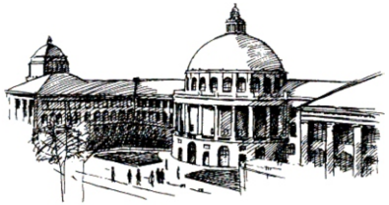
Precision measurements of the ionization energies of H_2, He and H

PREN 2022, Paris, 23 June 2022



Physical Chemistry Laboratory, ETH Zurich

Introduction

Experimental approach

The ionization energy of metastable helium
Work by Gloria Clausen, Paul Jansen and Simon Scheidegger

Ionization and dissociation energies of H_2, HD and D_2
Work by Andreas Osterwalder, Jinjun Liu, Daniel Sprecher, Maximilian Beyer, Nicolas Hölsch, Ioana Doran, in collaboration with the groups of Wim Ubachs, Kjeld Eikema, VU Amsterdam, and Christian Jungen, CNRS, Orsay

The ionization energy of H
Work by Simon Scheidegger

Conclusions

Financial support:
- Swiss National Science Foundation
- ERC advanced-grant program

LaserLaB Amsterdam
VU VRIJE UNIVERSITEIT AMSTERDAM

Cunfeng Cheng
Joël Hussels
Edcel Salumbides
Wim Ubachs

Robert Altmann
Kjeld Eikema

Christian Jungen
(CNRS, Orsay)

Precision measurements at low energies in few-particle atoms and molecules

Atomic systems: precision measurements in H, He^+, He atom, ...

- electronic transitions
- fine structure
- hyperfine structure

Theory ↔

- fundamental constants (R,α,...)
- nuclear/particle properties
- fundamental interactions

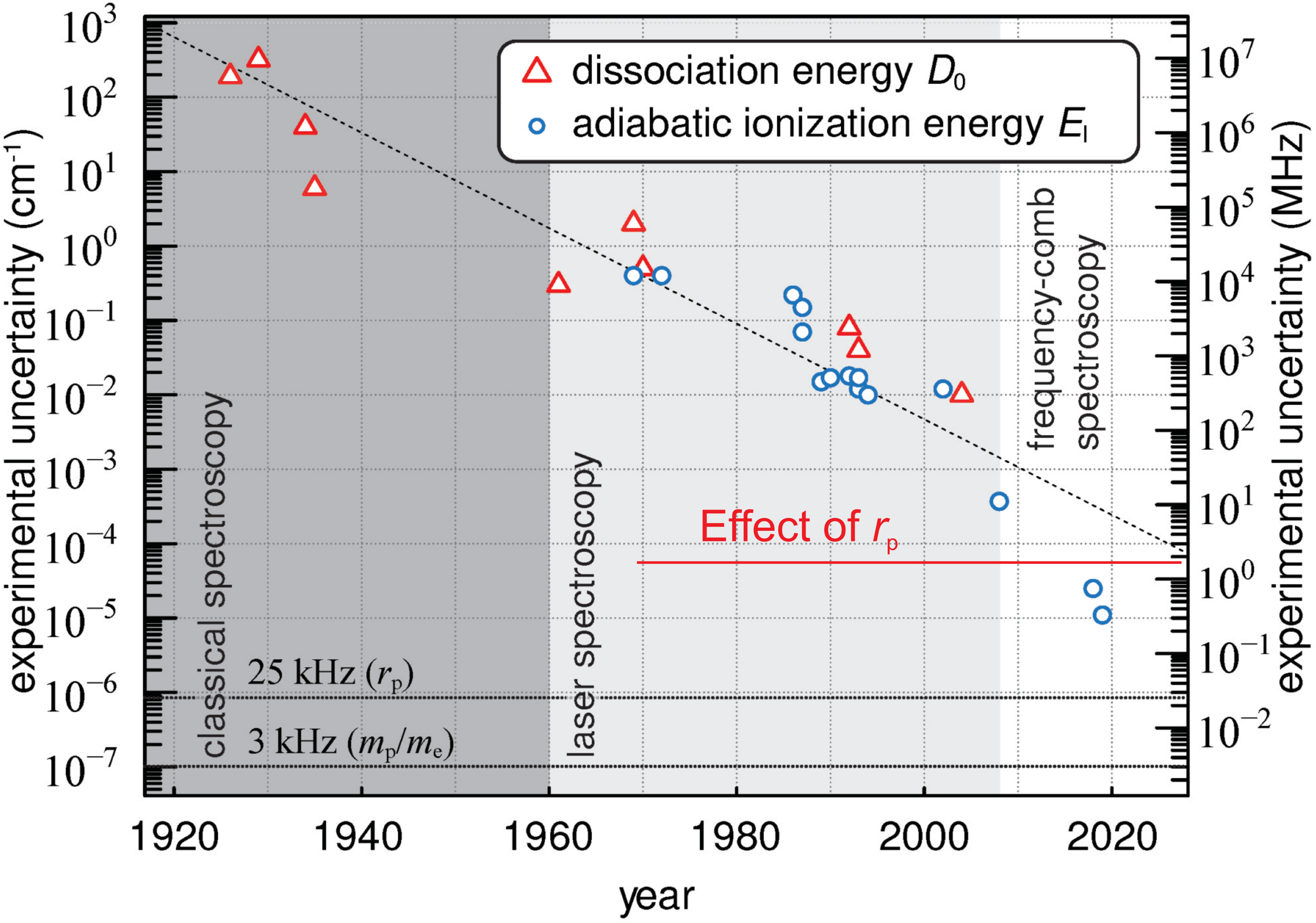
Molecular physics: precision spectroscopy in H_2^+, H_2, H_3^+, ...

- electronic transitions
- fine, hyperfine structures
- rotational, vivrational structures
- permanent dipole moments

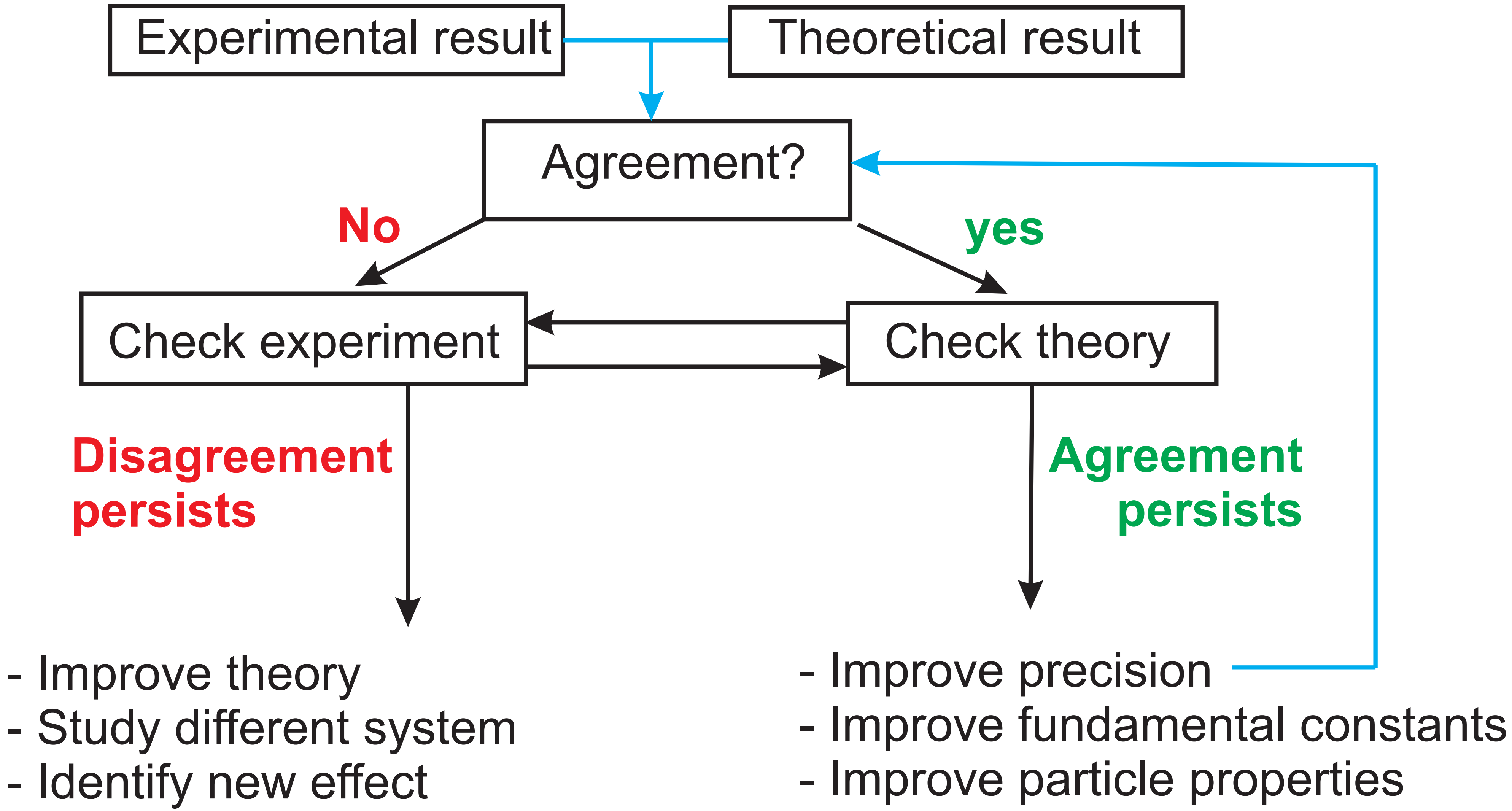
Theory ↔

- molecule structure
- reactivity, dynamics
- nuclear properties
- fundamental constants

Uncertainties in the dissociation energy of H_2



Comparison theory-experiment



Experimental result

Theoretical result

Agreement?

No

yes

Check experiment

Check theory

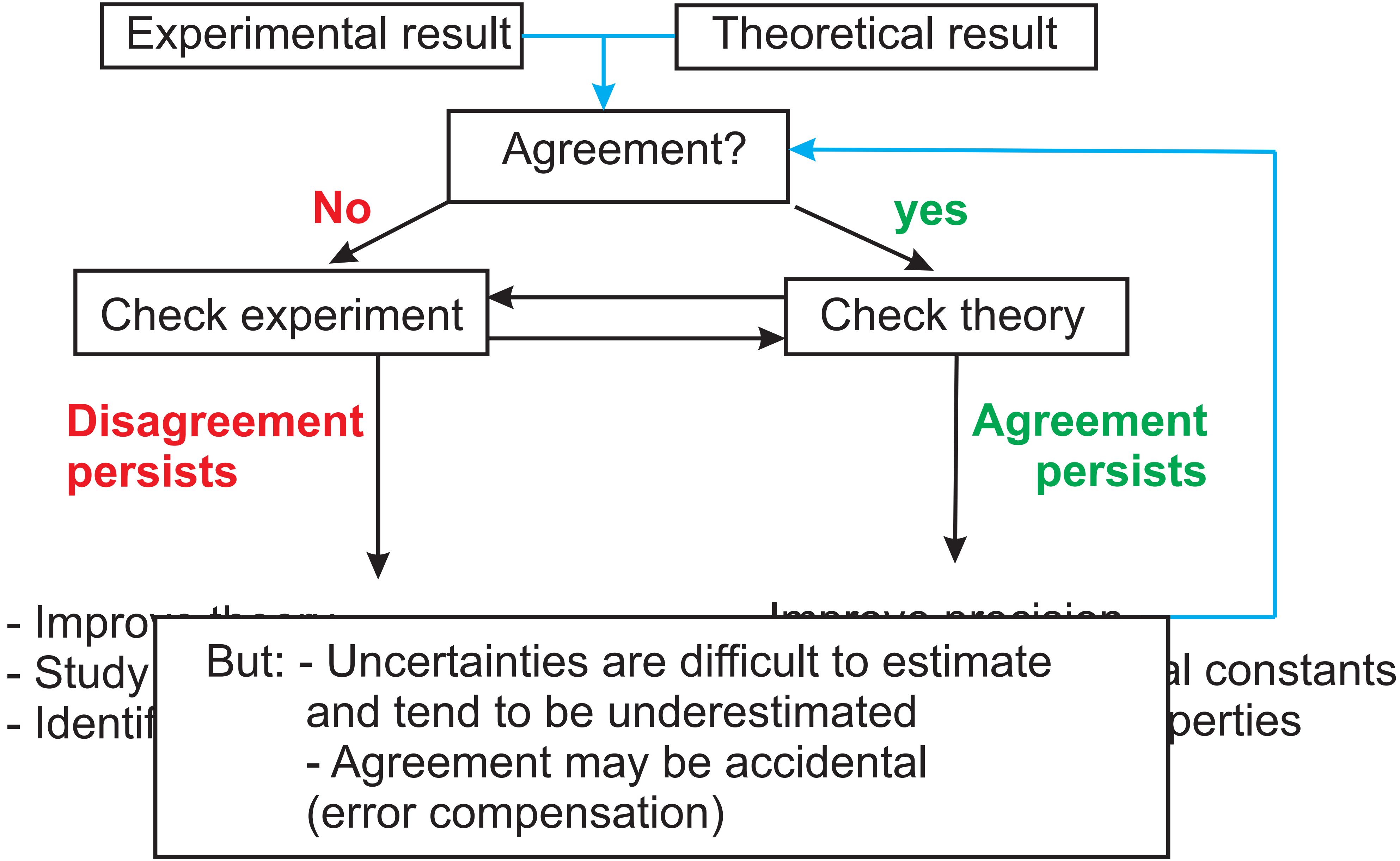
Disagreement persists

Agreement persists

- Improve theory
- Study different system
- Identify new effect

- Improve precision
- Improve fundamental constants
- Improve particle properties

Comparison theory-experiment



Experimental result

Theoretical result

Agreement?

