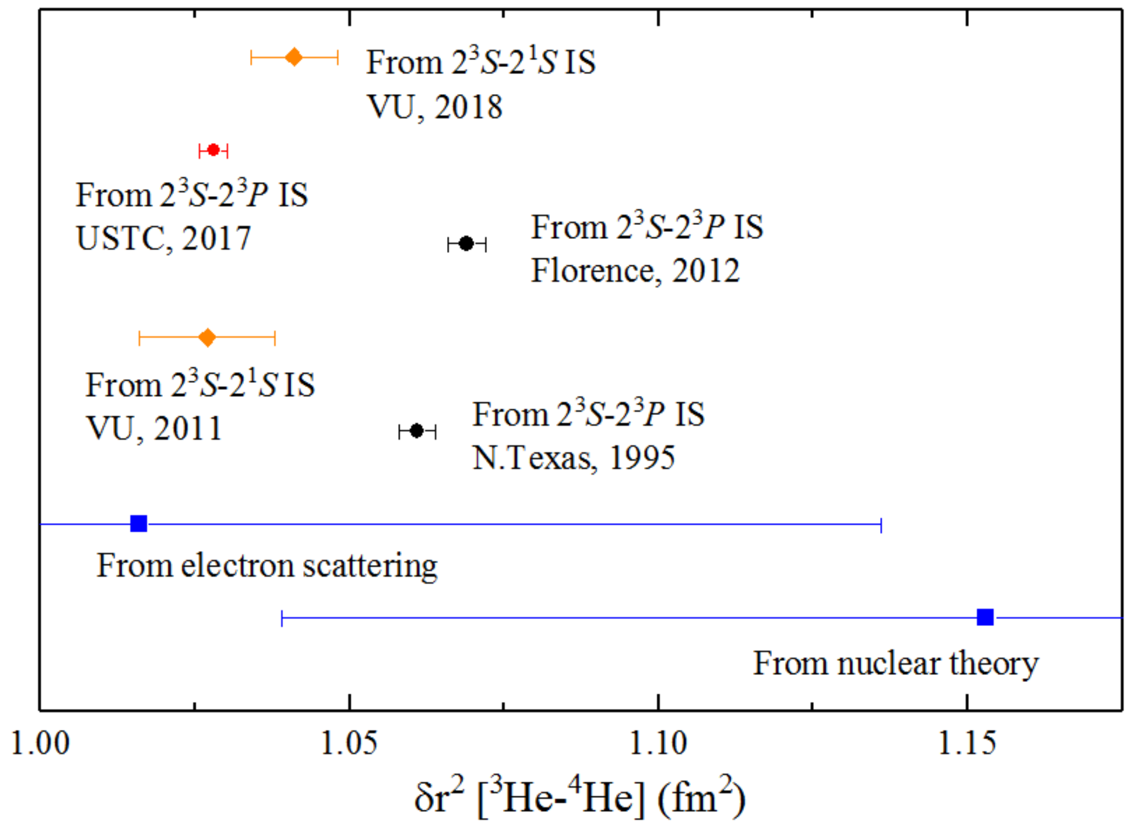


"Cat's eye" scheme
PZT locked scheme
715
710
705
700
695
690
f(2³S₁ - 2³P₁) - 276,734,477,700 (kHz)
Cat's eye 平均
主动反馈平均
4月2017
7月2017

误差来源	修正	$\Delta f\ (1\sigma)$
统计误差		0.45
一阶多普勒		1.1
二阶多普勒	0.70	0.15
频率校准		0.55
光谱线型		0.30
量子干涉	0.60	0.10
激光功率		0.10
塞曼效应		0.01
反冲效应	-42.20	-
PRL 17 @ Hefei	276,734,477,7**03.8**	1.4
PRL 04@Florence	276,736,477,7**52.5**	2.0

X. Zheng, *et al.*, PRL **119**, 263002 (2017)

“He同位素半径之谜”

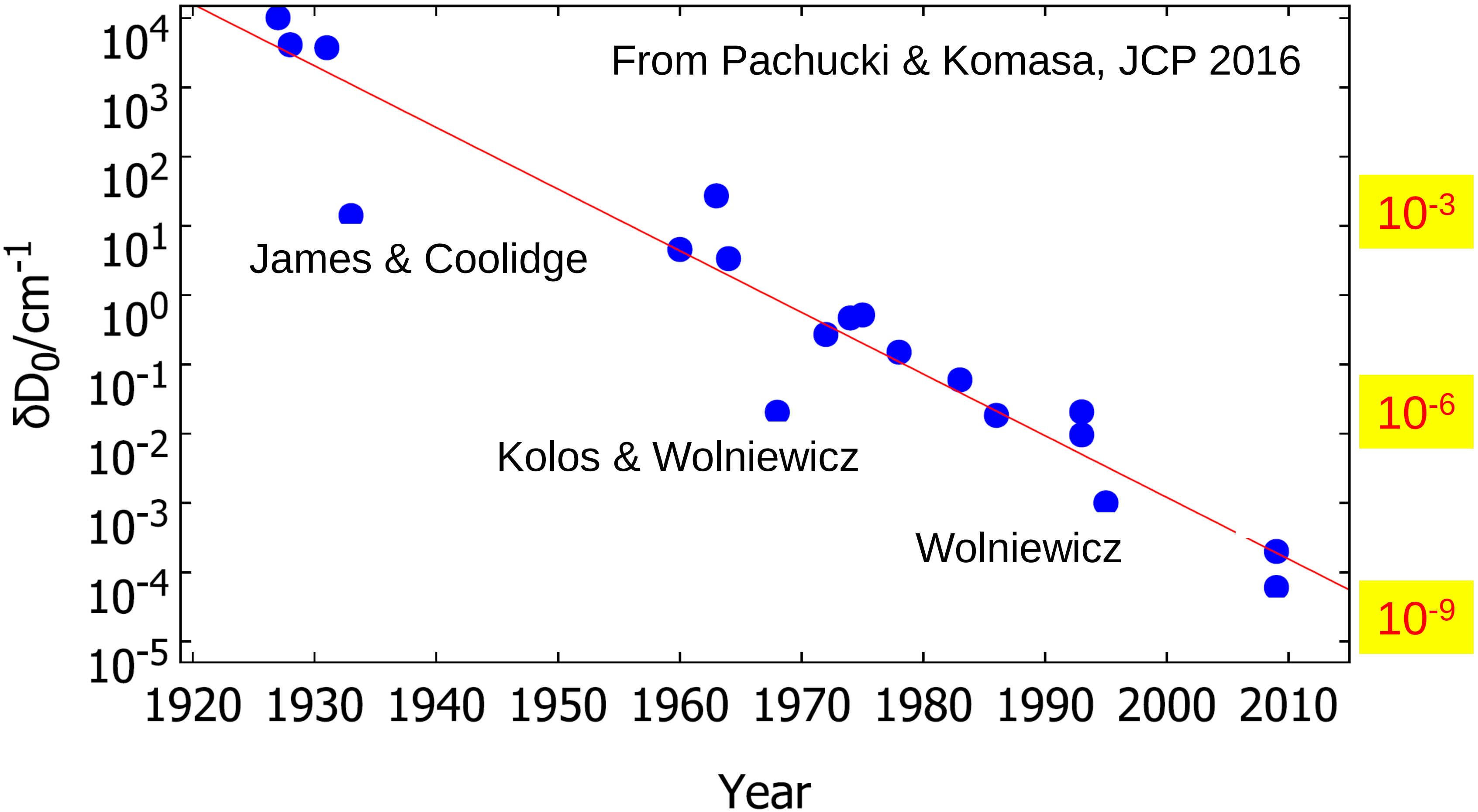


- 仍需要独立的^{3}He-跃迁频率测定
- 与CREMA μ-He$^+$结果比较

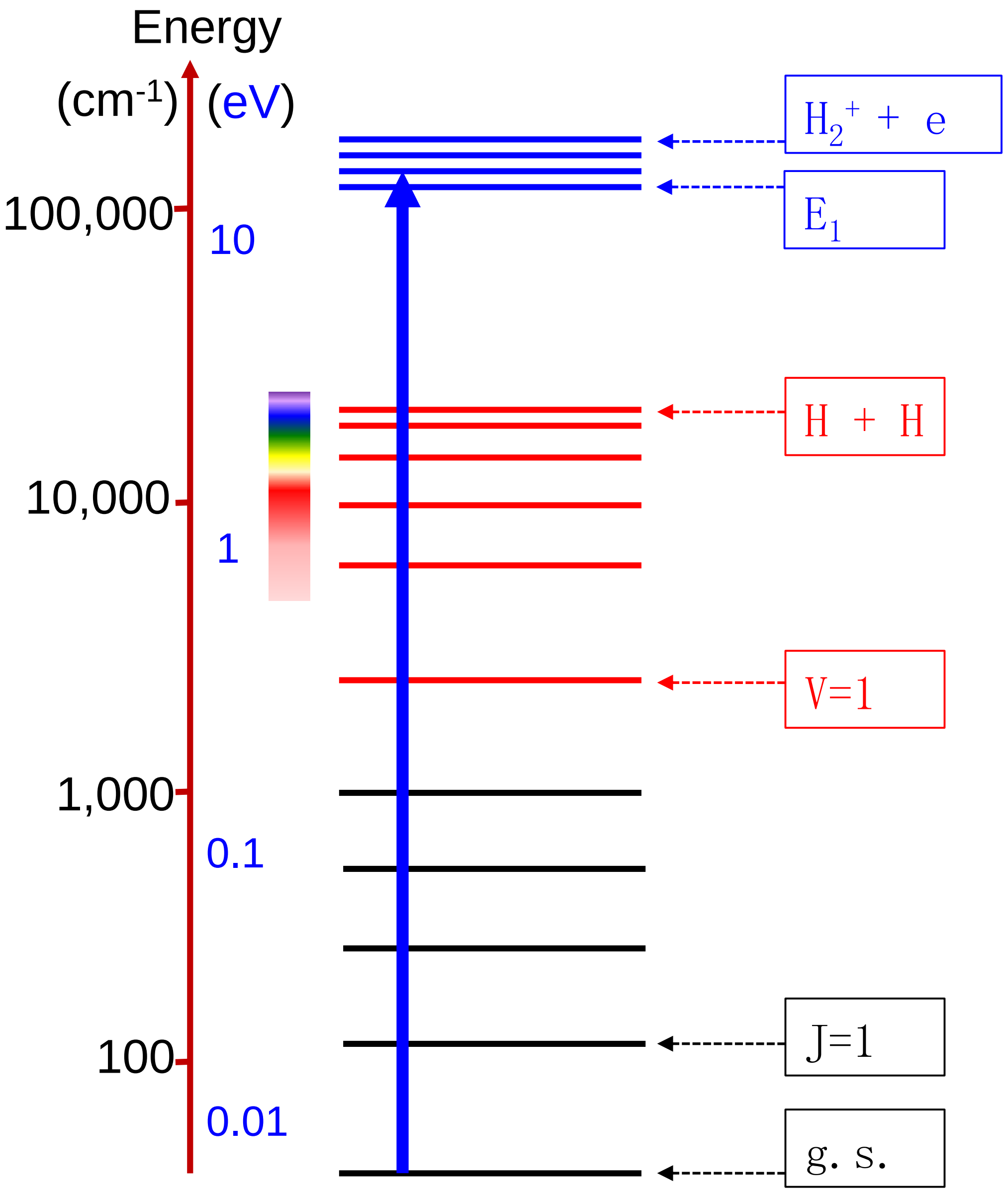
H_2: the Most Abundant Molecule in the Universe

Non-relativistic Dissociation Energy of H_2

Pachucki et al., *JCP* **114**:164306 (2016); *PRL* **117**:263002 (2016); *PRA* **95**:052506 (2017)



Energy Levels of H_2

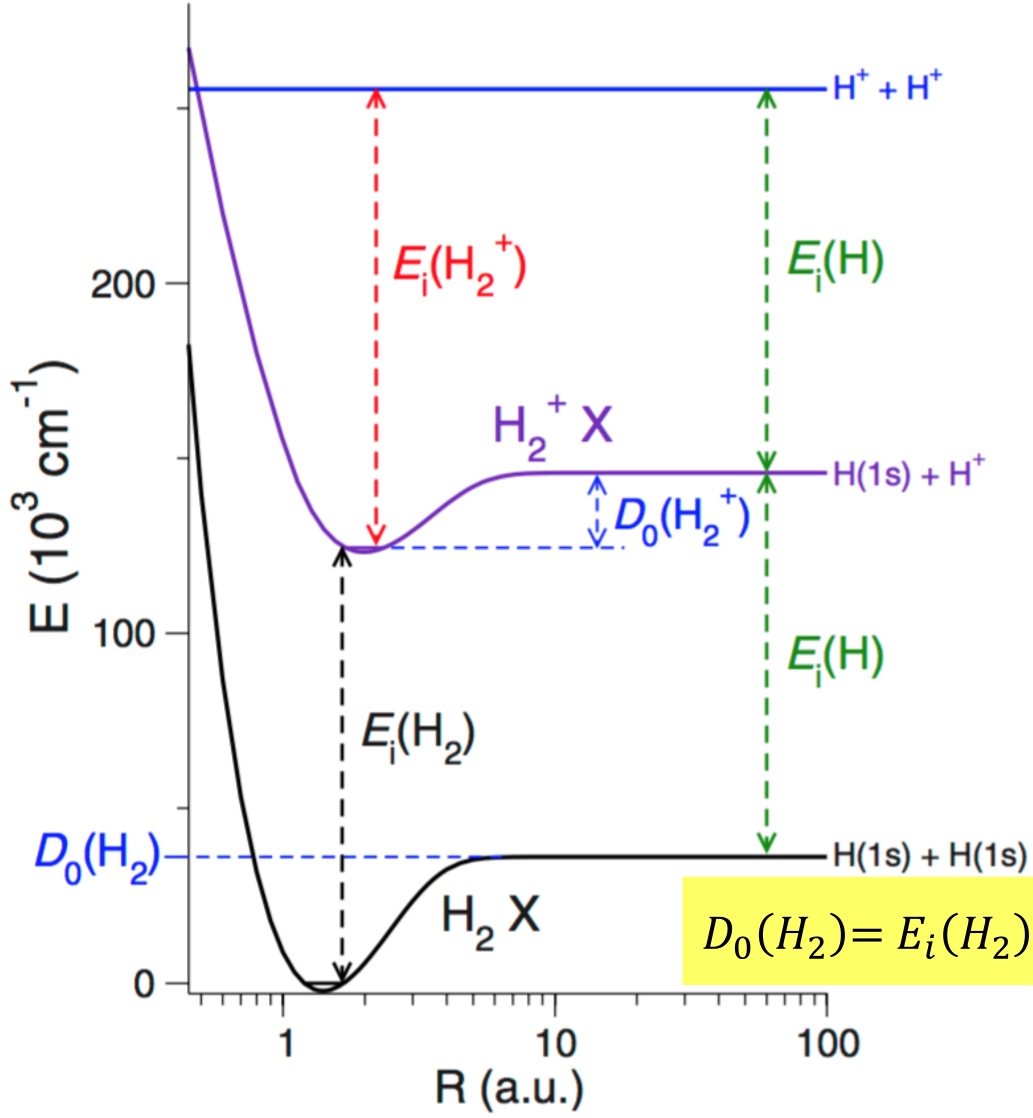


Electronic transition (VUV)

- ✓ Strong
- ☐ No SF VUV laser source

Shuiming Hu, smhu@ustc.edu.cn

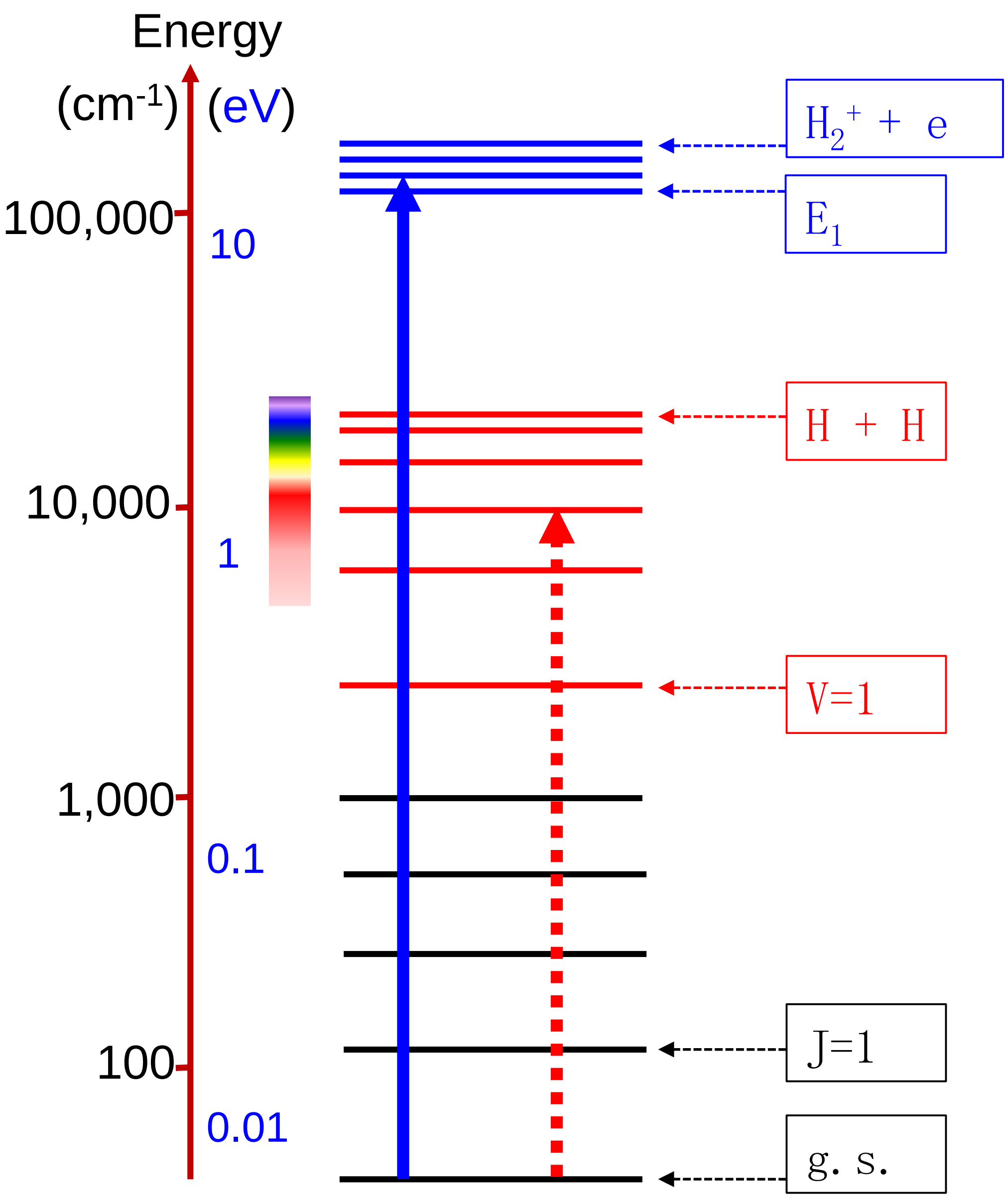
Adiabatic potential of H_2 system



$$D_0(H_2) = E_i(H_2) + E_i\left(H_2{}^+\right) - 2E_i(H)$$

Korobov, PRL 2017
Mohr, RMP 2016
Liu, JCP 2009

Energy Levels of H_2



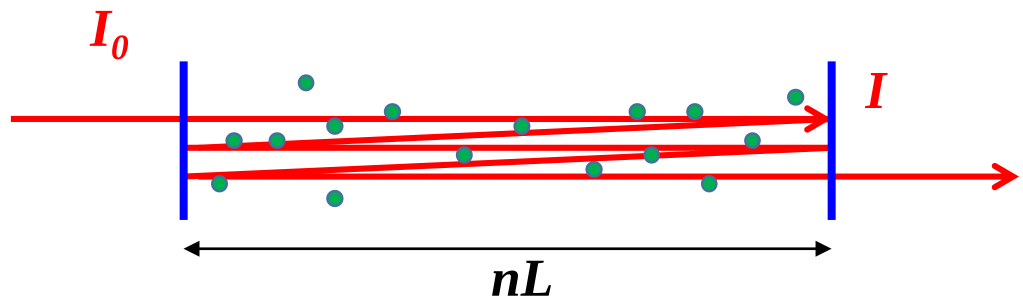
Electronic transition (VUV)

- ✓ Strong
- No SF VUV laser source

IR or VIS

- ✓ Best lasers available
- No dipole transition
- Extremely weak quadrupole transitions

H_2 electric-quadrupole transition at 0.8um



Beer-Lambert's law: $I = I_0 \exp(-\alpha L)$

G. Herzburg, Nature 163:170, 1949

Cell length: 22 meters, 10atm H2, multi-pass:250

Quadrupole Rotation-Vibration Spectrum of the Hydrogen Molecule

considered that molecular hydrogen
an infra-red rotation-vibration spec-
r, such a spectrum may be expected
ransition made possible by the change
moment during the vibration[1]. The
sity of this spectrum is so low that a
er of 10 km. at atmospheric pressure
btain it in absorption[1,2].

G. Herzberg

H_2: 80% of the atmosphere of Jupiter

27 March 1970, Volume 167, Number 3926 **SCIENCE**

The Atmosphere of Jupiter

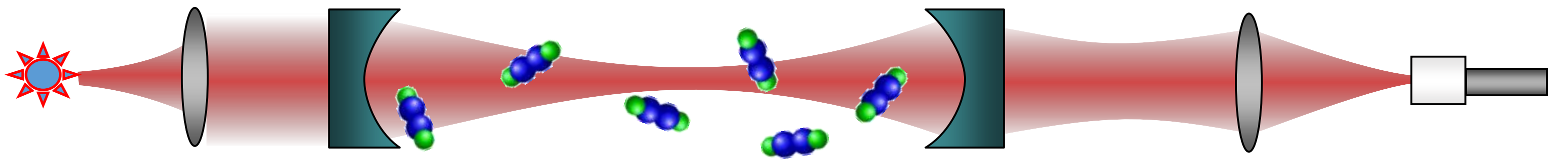
This giant planet appears to represent an early stage in the history of the solar system.