No

yes

Check experiment

Check theory

Disagreement persists

Agreement persists

- Impro
- Study
- Identif

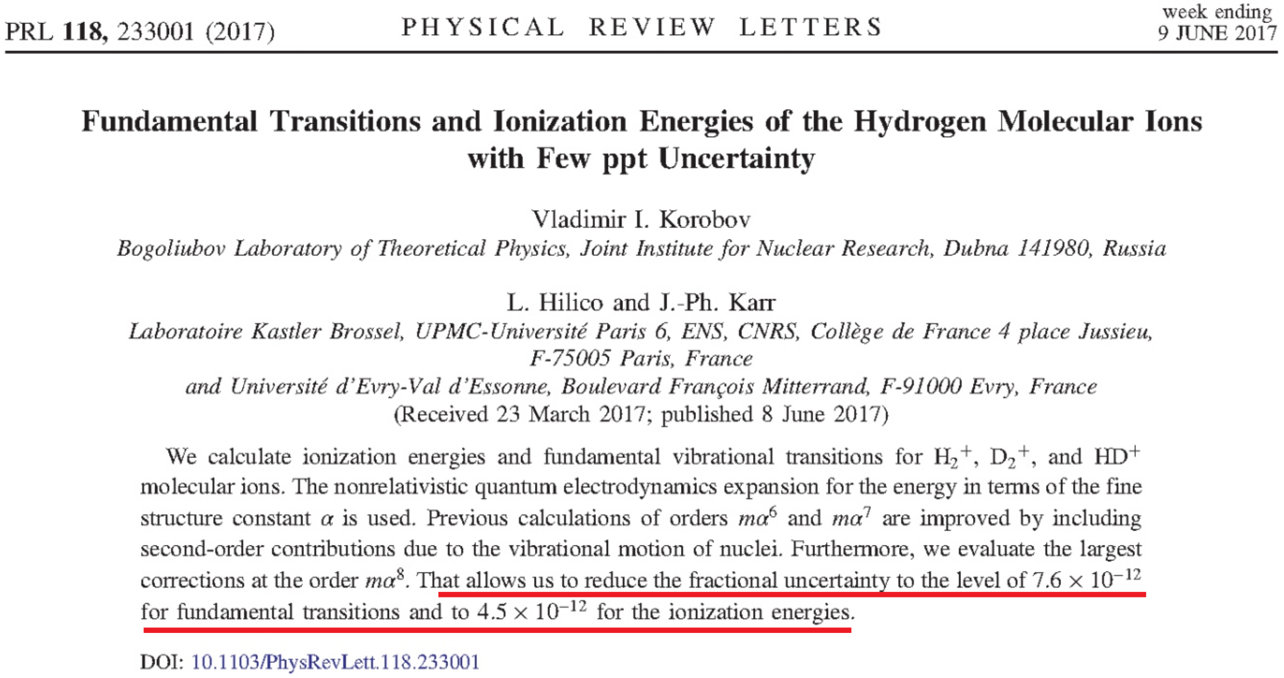
Improve precision

al constants

perties

But: - Uncertainties are difficult to estimate and tend to be underestimated
- Agreement may be accidental (error compensation)

Accuracy of ab initio calculations for one-electron molecules



PRL **118,** 233001 (2017) PHYSICAL REVIEW LETTERS week ending 9 JUNE 2017

Fundamental Transitions and Ionization Energies of the Hydrogen Molecular Ions with Few ppt Uncertainty

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(Received 23 March 2017; published 8 June 2017)

We calculate ionization energies and fundamental vibrational transitions for $H_2{}^+$, $D_2{}^+$, and HD^+ molecular ions. The nonrelativistic quantum electrodynamics expansion for the energy in terms of the fine structure constant α is used. Previous calculations of orders $m\alpha^6$ and $m\alpha^7$ are improved by including second-order contributions due to the vibrational motion of nuclei. Furthermore, we evaluate the largest corrections at the order $m\alpha^8$. That allows us to reduce the fractional uncertainty to the level of 7.6×10^{-12} for fundamental transitions and to 4.5×10^{-12} for the ionization energies.

DOI: 10.1103/PhysRevLett.118.233001

$H_2{}^+$, HD^+, $D_2{}^+$

(2-3 kHz)

$$\boxed{E = E^{(0)} + \alpha^2 E^{(2)} + \alpha^3 E^{(3)} + \alpha^4 E^{(4)} + \dots,}$$

α^2 α^4 α^5 α^6

dependence of transition lines on the masses and on the proton and deuteron charge radii

$$\nu(H_2^+) = \nu_0(H_2^+) + \frac{\Delta R_\infty}{R_\infty}\nu_0(H_2^+) + 2(R_\infty c) \times [-2.55528 \times 10^{-6}\Delta\mu_p - 8.117 \times 10^{-12}\Delta r_p],$$

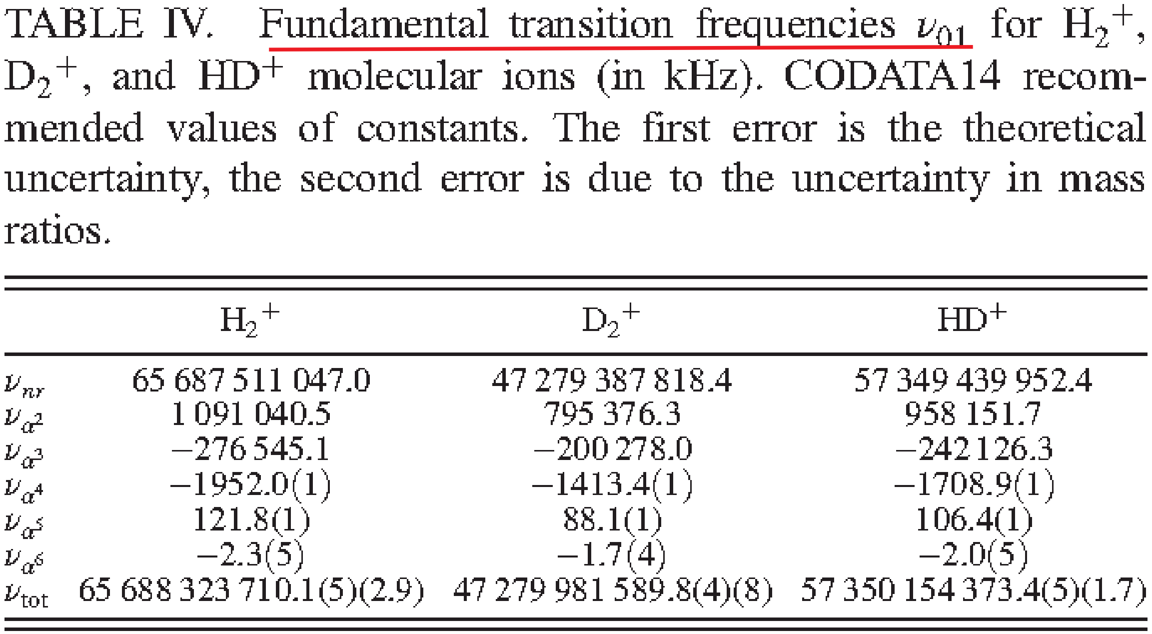
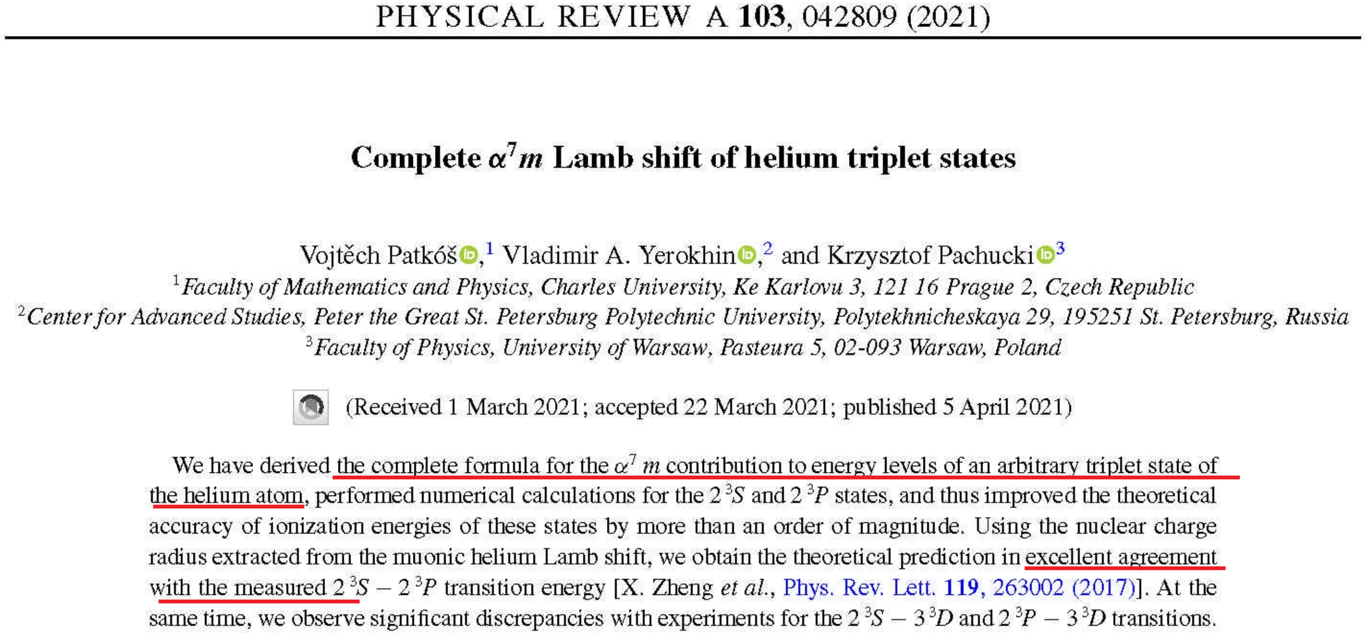


TABLE IV. Fundamental transition frequencies ν_{01} for $H_2{}^+$, $D_2{}^+$, and HD^+ molecular ions (in kHz). CODATA14 recommended values of constants. The first error is the theoretical uncertainty, the second error is due to the uncertainty in mass ratios.

	$H_2{}^+$	$D_2{}^+$	HD^+
ν_{nr}	65 687 511 047.0	47 279 387 818.4	57 349 439 952.4
ν_{α^2}	1 091 040.5	795 376.3	958 151.7
ν_{α^3}	−276 545.1	−200 278.0	−242 126.3
ν_{α^4}	−1952.0(1)	−1413.4(1)	−1708.9(1)
ν_{α^5}	121.8(1)	88.1(1)	106.4(1)
ν_{α^6}	−2.3(5)	−1.7(4)	−2.0(5)
$\nu_{\rm tot}$	65 688 323 710.1(5)(2.9)	47 279 981 589.8(4)(8)	57 350 154 373.4(5)(1.7)

Ab initio calculations in two-electron atoms



PHYSICAL REVIEW A **103**, 042809 (2021)

Complete $\alpha^7 m$ Lamb shift of helium triplet states

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(Received 1 March 2021; accepted 22 March 2021; published 5 April 2021)

We have derived the complete formula for the $\alpha^7 m$ contribution to energy levels of an arbitrary triplet state of the helium atom, performed numerical calculations for the $2\,^3S$ and $2\,^3P$ states, and thus improved the theoretical accuracy of ionization energies of these states by more than an order of magnitude. Using the nuclear charge radius extracted from the muonic helium Lamb shift, we obtain the theoretical prediction in excellent agreement with the measured $2\,^3S - 2\,^3P$ transition energy [X. Zheng *et al.*, Phys. Rev. Lett. **119**, 263002 (2017)]. At the same time, we observe significant discrepancies with experiments for the $2\,^3S - 3\,^3D$ and $2\,^3P - 3\,^3D$ transitions.

(about 50 kHz)

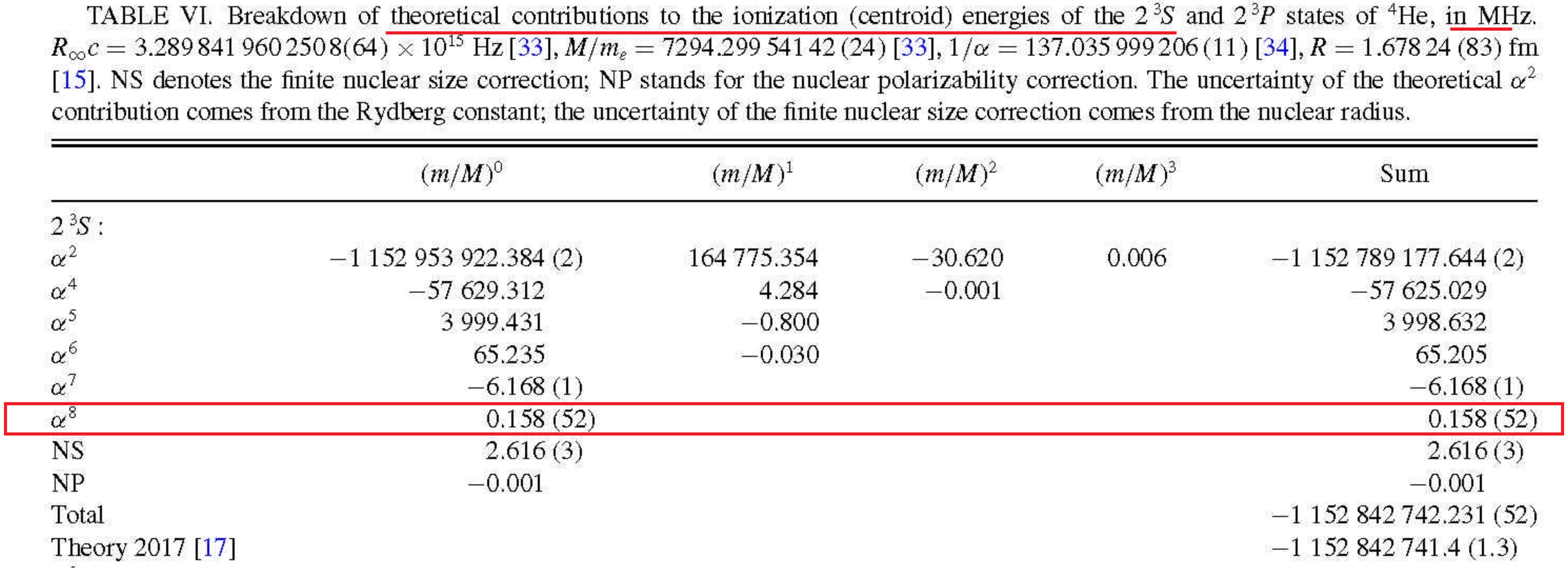
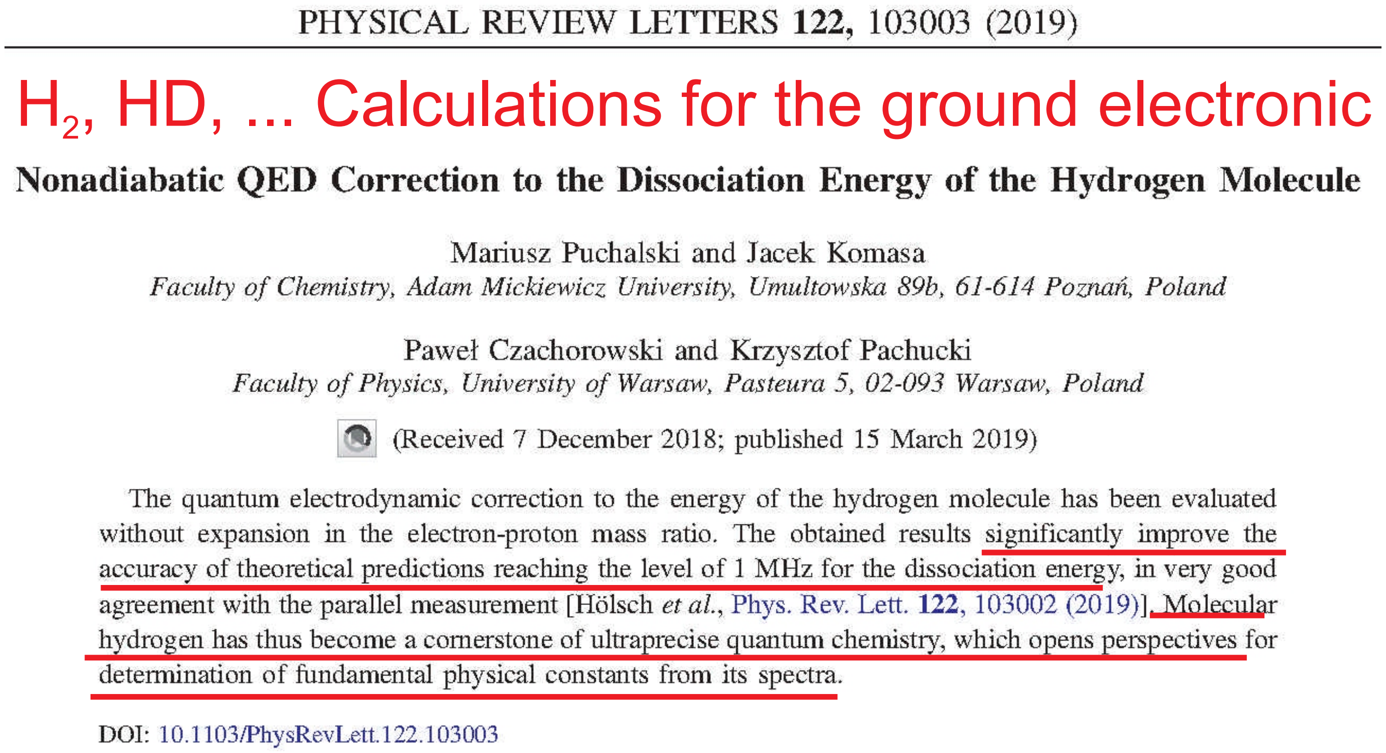


TABLE VI. Breakdown of theoretical contributions to the ionization (centroid) energies of the $2\,^3S$ and $2\,^3P$ states of ^{4}He, in MHz. $R_\infty c = 3.289\,841\,960\,250\,8(64) \times 10^{15}$ Hz [33], $M/m_e = 7294.299\,541\,42\,(24)$ [33], $1/\alpha = 137.035\,999\,206\,(11)$ [34], $R = 1.678\,24\,(83)$ fm [15]. NS denotes the finite nuclear size correction; NP stands for the nuclear polarizability correction. The uncertainty of the theoretical α^2 contribution comes from the Rydberg constant; the uncertainty of the finite nuclear size correction comes from the nuclear radius.

	$(m/M)^0$	$(m/M)^1$	$(m/M)^2$	$(m/M)^3$	Sum
$2\,^3S$:					
α^2	−1 152 953 922.384 (2)	164 775.354	−30.620	0.006	−1 152 789 177.644 (2)
α^4	−57 629.312	4.284	−0.001		−57 625.029
α^5	3 999.431	−0.800			3 998.632
α^6	65.235	−0.030			65.205
α^7	−6.168 (1)				−6.168 (1)
α^8	0.158 (52)				0.158 (52)
NS	2.616 (3)				2.616 (3)
NP	−0.001				−0.001
Total					−1 152 842 742.231 (52)
Theory 2017 [17]					−1 152 842 741.4 (1.3)

Calculations in two-electron molecules



PHYSICAL REVIEW LETTERS **122,** 103003 (2019)

H_2, HD, ... Calculations for the ground electronic state

Nonadiabatic QED Correction to the Dissociation Energy of the Hydrogen Molecule

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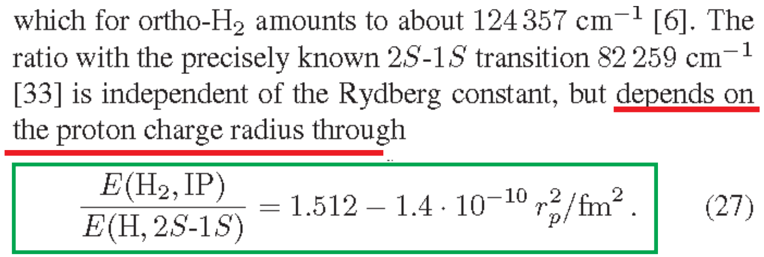
(Received 7 December 2018; published 15 March 2019)

The quantum electrodynamic correction to the energy of the hydrogen molecule has been evaluated without expansion in the electron-proton mass ratio. The obtained results significantly improve the accuracy of theoretical predictions reaching the level of 1 MHz for the dissociation energy, in very good agreement with the parallel measurement [Hölsch *et al.*, Phys. Rev. Lett. **122**, 103002 (2019)]. Molecular hydrogen has thus become a cornerstone of ultraprecise quantum chemistry, which opens perspectives for determination of fundamental physical constants from its spectra.

DOI: 10.1103/PhysRevLett.122.103003



which for ortho-H_2 amounts to about 124 357 cm^{-1} [6]. The ratio with the precisely known $2S$-$1S$ transition 82 259 cm^{-1} [33] is independent of the Rydberg constant, but depends on the proton charge radius through

$$\boxed{\frac{E(\mathrm{H}_2,\mathrm{IP})}{E(\mathrm{H},2S\text{-}1S)} = 1.512 - 1.4\cdot 10^{-10}\, r_p^2/\mathrm{fm}^2\,.} \qquad (27)$$

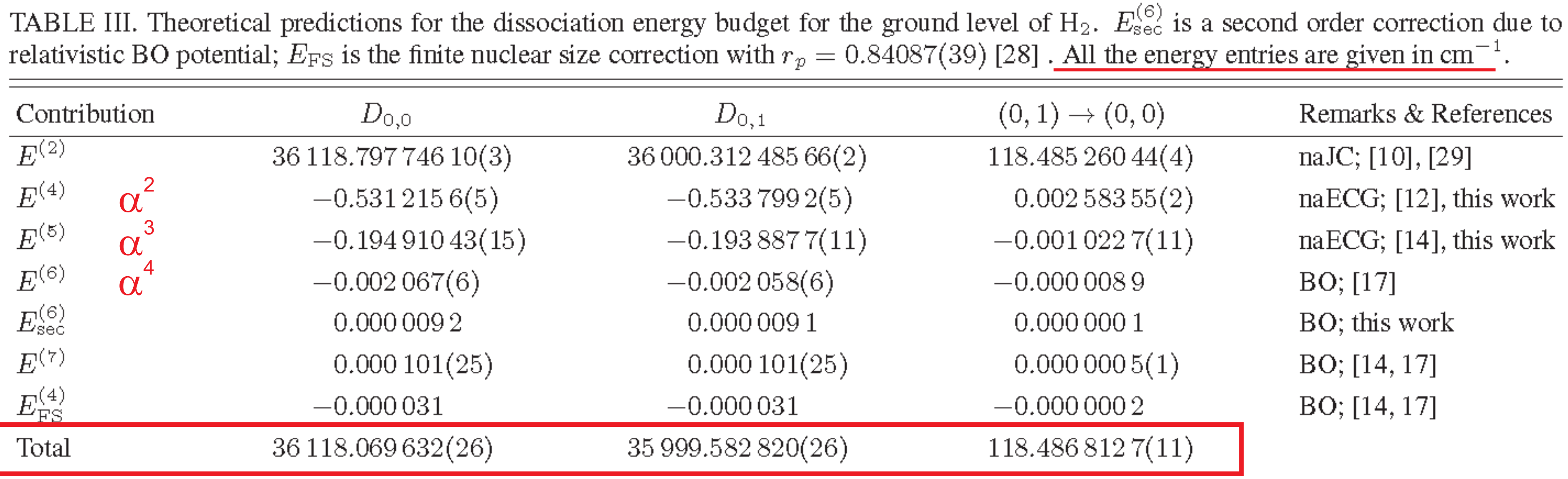
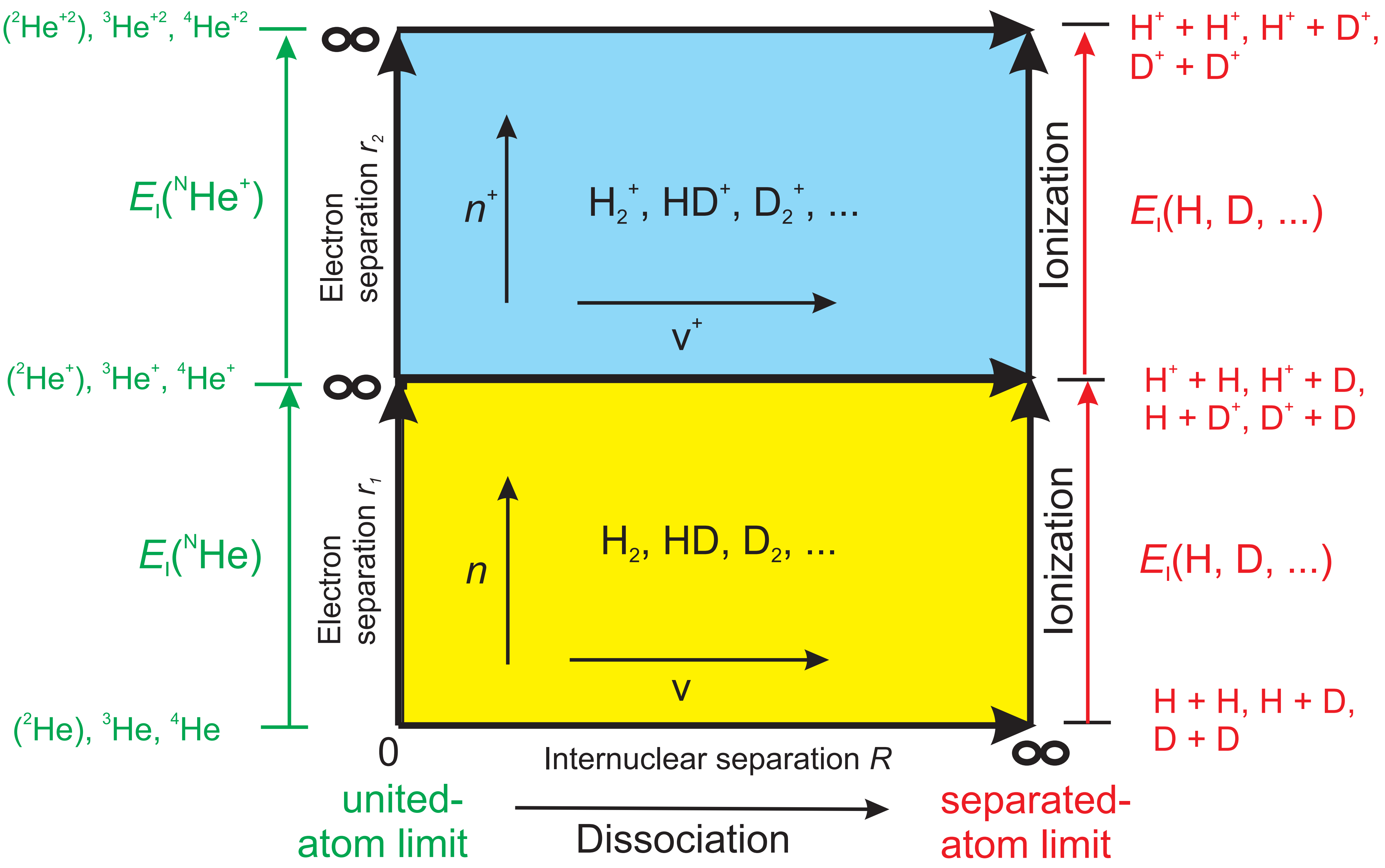


TABLE III. Theoretical predictions for the dissociation energy budget for the ground level of H_2. $E^{(6)}_{\text{sec}}$ is a second order correction due to relativistic BO potential; E_{FS} is the finite nuclear size correction with $r_p = 0.84087(39)$ [28] . All the energy entries are given in cm^{-1}.