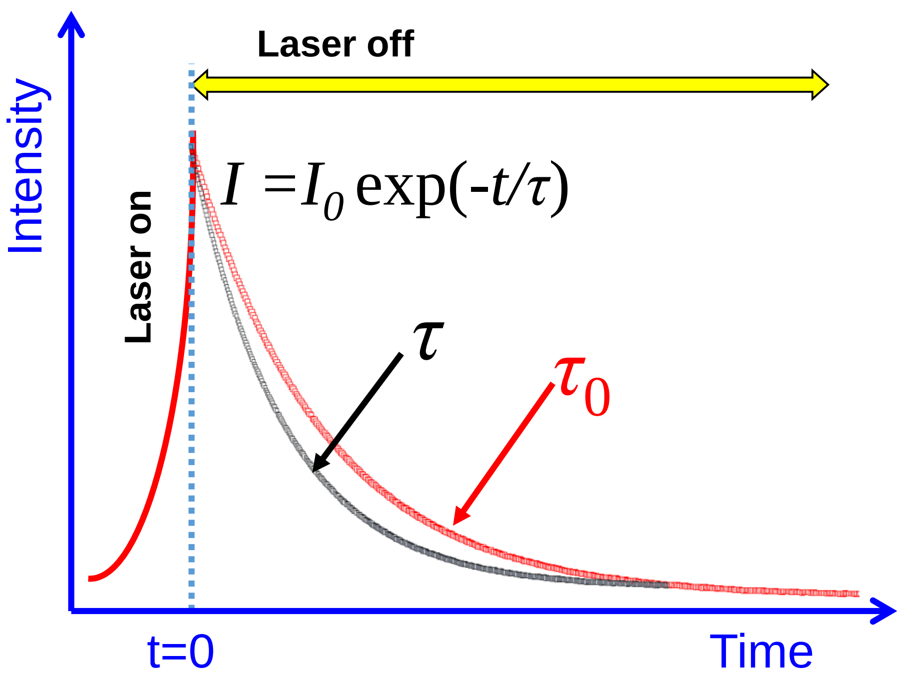
Tobias Owen

Rutherfurd (*1*). In 1863 he wrote that, in addition to the customary Fraunhofer lines present in the reflected solar radiation, the spectrum of Jupiter contained "two bands in the red and orange, between C and D, which are not found in the solar spectrum" (Fig. 1). He suggested that these might be caused by a Jovian atmosphere. Some 70 years later these absorptions were identified by Wildt, who showed that they are produced by methane and ammonia (*2*).

Many other absorption bands of

Cavity ring-down spectroscopy (CRDS)





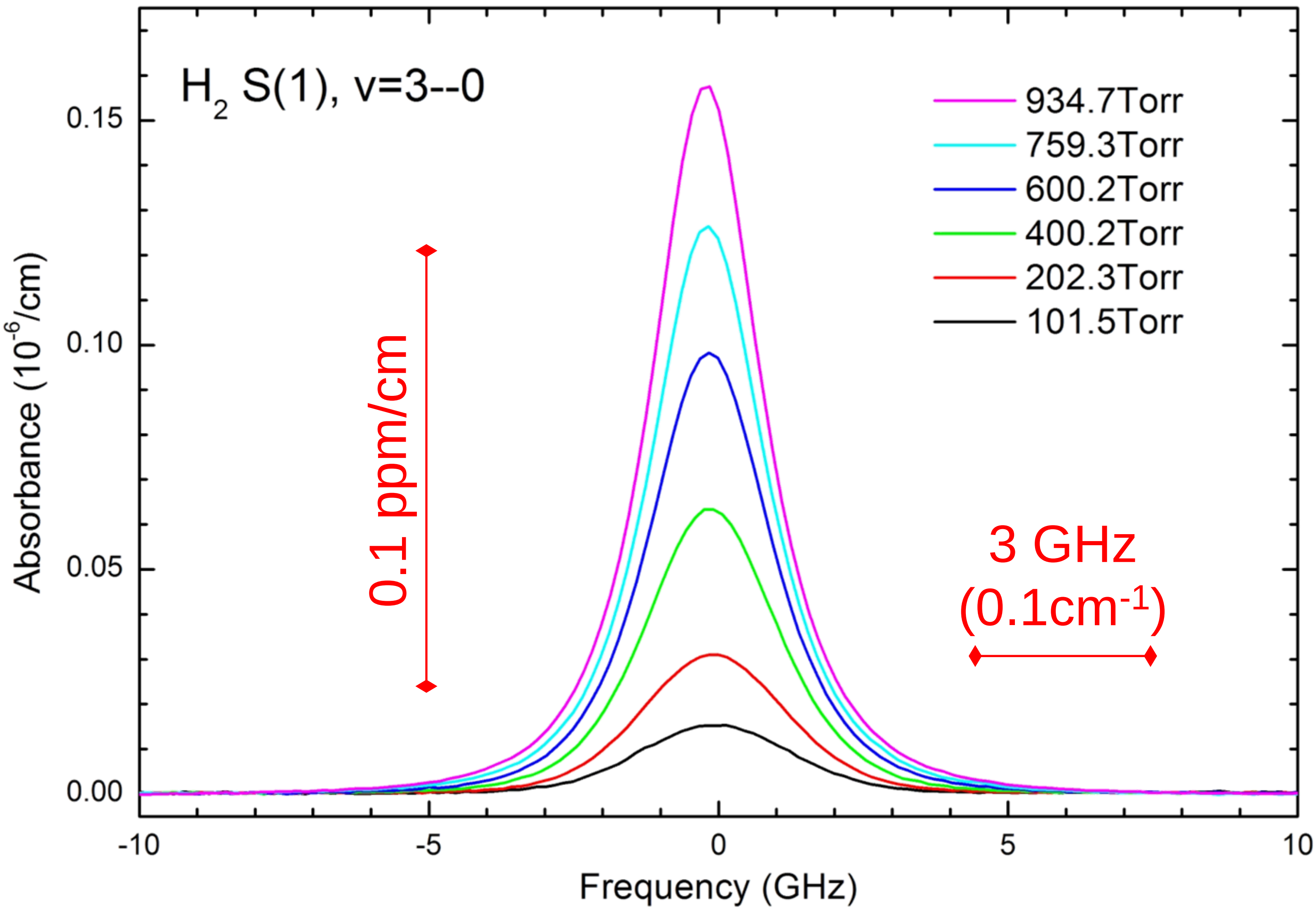
$$\alpha(\nu) = \frac{1}{c\tau(\nu)} - \frac{1}{c\tau_0}$$

☺ **Ultra Sensitive** $L_{eff} \sim 10^2$km

☺ **Immune to laser power noise**

Shuiming Hu, smhu@ustc.edu.cn

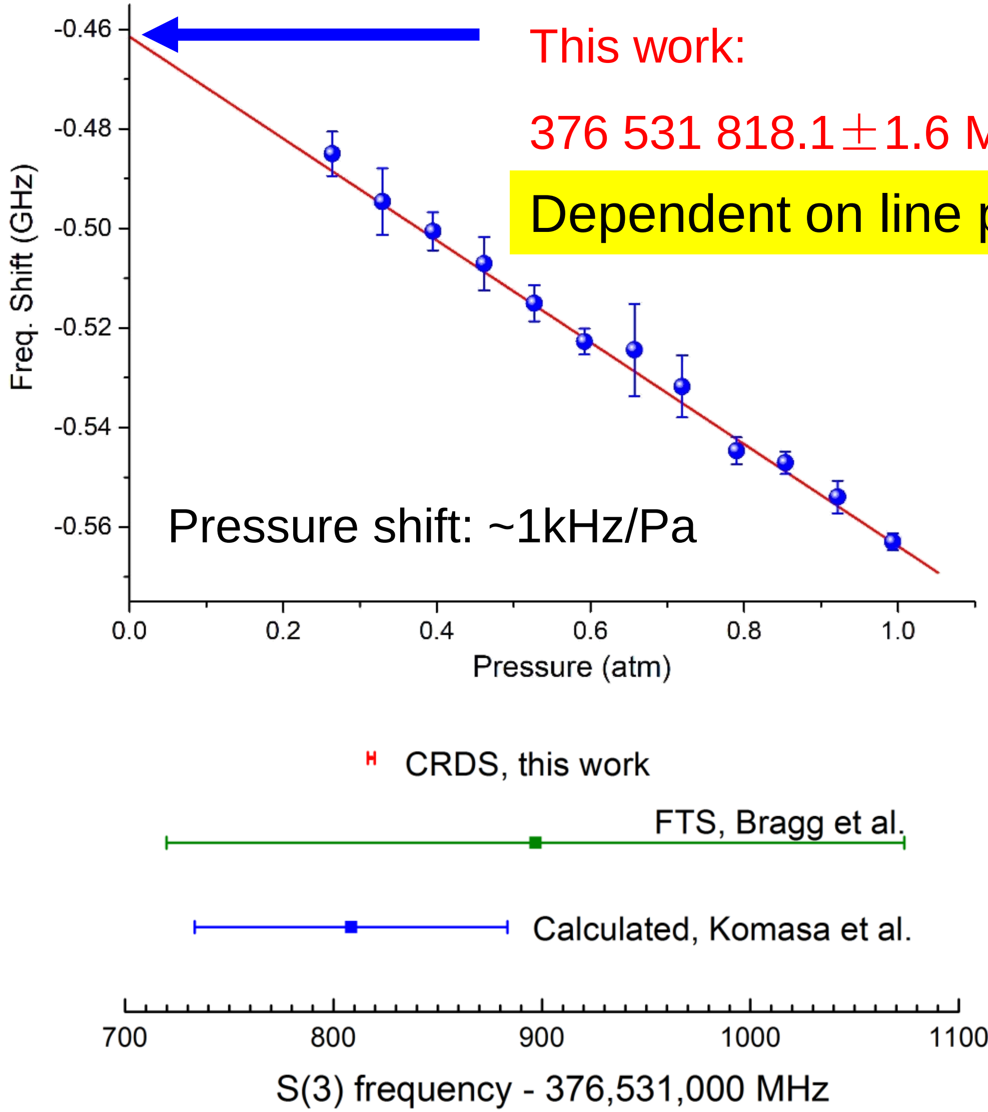
$S_3(1)$ (v=3←0, J=3←1) line of H_2 @ 815nm



Hu et al. *Astrophys J* **749**:76, 2012

Shuiming Hu, smhu@ustc.edu.cn

Line position of $S_3(3)$ (V=3←0, J=5←3) of H_2



This work:

376 531 818.1±1.6 MHz (4ppb)

Dependent on line profile model!