Contribution		$D_{0,0}$	$D_{0,1}$	$(0,1) \to (0,0)$	Remarks & References
$E^{(2)}$		36 118.797 746 10(3)	36 000.312 485 66(2)	118.485 260 44(4)	naJC; [10], [29]
$E^{(4)}$	α^2	−0.531 215 6(5)	−0.533 799 2(5)	0.002 583 55(2)	naECG; [12], this work
$E^{(5)}$	α^3	−0.194 910 43(15)	−0.193 887 7(11)	−0.001 022 7(11)	naECG; [14], this work
$E^{(6)}$	α^4	−0.002 067(6)	−0.002 058(6)	−0.000 008 9	BO; [17]
$E^{(6)}_{\text{sec}}$		0.000 009 2	0.000 009 1	0.000 000 1	BO; this work
$E^{(7)}$		0.000 101(25)	0.000 101(25)	0.000 000 5(1)	BO; [14, 17]
$E^{(4)}_{\text{FS}}$		−0.000 031	−0.000 031	−0.000 000 2	BO; [14, 17]
Total		36 118.069 632(26)	35 999.582 820(26)	118.486 812 7(11)	

(about 1 MHz) (about 30 kHz)

Connection between one- and two-electron atoms and molecules



$(^{2}\mathrm{He}^{+2})$, $^{3}\mathrm{He}^{+2}$, $^{4}\mathrm{He}^{+2}$

$E_{\mathrm{I}}(^{N}\mathrm{He}^{+})$

$(^{2}\mathrm{He}^{+})$, $^{3}\mathrm{He}^{+}$, $^{4}\mathrm{He}^{+}$

$E_{\mathrm{I}}(^{N}\mathrm{He})$

$(^{2}\mathrm{He})$, $^{3}\mathrm{He}$, $^{4}\mathrm{He}$

∞

Electron separation r_2

n^{+}

H_2^{+}, HD^{+}, D_2^{+}, ...

v^{+}

∞

Electron separation r_1

n

H_2, HD, D_2, ...

v

0

Internuclear separation R

∞

Ionization

Ionization

$H^{+} + H^{+}$, $H^{+} + D^{+}$,
$D^{+} + D^{+}$

E_{I}(H, D, ...)

H^{+} + H, H^{+} + D,
H + D^{+}, D^{+} + D

E_{I}(H, D, ...)

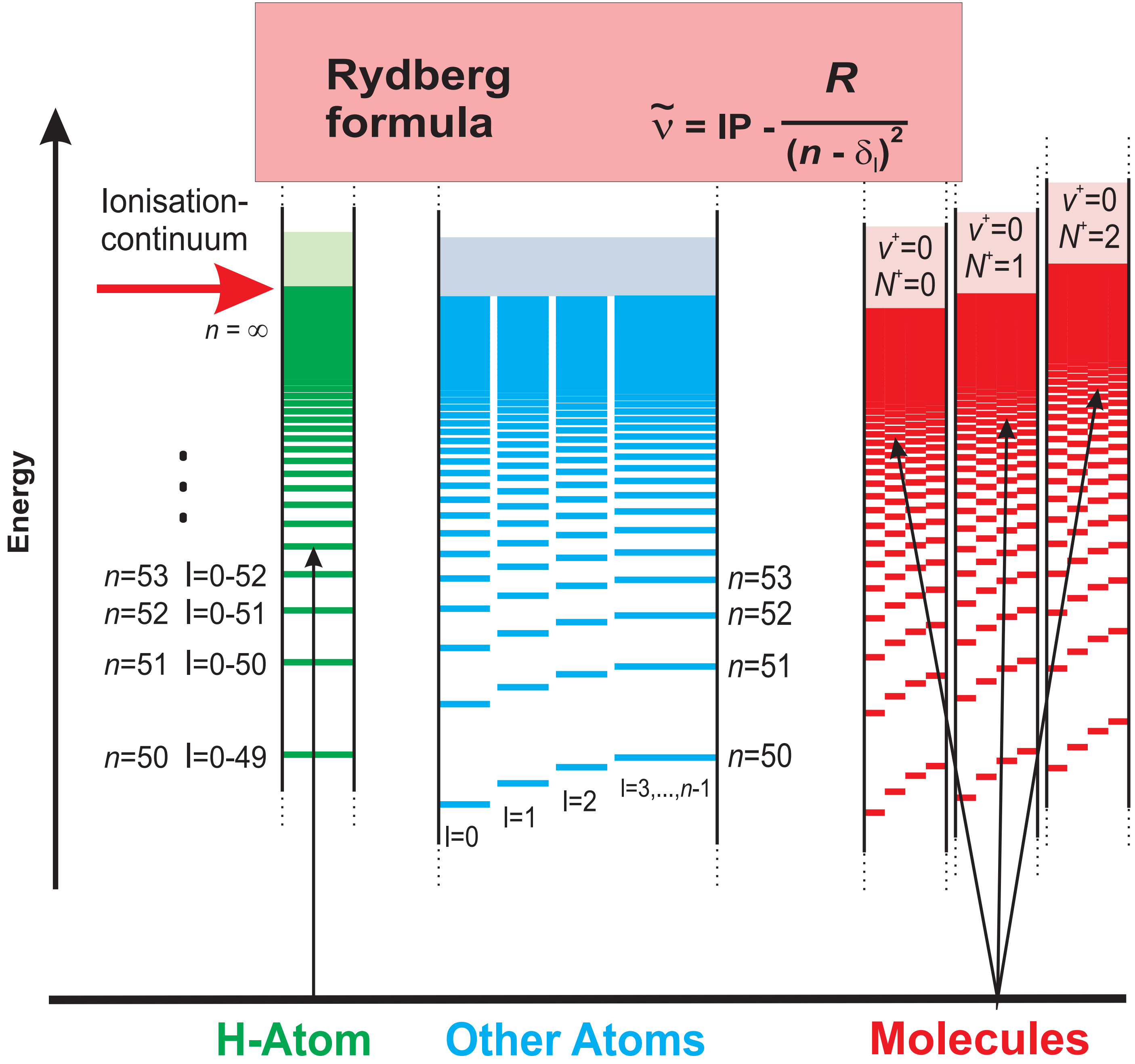
H + H, H + D,
D + D

united-
atom limit

Dissociation

separated-
atom limit

II. Experimental approach: Rydberg-series extrapolation



Rydberg formula

$$\tilde{\nu} = \mathbf{IP} - \frac{\boldsymbol{R}}{(\boldsymbol{n} - \delta_l)^2}$$

- Cold samples
- Supersonic beams
- cw lasers
- frequency combs
- ultrahigh vacuum
- resonant multi-photon excitation

Properties of Rydberg states

Property	**n-dependence**	**n=100**
Classical radius	$a_0 n^2$	0.5 µm
Binding energy	$-R n^{-2}$	1.3 meV ~11 cm^{-1}
Ionisation field (V/cm)	$\propto n^{-4}$	2.5 V/cm
Radiative lifetime		> 100 µs
Max. Induced dipole moment	$e a_0 n^2$	30’000 Debye

Further properties:

Spacing between neighboring states of a series: $\propto n^3$

Resonant dipole-dipole interaction: $\propto n^4$

Polarisability: $\propto n^7$

Van der Waals interaction: $\propto n^{11}$

Rydberg states: From atoms to molecules

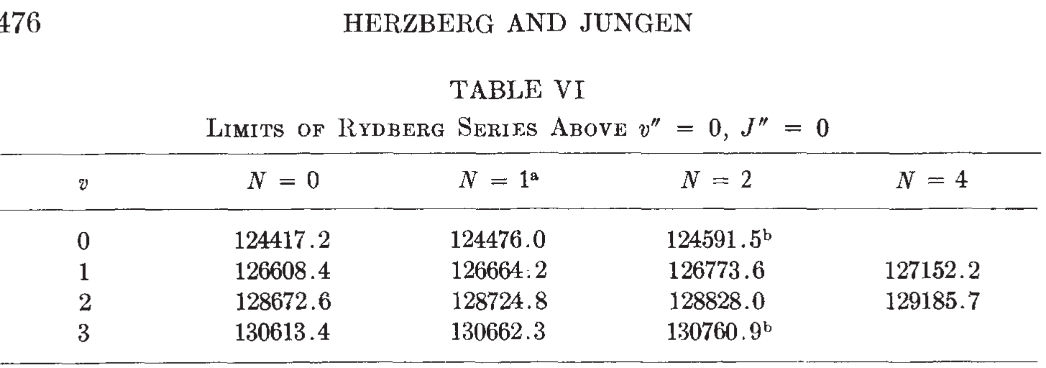


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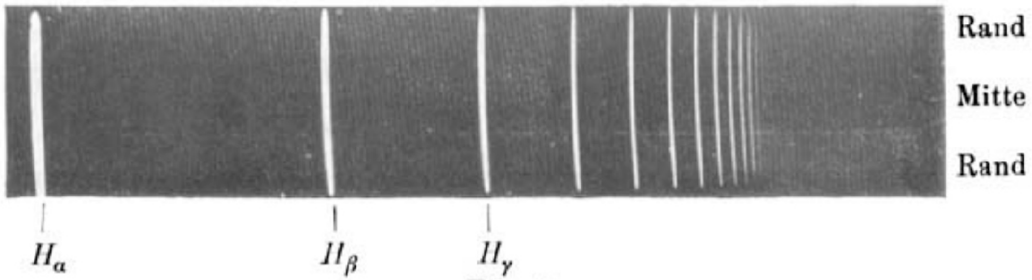
TABLE VI

Limits of Rydberg Series Above $v'' = 0$, $J'' = 0$

v	$N = 0$	$N = 1^a$	$N = 2$	$N = 4$
0	124417.2	124476.0	124591.5^b	
1	126608.4	126664.2	126773.6	127152.2
2	128672.6	128724.8	128828.0	129185.7
3	130613.4	130662.3	130760.9^b	

(Precision: about 30 GHz)

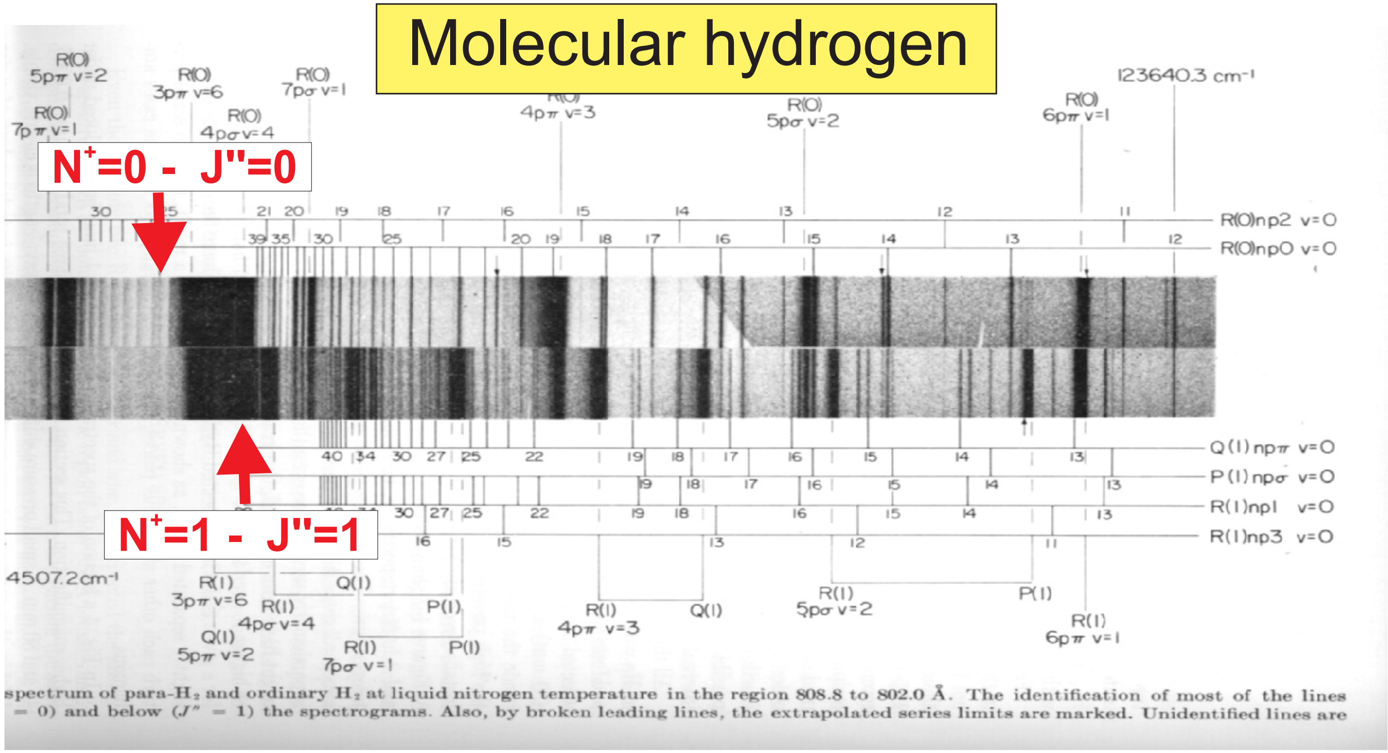
Atomic hydrogen



G. Herzberg, Ann. Phys. 84, 565 (1927)

G. Herzberg

Molecular hydrogen

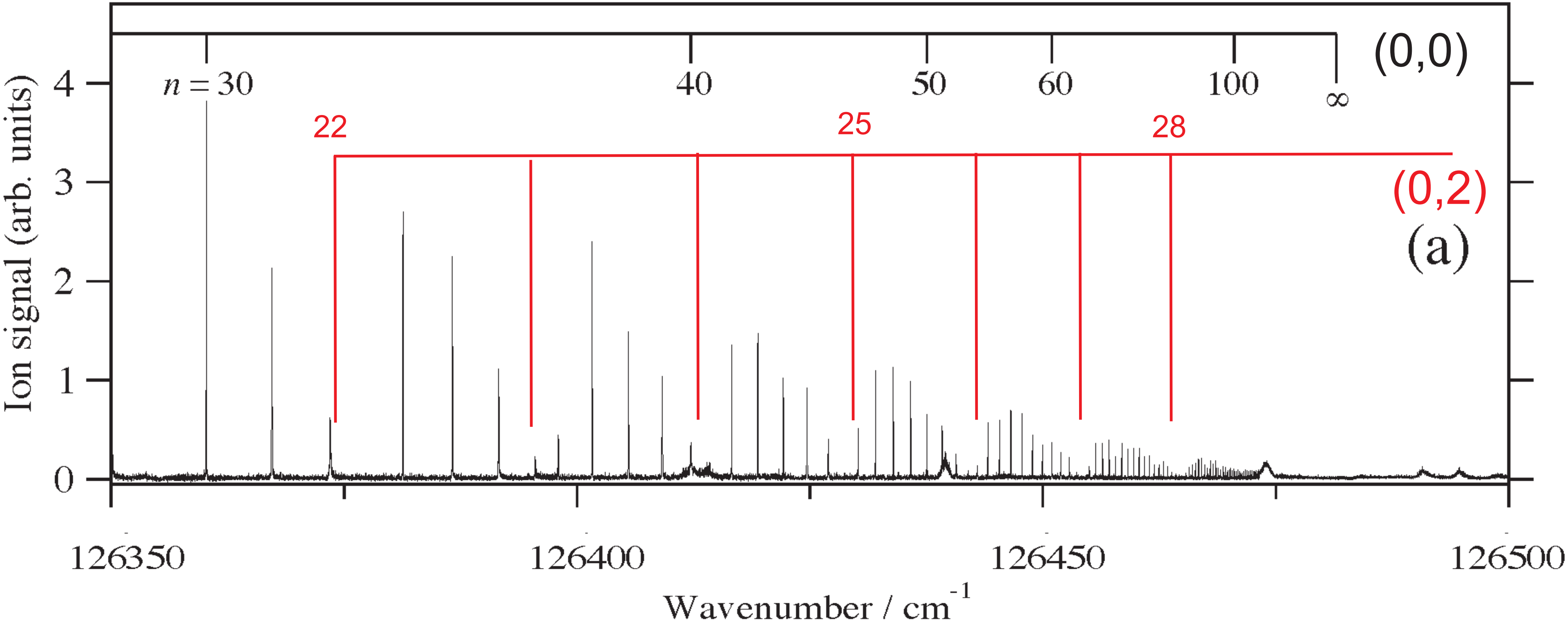


spectrum of para-H_2 and ordinary H_2 at liquid nitrogen temperature in the region 808.8 to 802.0 Å. The identification of most of the lines = 0) and below ($J'' = 1$) the spectrograms. Also, by broken leading lines, the extrapolated series limits are marked. Unidentified lines are

Extrapolation by multichannel quantum defect theory

G. Herzberg and Ch. Jungen, J. Mol. Spec. 41, 425 (1972)

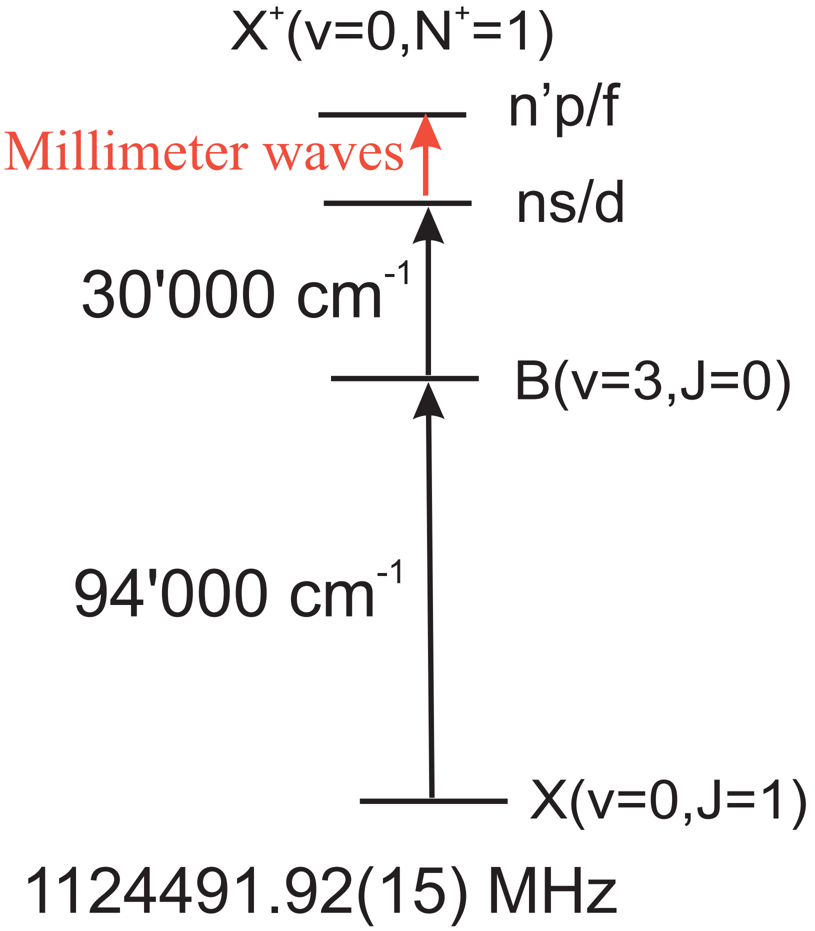
The Rydberg spectrum of HD (X $^1\Sigma_g^+$ (v=0,N=0) ⟶ np[X$^+$ $^2\Sigma_g^+$ (v=0,N=0,2)]