Pressure shift: ~1kHz/Pa

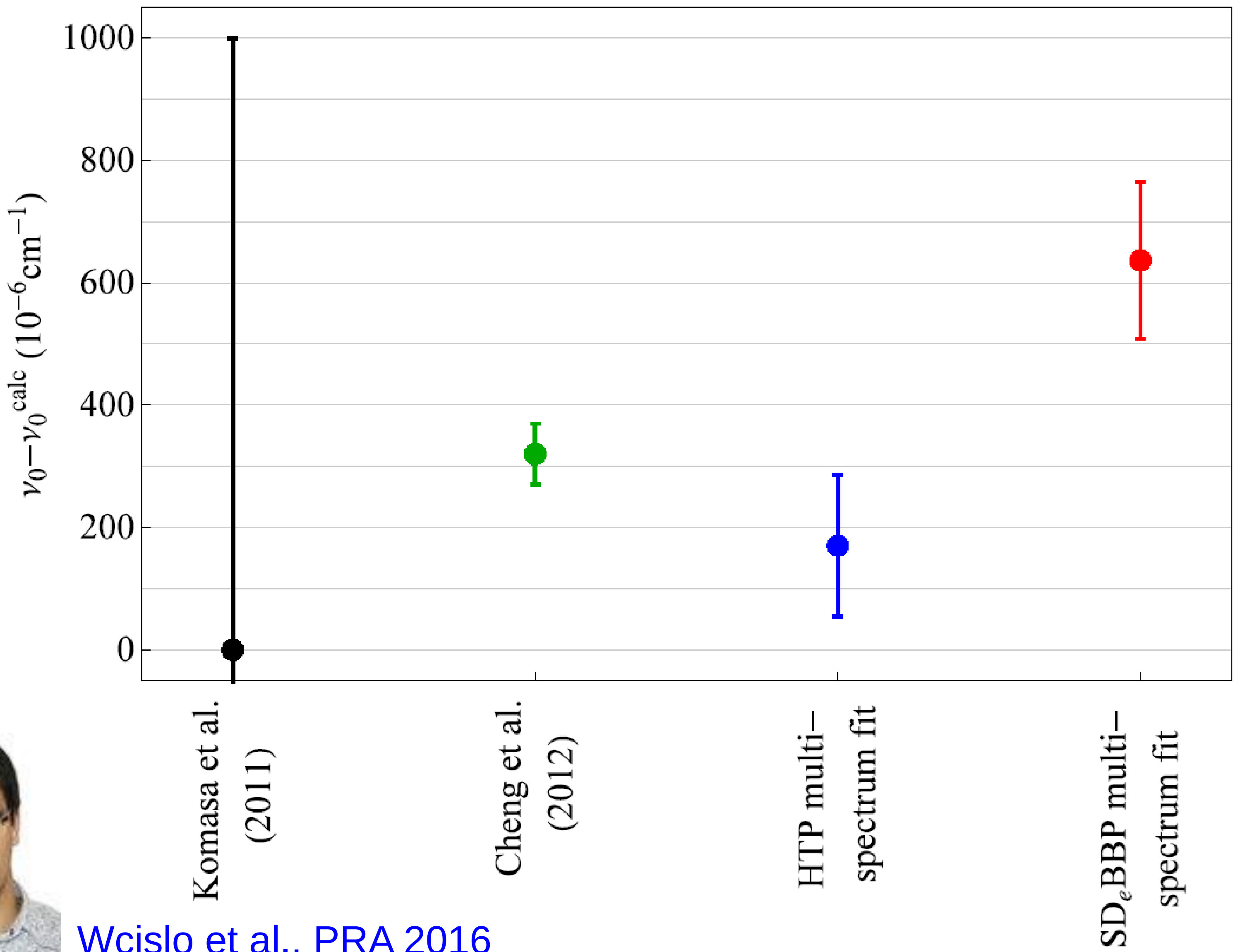
程存峰

30 GHz = 1cm^{-1}

Cheng et al. *PRA* **85**:024501, 2012

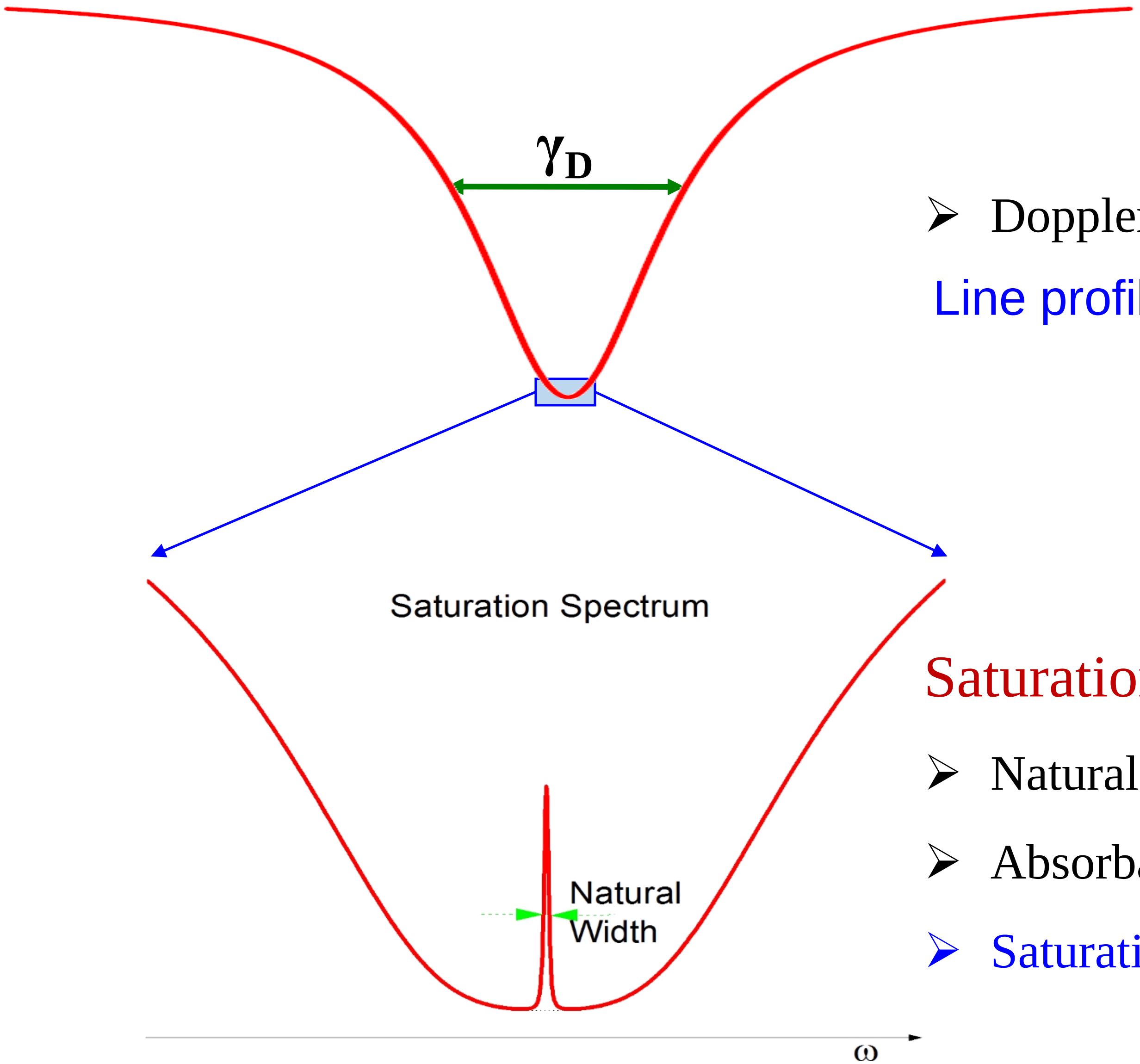
Shuiming Hu, smhu@ustc.edu.cn

Line position of H_2, $S_3(3)$ (V=3←0, J=5←3)



Wcislo et al., PRA 2016

Precision spectroscopy of molecular hydrogen



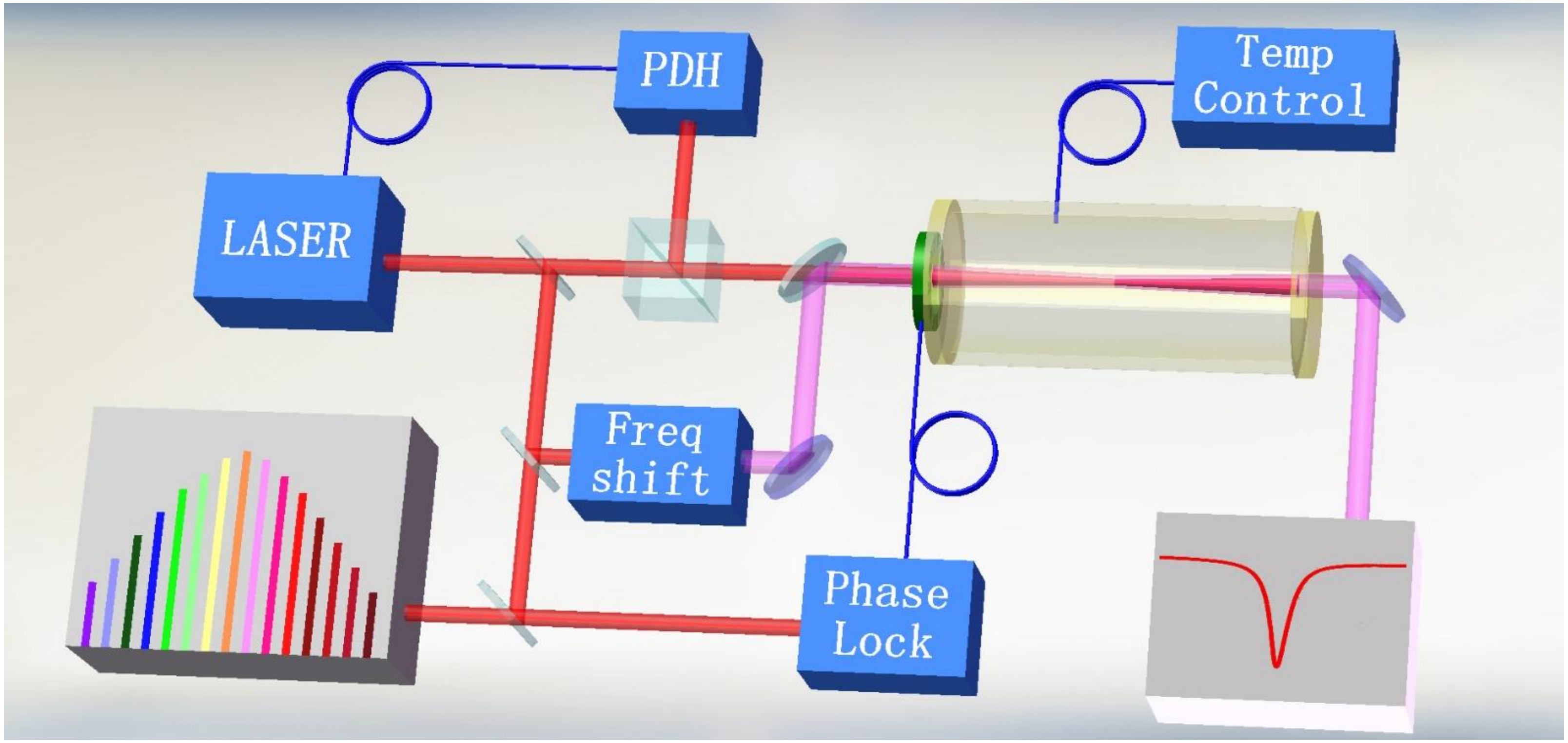
- Doppler Width ~ 1GHz

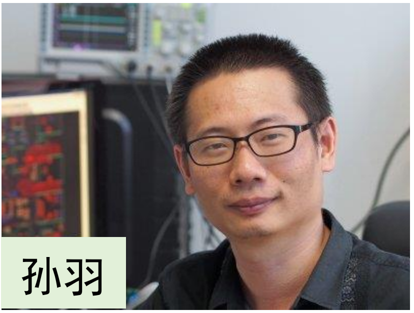
Line profile model!