Rydberg-state binding energy by millimeter-wave spectroscopy

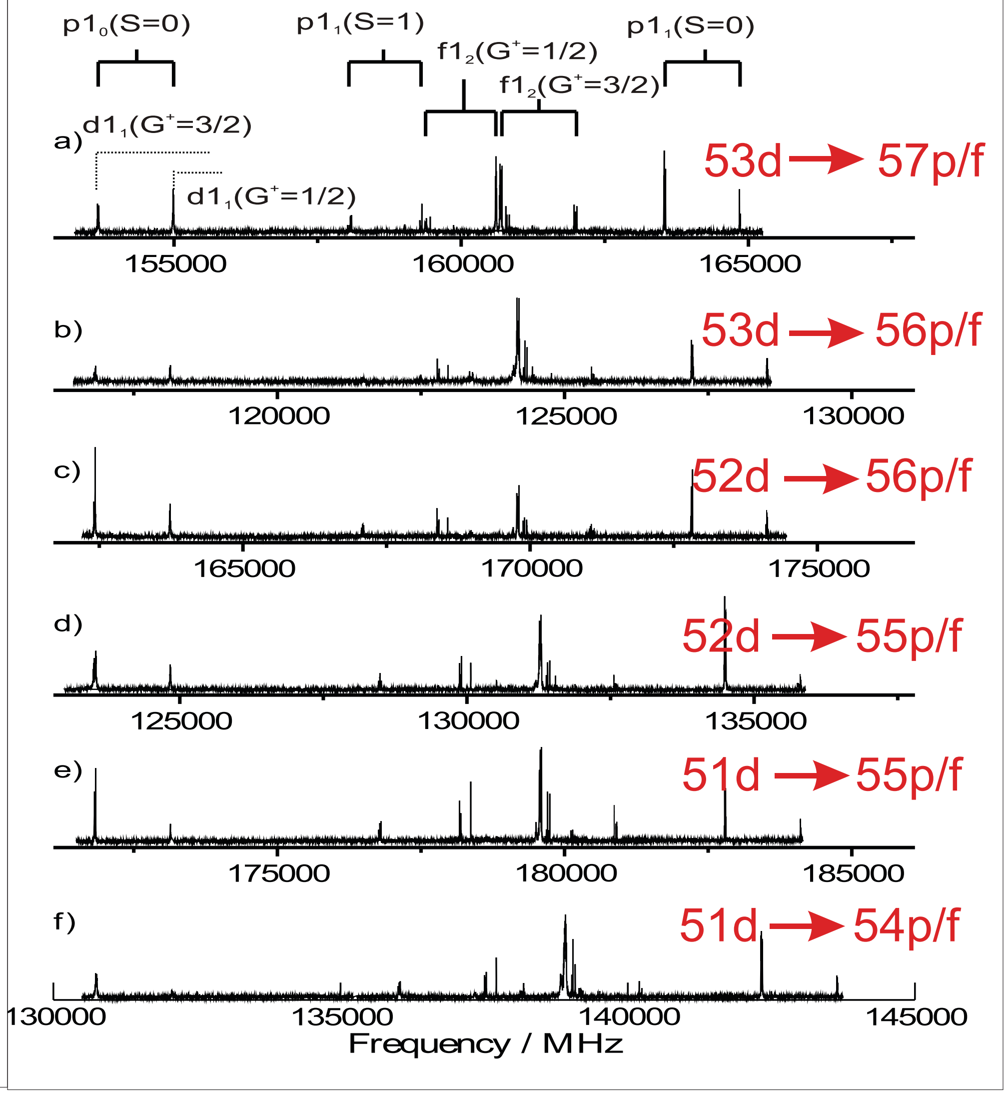
E_b(56p1)= 34.881'112(10) cm^{-1}

Accuracy: about 300 kHz



Gerade states

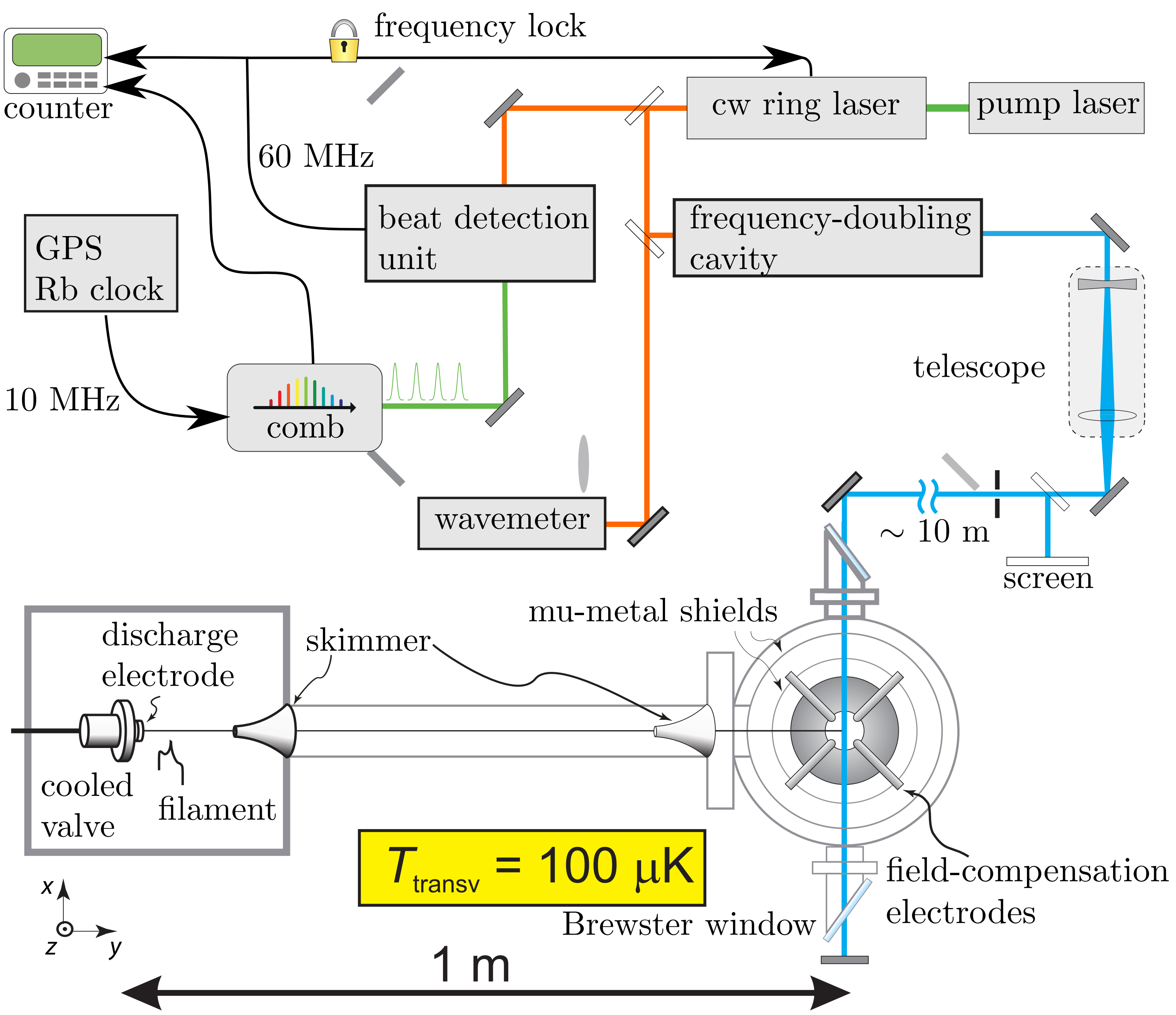
Metastable series: nd(N^+=1,N=1) ⟶ np/ nf



34.881'112(10) cm^{-1}

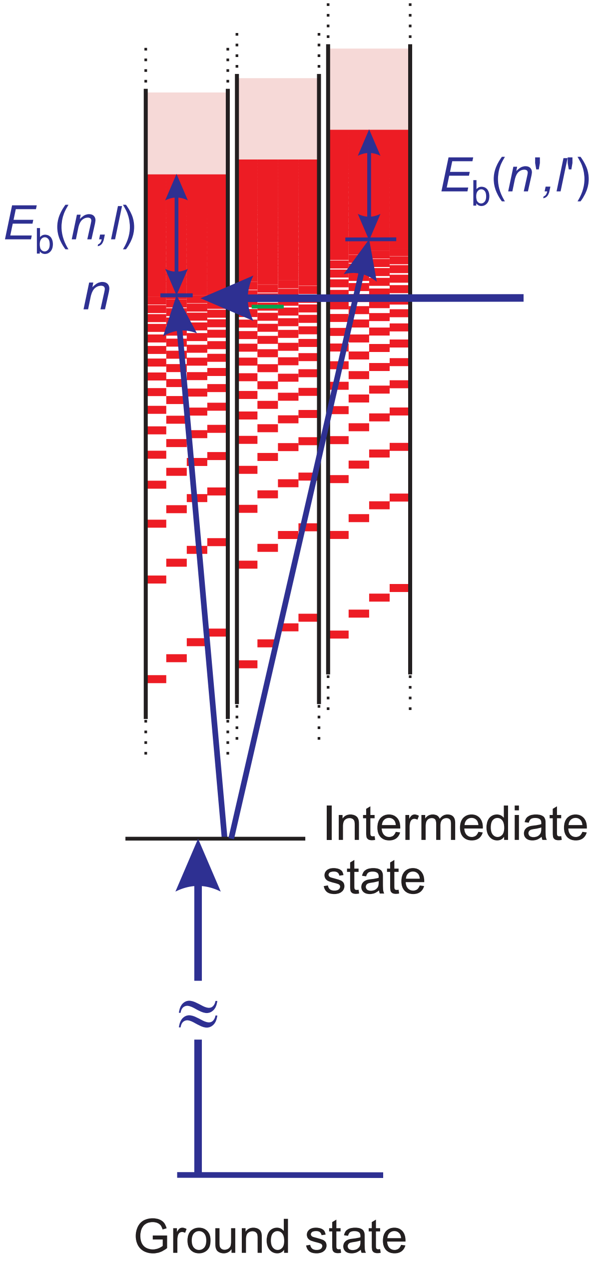
Osterwalder, Wüest, FM, Jungen, JCP **121**, 11810 (2004)
Sprecher, Jungen, FM, JCP **140**, 104303 (2014)

Experimental setup



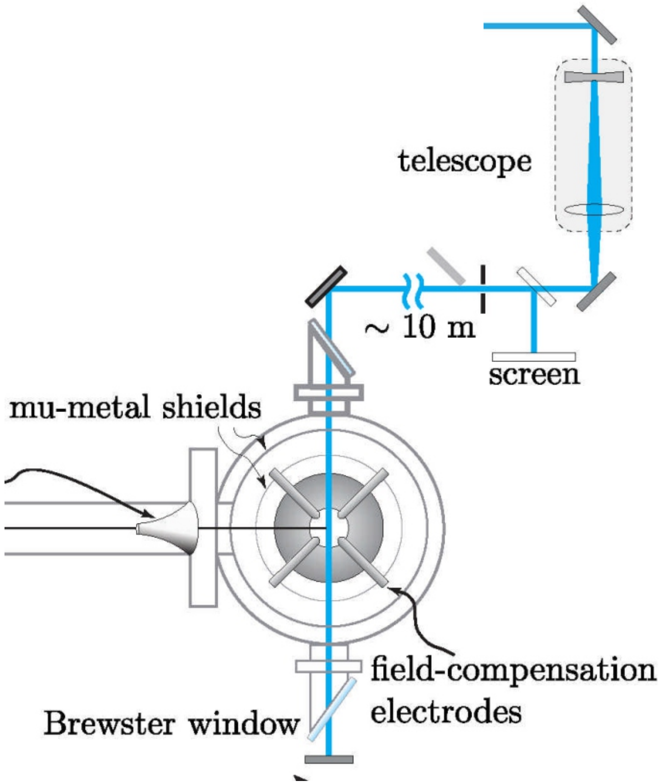
frequency lock
counter
60 MHz
cw ring laser
pump laser
beat detection unit
frequency-doubling cavity
GPS Rb clock
10 MHz
comb
telescope
wavemeter
~ 10 m
screen
mu-metal shields
skimmer
discharge electrode
cooled valve
filament
field-compensation electrodes
Brewster window
x
z
y
1 m

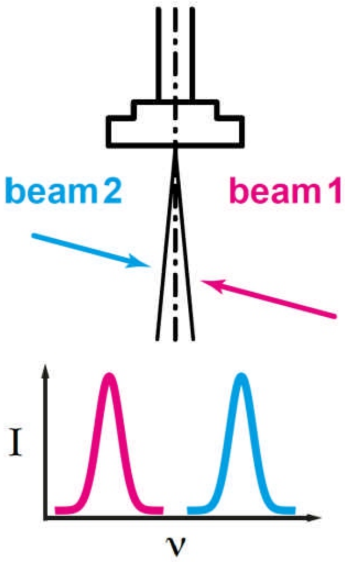
$T_{\text{transv}} = 100\ \mu\text{K}$

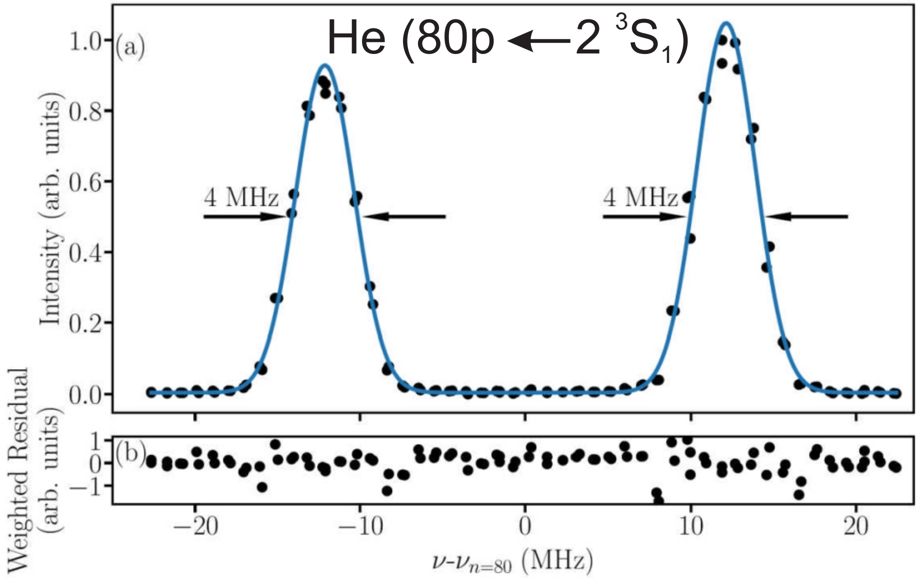


$E_b(n,l)$
n
$E_b(n',l')$
Intermediate state
≈
Ground state

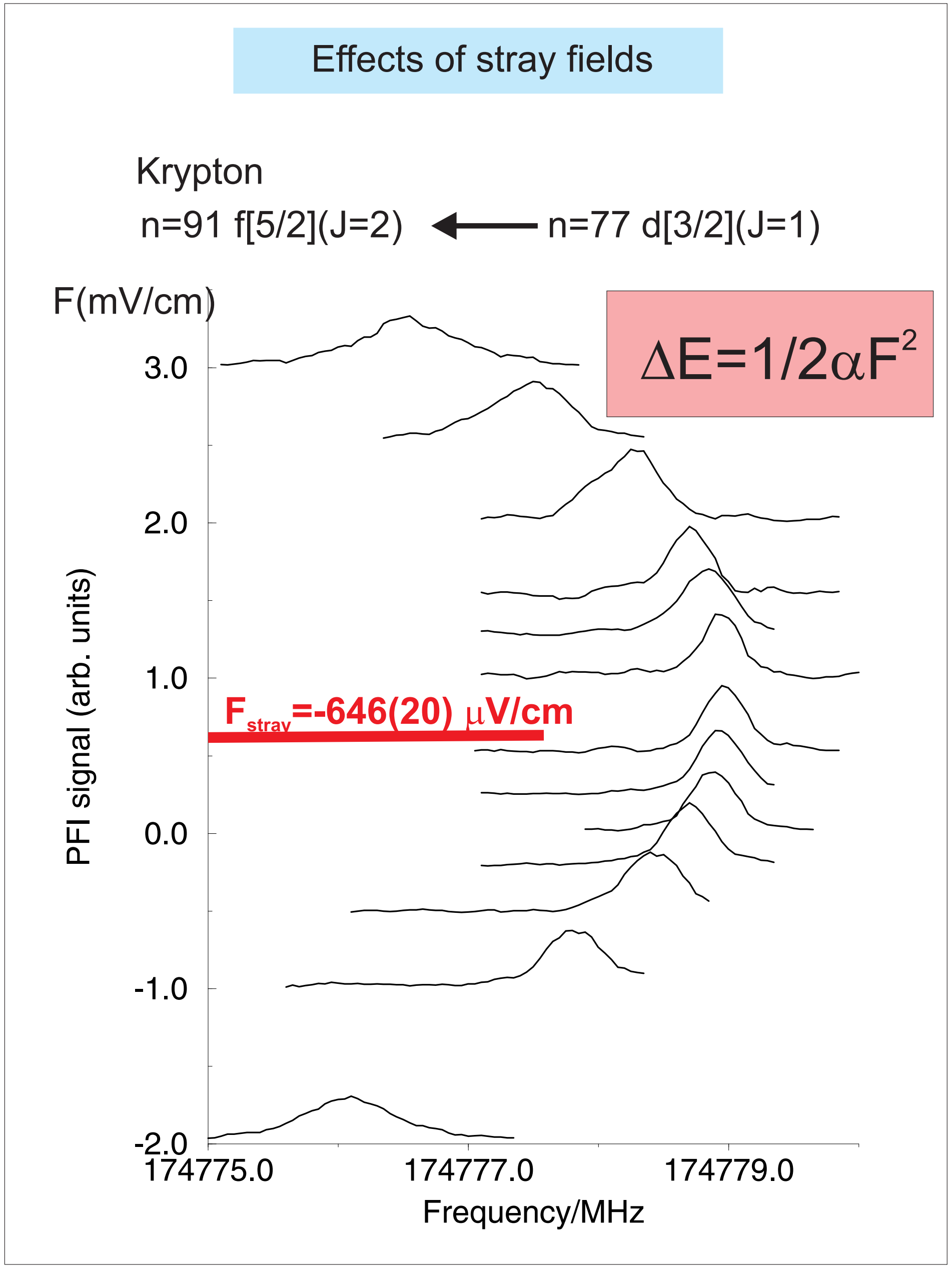
Doppler effect





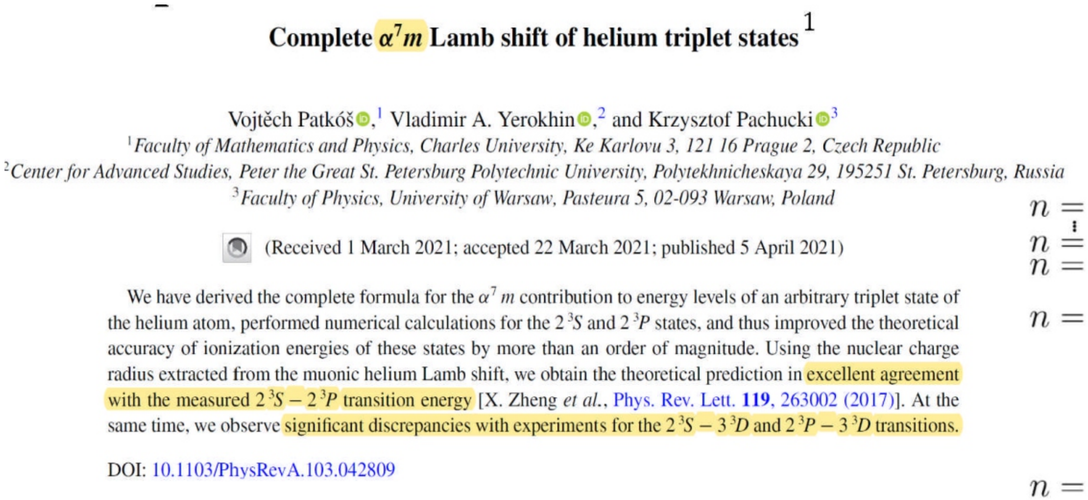


Field compensation



$$\Delta E = 1/2\alpha F^2$$

III. The ionization energy of metastable helium



Complete $\alpha^7 m$ Lamb shift of helium triplet states 1

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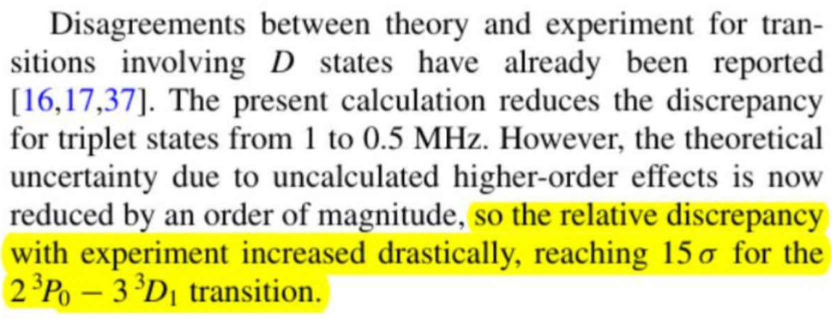
(Received 1 March 2021; accepted 22 March 2021; published 5 April 2021)

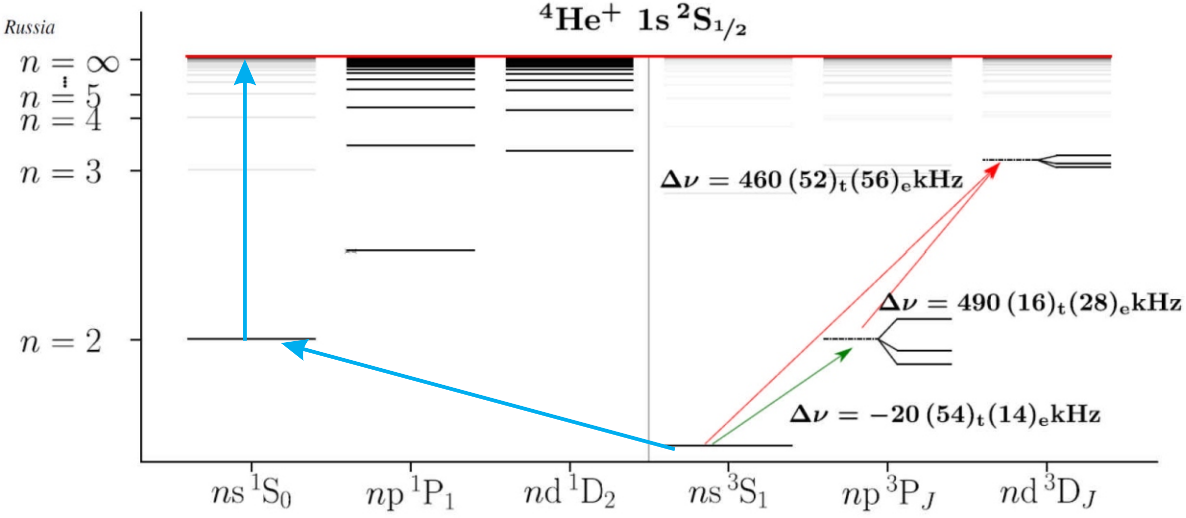
We have derived the complete formula for the $\alpha^7 m$ contribution to energy levels of an arbitrary triplet state of the helium atom, performed numerical calculations for the $2\,{}^3S$ and $2\,{}^3P$ states, and thus improved the theoretical accuracy of ionization energies of these states by more than an order of magnitude. Using the nuclear charge radius extracted from the muonic helium Lamb shift, we obtain the theoretical prediction in excellent agreement with the measured $2\,{}^3S - 2\,{}^3P$ transition energy [X. Zheng *et al.*, Phys. Rev. Lett. **119**, 263002 (2017)]. At the same time, we observe significant discrepancies with experiments for the $2\,{}^3S - 3\,{}^3D$ and $2\,{}^3P - 3\,{}^3D$ transitions.

DOI: 10.1103/PhysRevA.103.042809



Disagreements between theory and experiment for transitions involving D states have already been reported [16,17,37]. The present calculation reduces the discrepancy for triplet states from 1 to 0.5 MHz. However, the theoretical uncertainty due to uncalculated higher-order effects is now reduced by an order of magnitude, so the relative discrepancy with experiment increased drastically, reaching $15\,\sigma$ for the $2\,{}^3P_0 - 3\,{}^3D_1$ transition.

$$E(\alpha) = \alpha^2 m E^{(2)} + \alpha^4 m E^{(4)} + \alpha^5 m E^{(5)} + \alpha^6 m E^{(6)} + \cdots$$



$2\,{}^3S$–$3\,{}^3D_1$

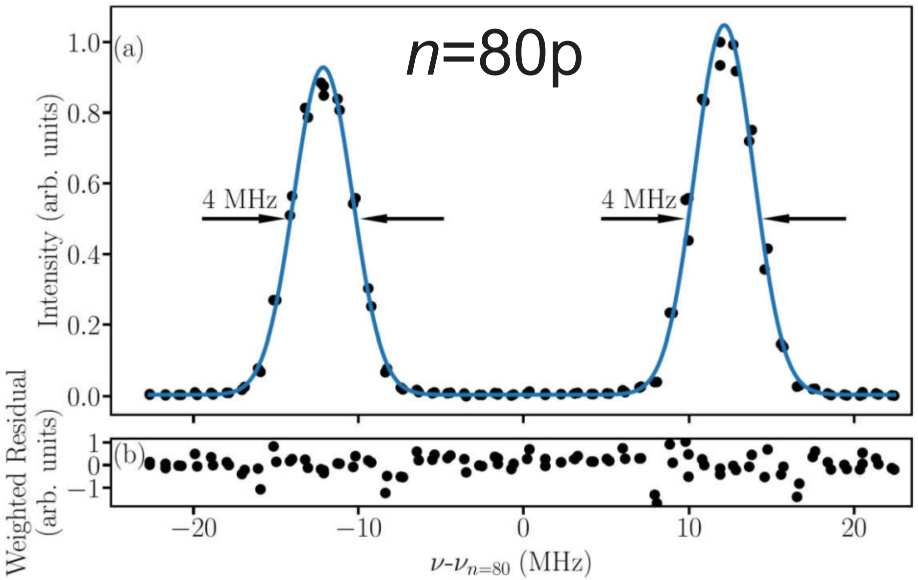
$\nu_{exp} = 786\,823\,850.002\,(56)$ MHz

$\nu_{calc.} = 786\,823\,849.540\,(52)$ MHz

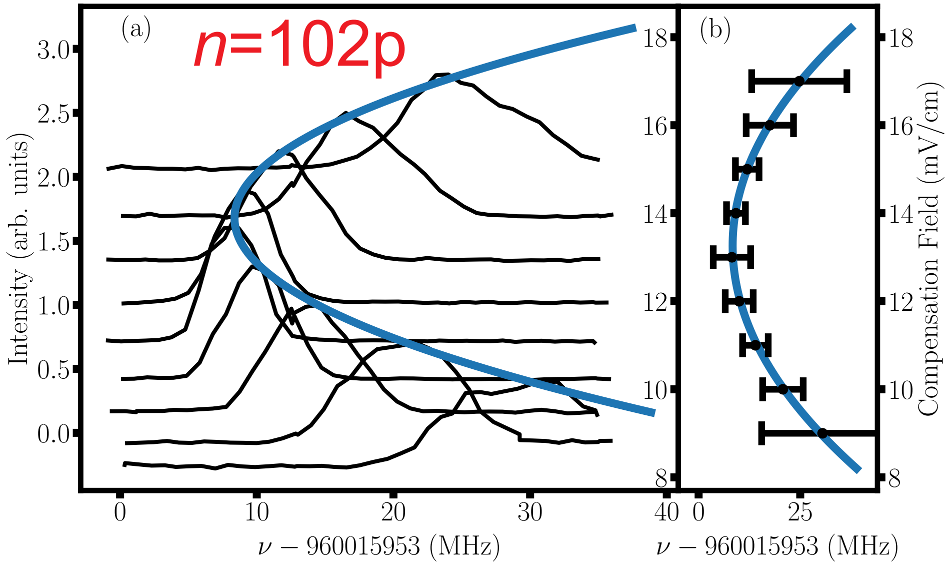
$\nu_{exp} - \nu_{calc} = 460(76)$ kHz

Patkóš et al., PRA 103, 042809 (2021)

Statistical and systematic errors



Stark effect



$$2\,^1\mathbf{S_0}\; E_\mathrm{I}/h = 960\,332\,040.491(0.025)_\mathrm{stat}(0.020)_\mathrm{syst}\quad \mathrm{MHz}$$