Saturation Spectroscopy of HD

- Natural Width ~ 10μHz
- Absorbance ~ 1ppt/cm
- Saturation intensity ~ 10MW/cm^2

Comb-Locked CRDS

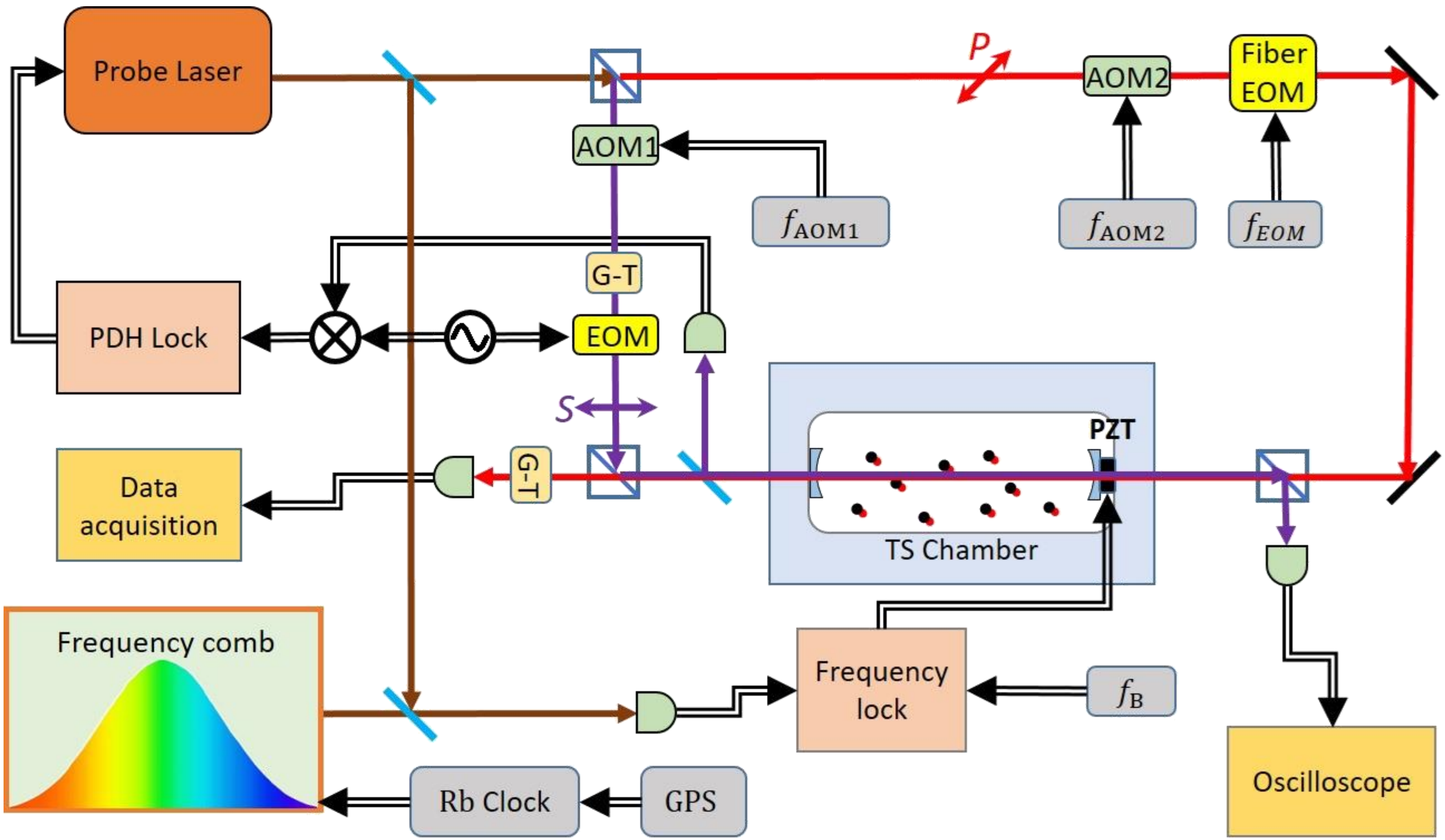




☺ Precision <0.1kHz ☺ Scan range >10GHz

☺ Sensitive L_{eff} ~ 10^2km ☺ Power enhancement: 10^4

Comb-Locked CRDS



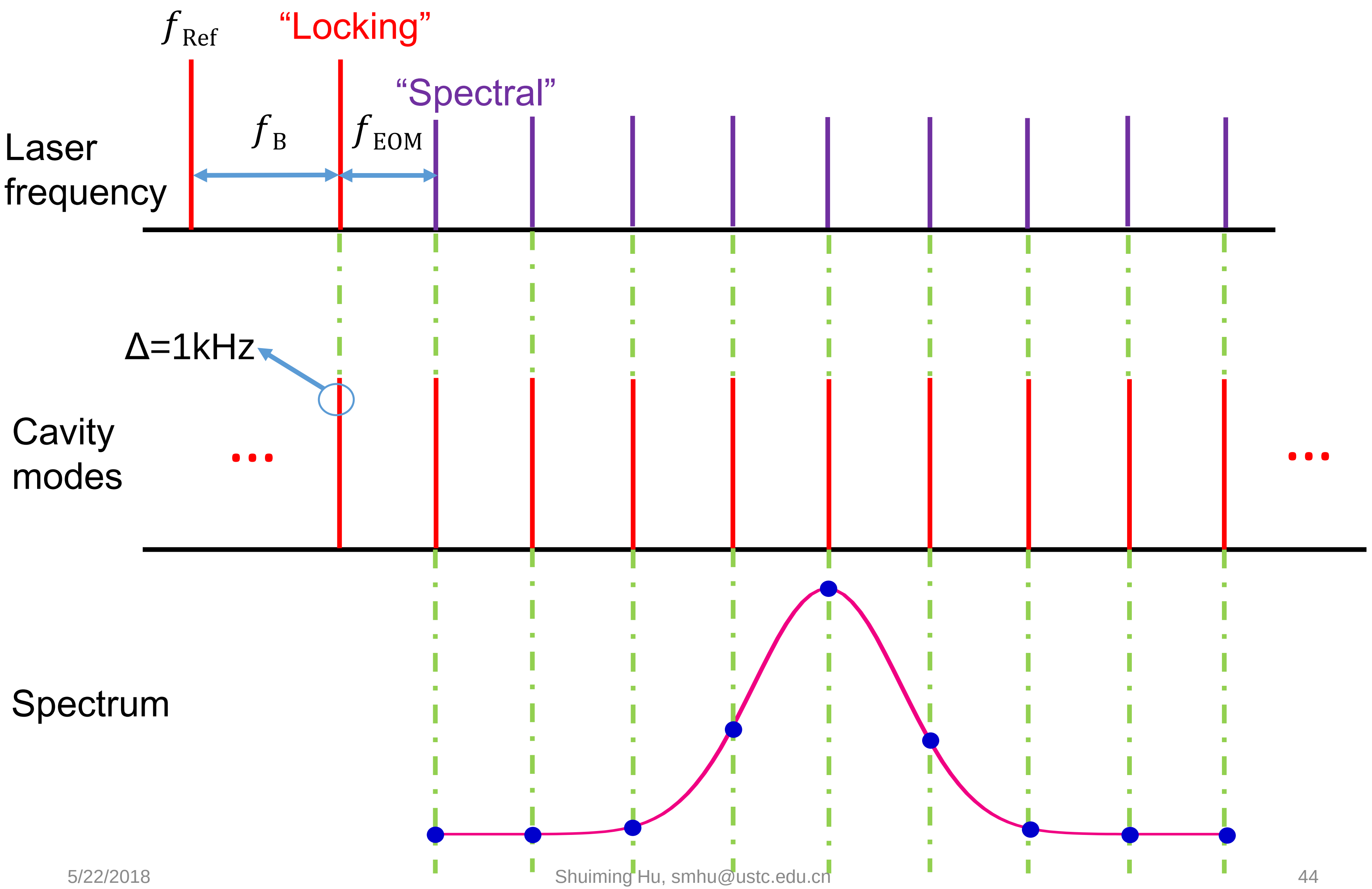
Cavity Mode Width: 1.7 kHz,

Intra-cavity Laser Power: 200 W;

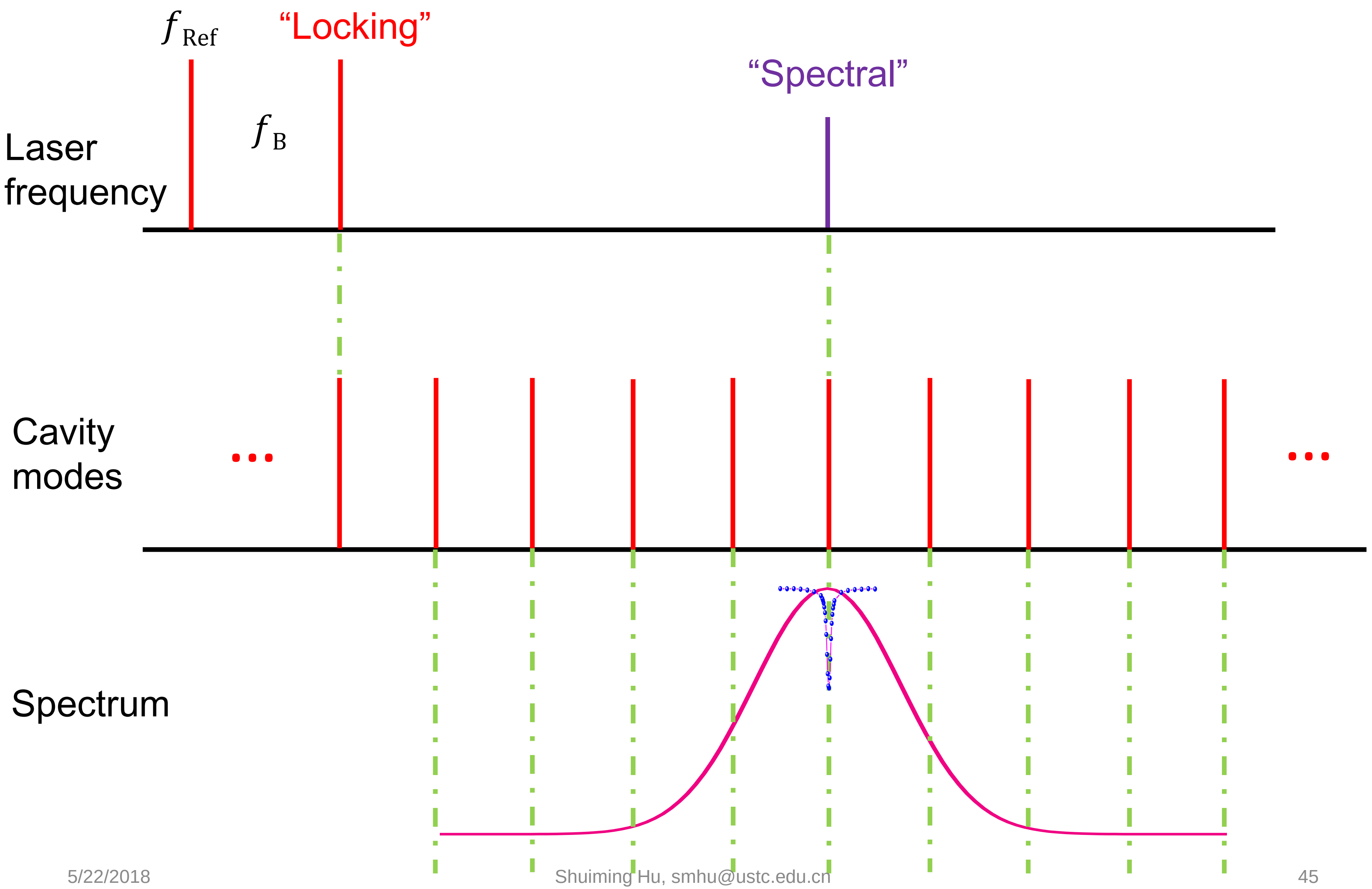
Finesse: 120 000

Beam Radius: 0.5 mm

Broad Scan: tuning f_{eom} with a step of FSR



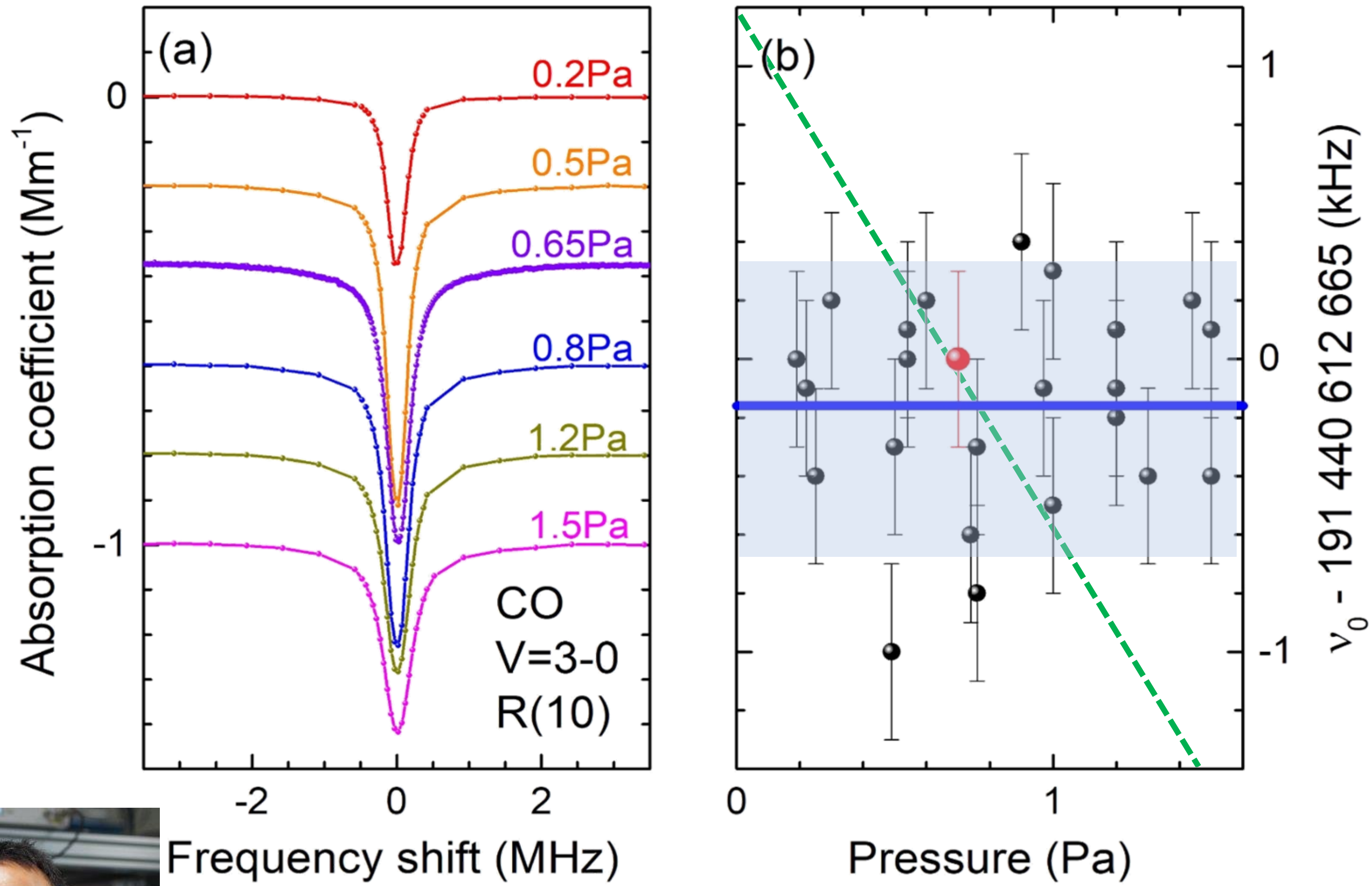
Fine Scan: tuning f_B

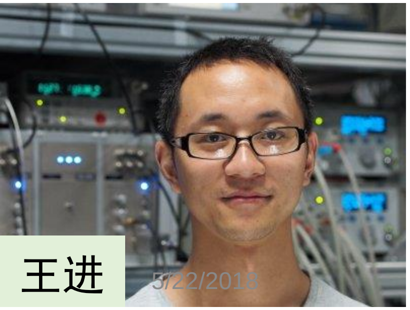


Shuiming Hu, smhu@ustc.edu.cn

CO: V=3-0, R(10), f = 191 440 612 662.2(5) kHz

Δf/f = 3E-12





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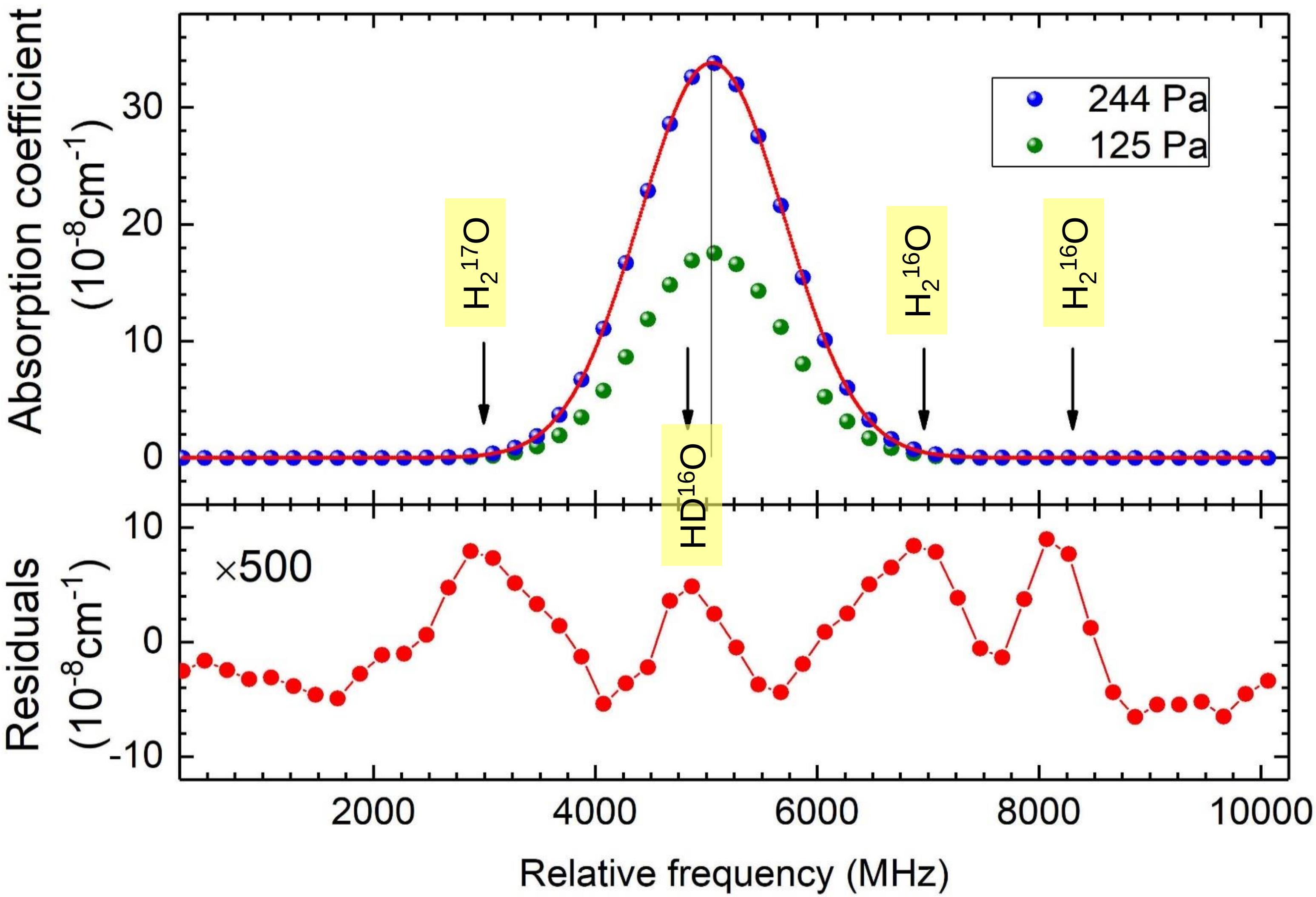
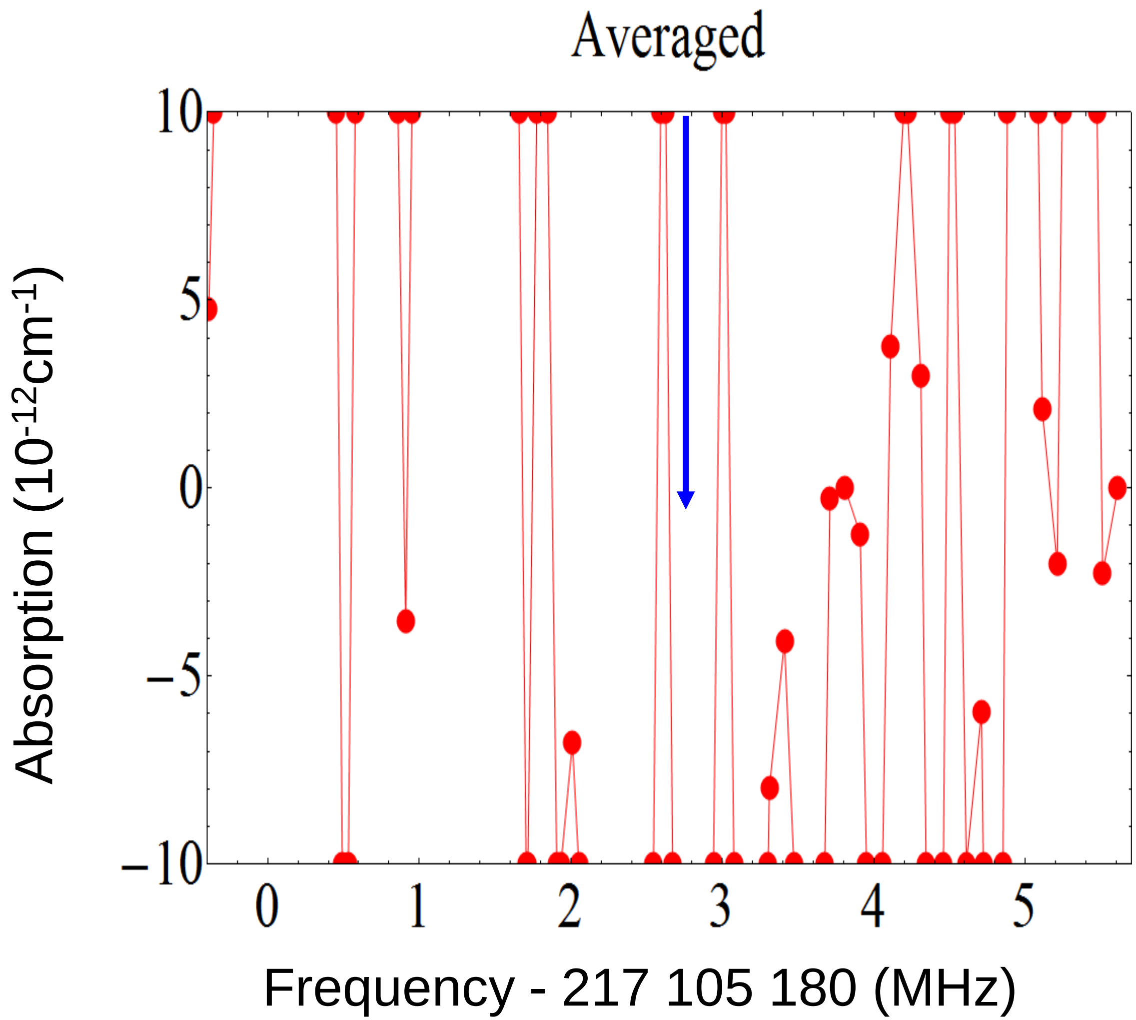
Wang et al. *RSI* **88**:043108, 2017; *JCP* **147**:091103, 2017

HD, v=2-0, R(1) line @ 1.38 um, Doppler Limited



HD, v=2-0, R(1), Lamb Dip

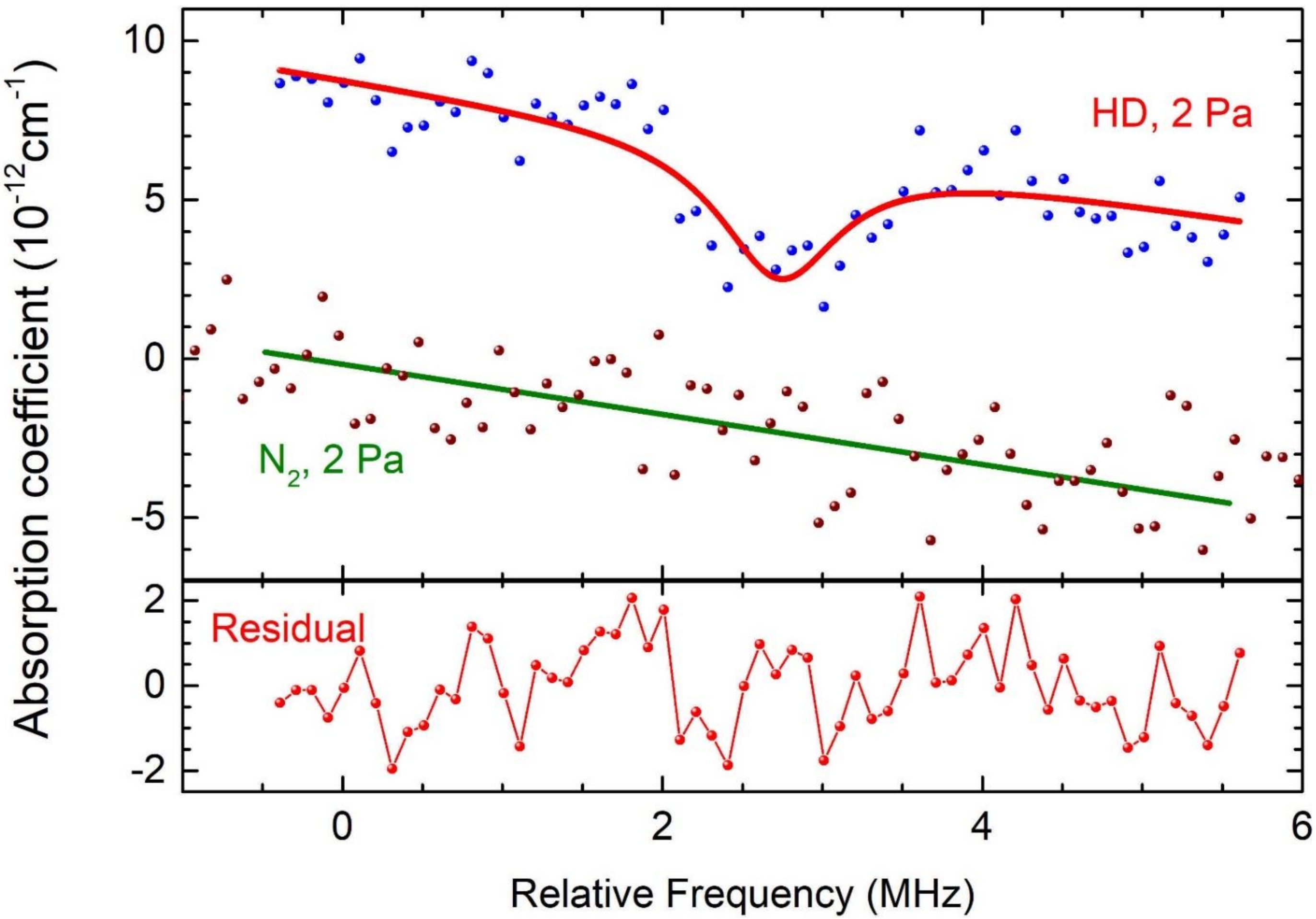


Cavity Mode Width: 1.7kHz, Finesse: 120000

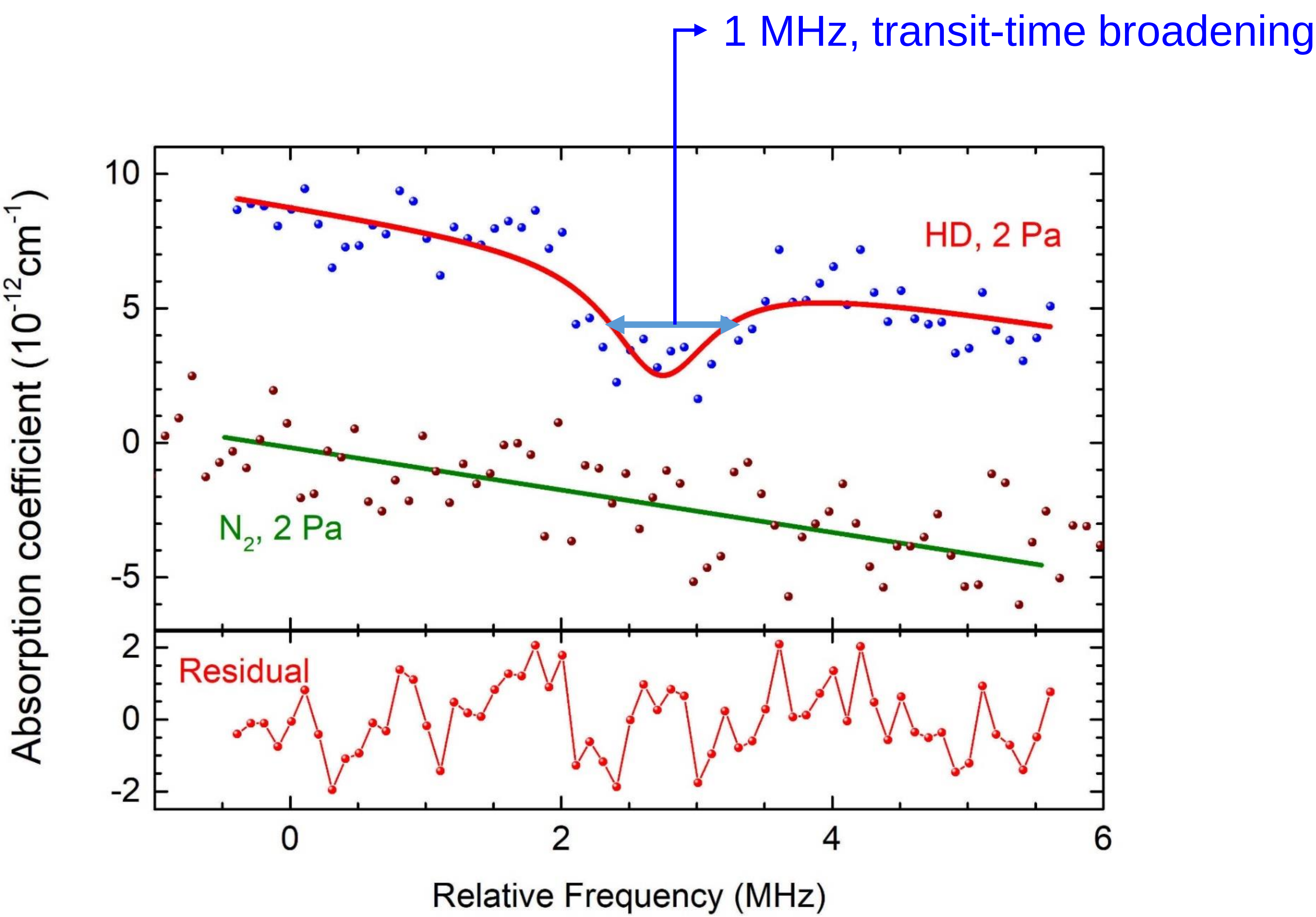
Intra-cavity Laser Power: 200 W; Beam Radius: 0.5mm

HD, v=2-0, R(1), Lamb Dip

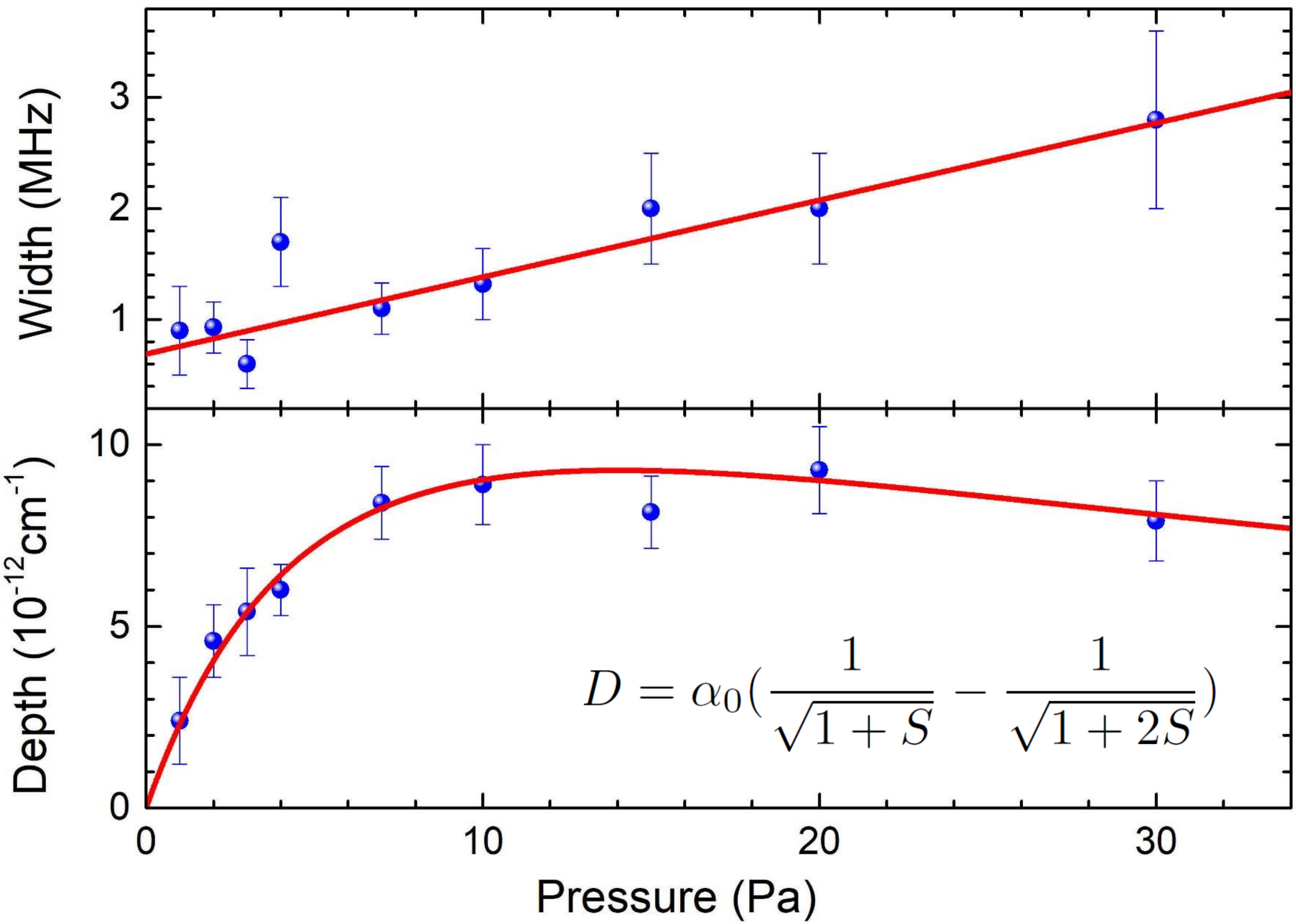
Saturation spectroscopy of extremely weak transition: A=2E-5/s



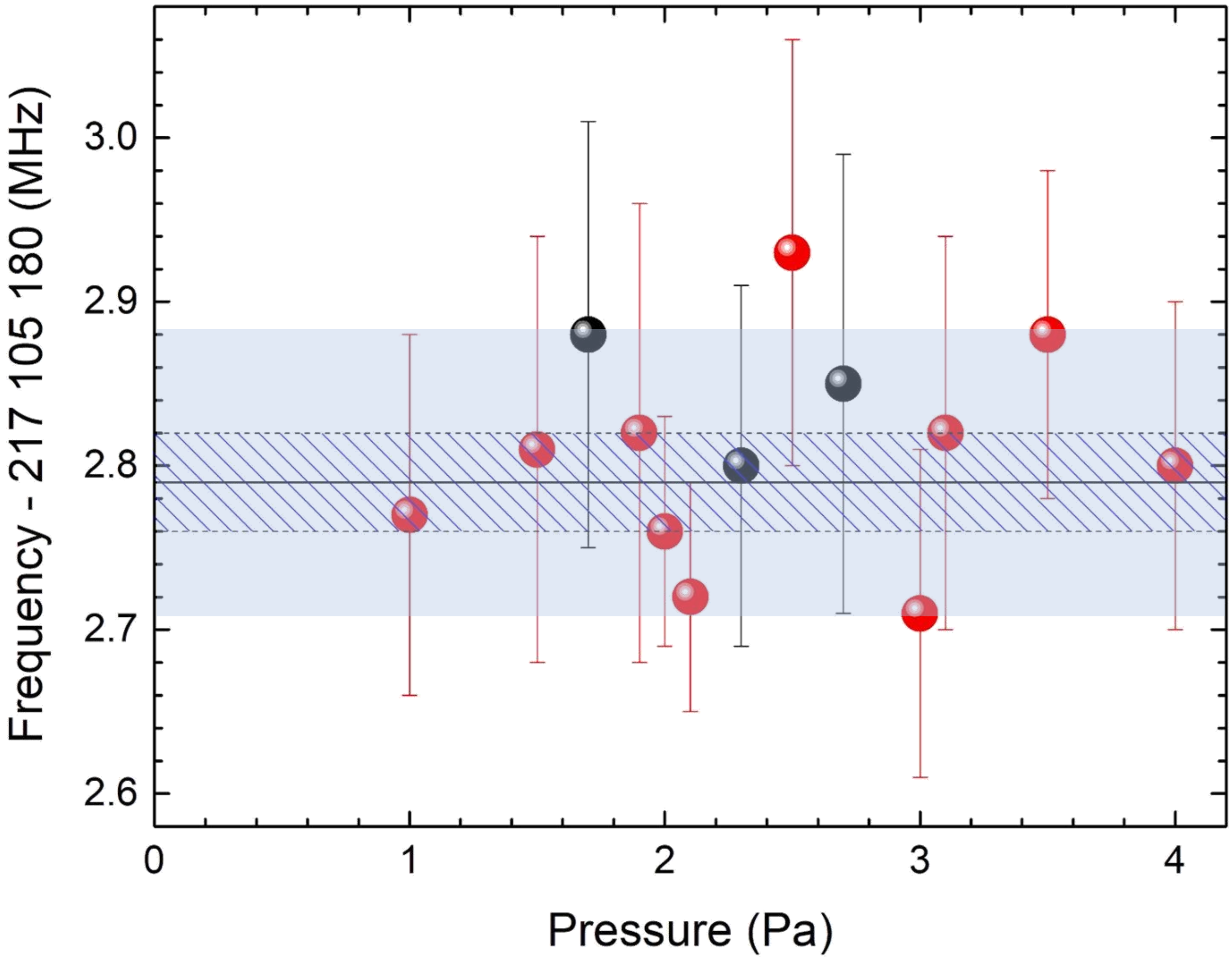
HD, v=2-0, R(1), Lamb Dip



HD, v=2-0, R(1), Lamb Dip



HD, v=2-0, R(1): f = 217 105 182.79 (9) MHz



HD transition frequency

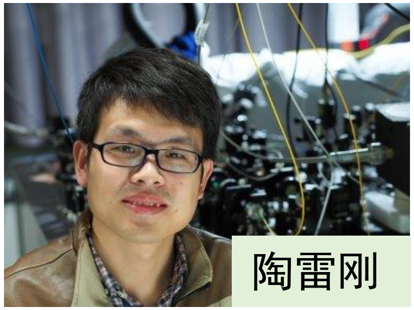
$$E = E^{(2)} + E^{(4)} + E^{(5)} + E^{(6)} + E^{(7)} + E_{\rm FS}$$

Calculation by Pachucki & Komasa

	D_0, (0,0), cm^{-1}	2-0, R(1), cm^{-1}
$E^{(2)}$	36406.510839(1)	7241.846169(1)
$E^{(4)}$	-0.531325(1)(425)[a]	0.040719(0)(32)[a]
$E^{(5)}$	-0.1964(2)(2)[a]	-0.03743(4)(3)[a]
$E^{(6)}$	-0.002080(6)	-0.000339
$E^{(7)}$	0.00012(6)	0.000021
E^{b}_{FS}	-0.000117	-0.000021
Total	36405.7810(5)	7241.84912(6)
Expt.	36405.78366(36)[c]	7241.849386(3)
Diff.	0.0026	0.00027

- Calc 2010: 0.001 cm^{-1} (30 MHz)
- Exp 2012: 0.001 cm^{-1} (30 MHz)

- Calc *this*: 0.000 06 cm^{-1} (2 MHz)
- Exp *this:* 0.000 003 cm^{-1} (0.1 MHz)
- Exp.-Calc.: 0.000 27cm^{-1} (8 MHz)



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Tao *et al.*, PRL 120:153001, 2018

Sensitivity to the Constants

$$\frac{d\nu}{\nu} = \beta_{R_y}\frac{dR_y}{R_y} + \beta_\alpha\frac{d\alpha}{\alpha} + \beta_{\mu_p}\frac{d\mu_p}{\mu_p} + \beta_{\mu_d}\frac{d\mu_d}{\mu_d} + \beta_{r^2}\frac{dr^2}{r^2}$$

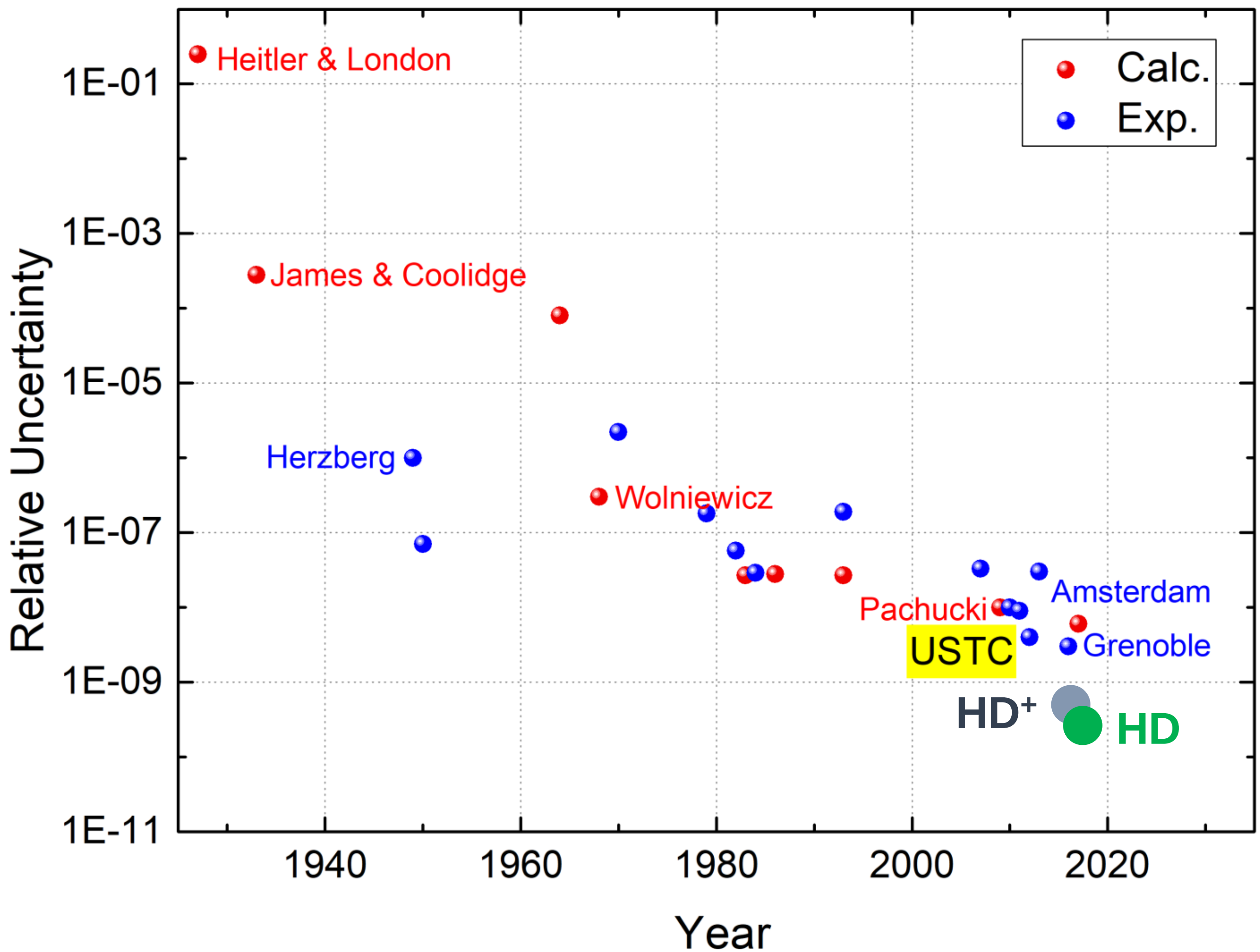
Constant	$\delta C/C$ CODATA	β	$\beta \times \delta C/C$
Ry	5.9E-12	1	6E-12
α	2.3E-10	-4.3E-6	-1E-15
$\mu_p = m_p/m_e$	9.5E-11	-0.31	-3E-11
$\mu_d = m_d/m_e$	3.5E-11	-0.060	-2E-12
$r^2 = r_d^2 + r_p^2$	0.004	-2.9E-9	-1E-11

$\delta\nu/\nu \sim (0.4\ \text{ppb})_{exp}\ (8\text{ppb})_{calc}$

➔ $\delta\mu_p/\mu_p \sim (1.3\text{ppb})_{exp}\ (30\text{ppb})_{calc}$

Calculation by Pachucki & Komasa

Ro-vibrational Energies of Molecular Hydrogen



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Thank you for your attention!