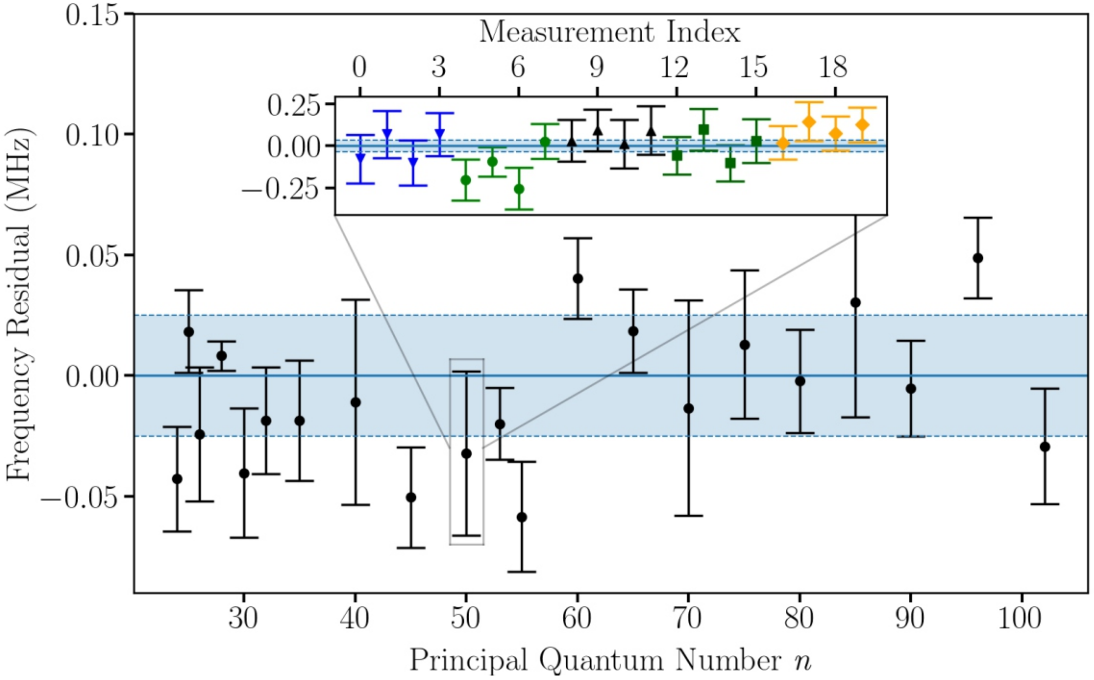


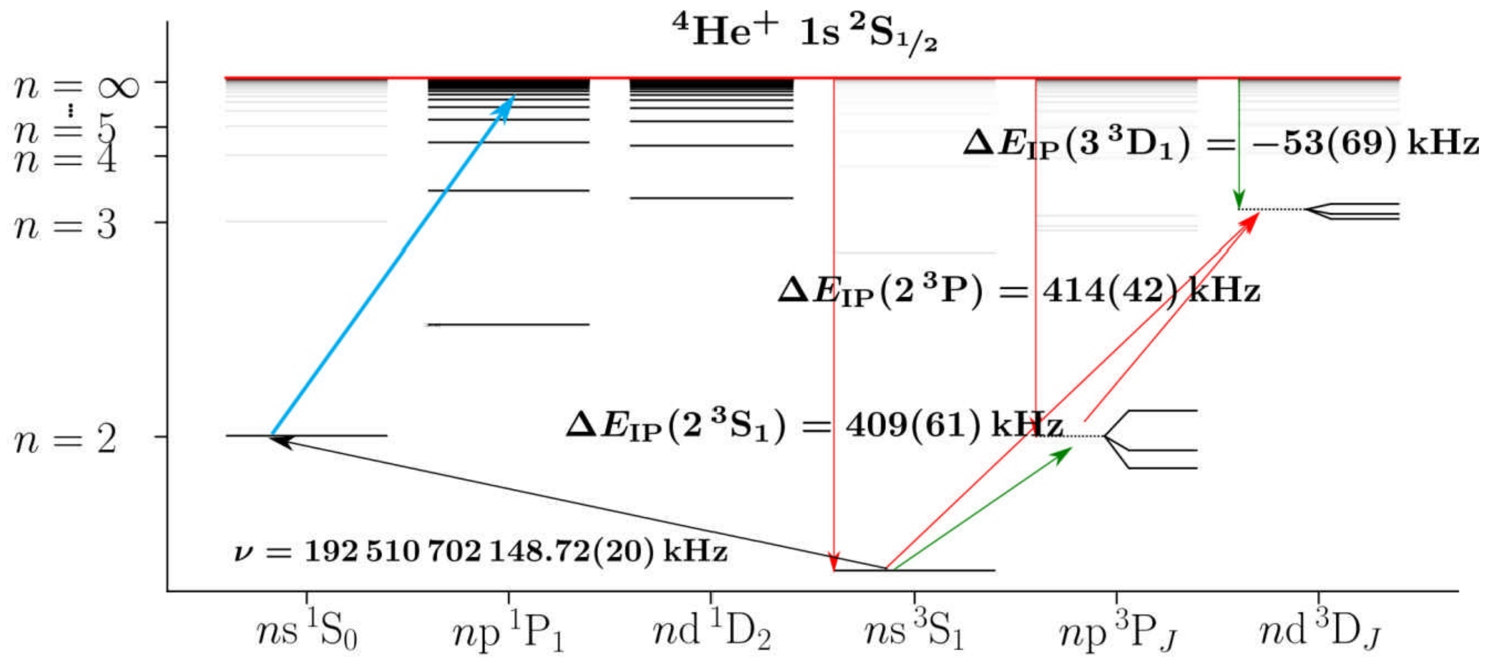
Table II. Overview of systematic shifts and systematic and statistical uncertainties.

Source	Shift	Uncertainty
Systematic		
Pressure Shift		< 0.8 kHz
DC-Stark Shift	accounted for in model	
AC-Stark Shift		< 5 kHz
2^nd Order Doppler Shift	−1.33 kHz	150 Hz
Photon-Recoil Shift	506 kHz	
Frequency Calibration		19 kHz
σ_syst		< 20 kHz
Statistics		
1^st Order Doppler Shift		25 kHz
σ_stat		25 kHz

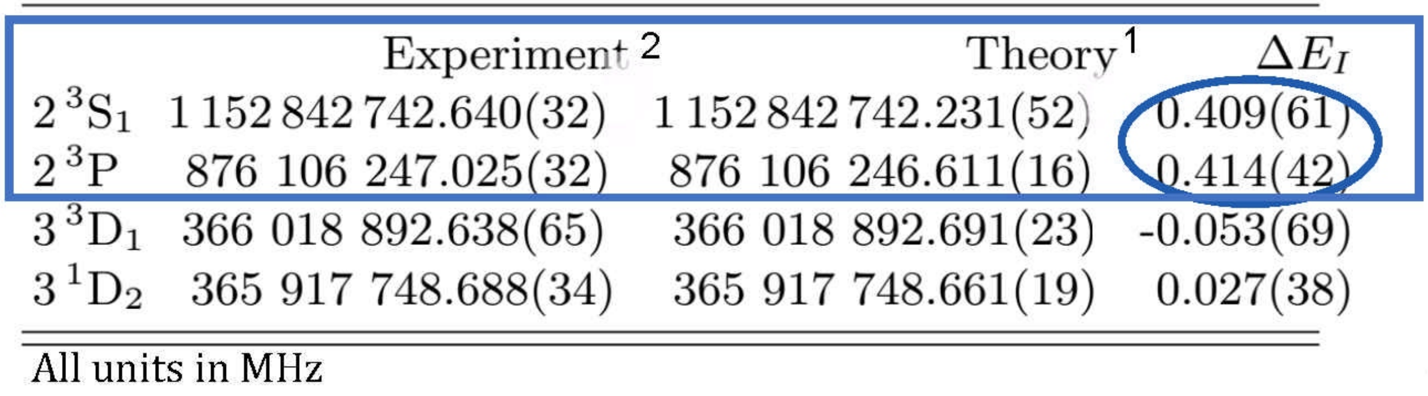
→ Final total uncertainty of 32 kHz (3×10^{-11} level

From Clausen *et al.*, PRL **127**, 093001 (2021)

Comparison experiment - theory



10σ discrepancy



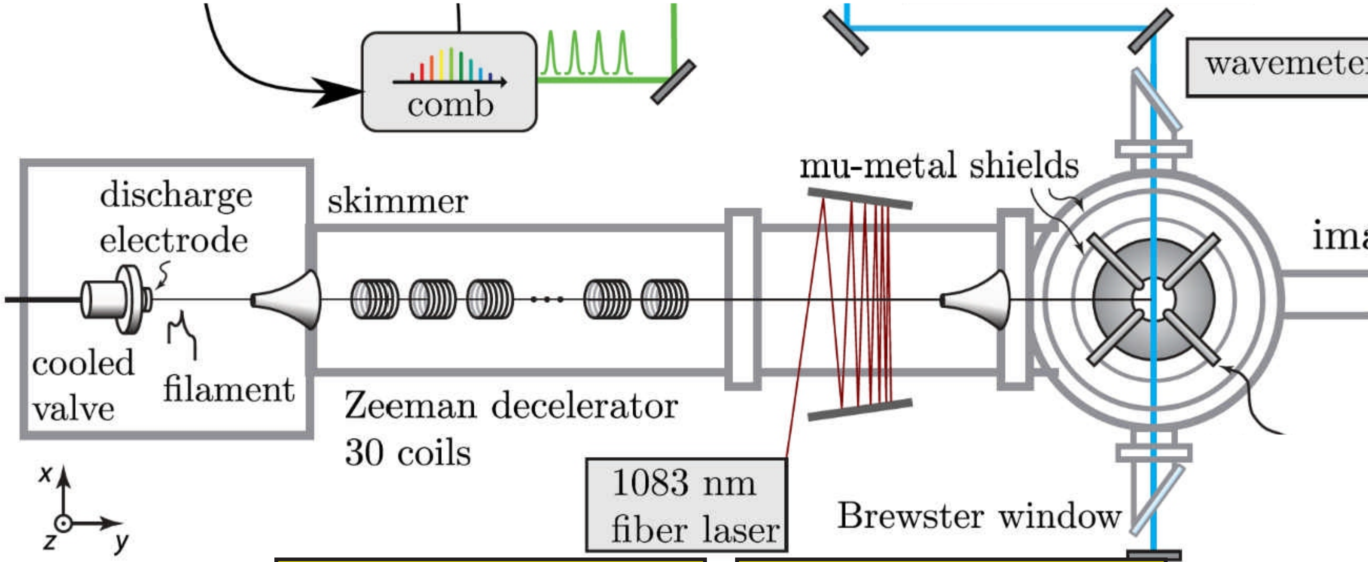
	Experiment[2]	Theory[1]	ΔE_I
$2\,^3\mathrm{S}_1$	1 152 842 742.640(32)	1 152 842 742.231(52)	0.409(61)
$2\,^3\mathrm{P}$	876 106 247.025(32)	876 106 246.611(16)	0.414(42)
$3\,^3\mathrm{D}_1$	366 018 892.638(65)	366 018 892.691(23)	-0.053(69)
$3\,^1\mathrm{D}_2$	365 917 748.688(34)	365 917 748.661(19)	0.027(38)

All units in MHz

[1] Patkóš *et al.*, PRA **103**, 042809 (2021)

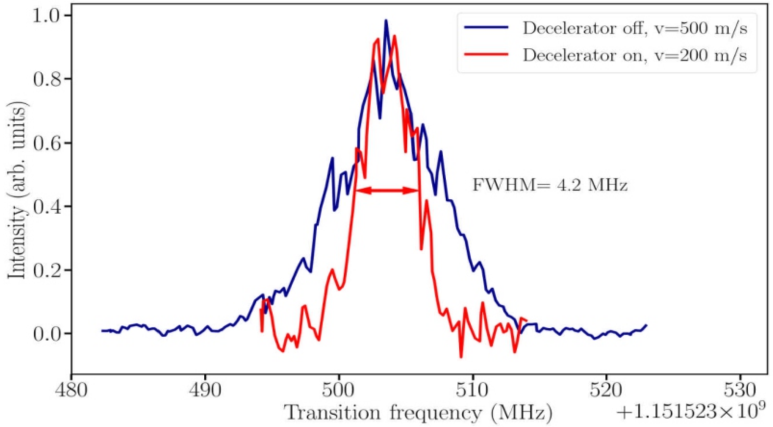
[2] Clausen *et al.*, PRL **127**, 093001 (2021)

Check the experiment with new measurement in He 2s $^3S_1$

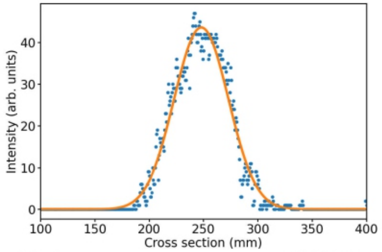


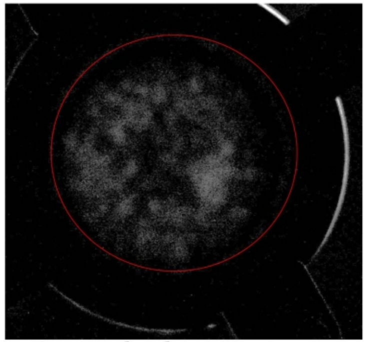
Zeeman deceleration

Transverse laser cooling

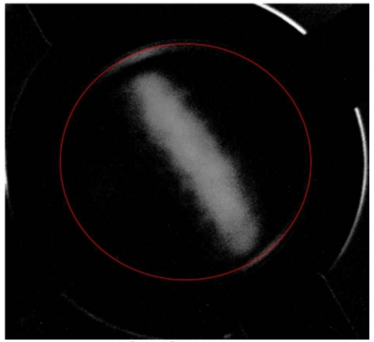


MCP Images

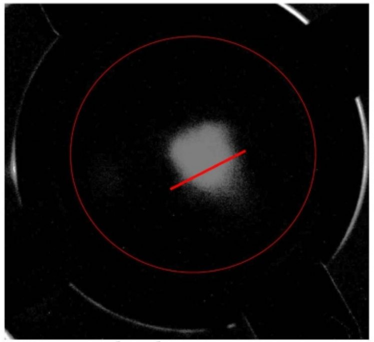




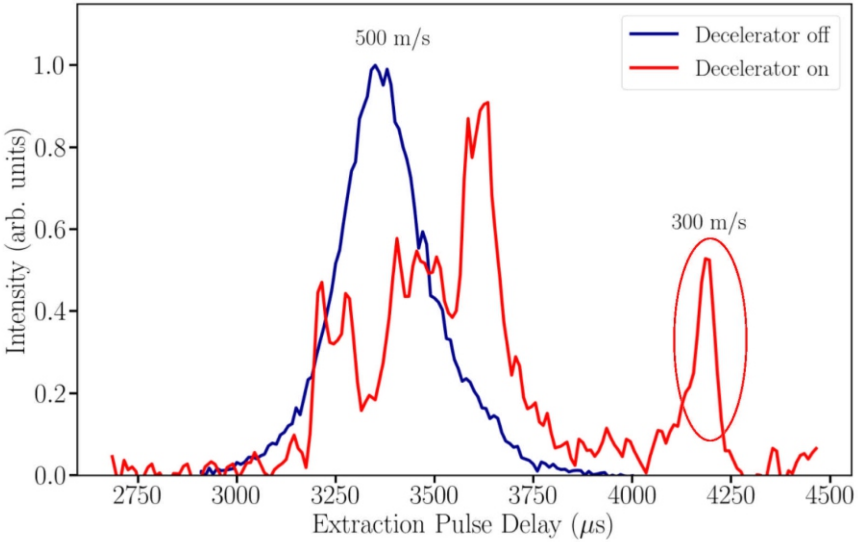
Zeeman deceleration on
Laser cooling off



Zeeman deceleration on
Laser cooling on one direction



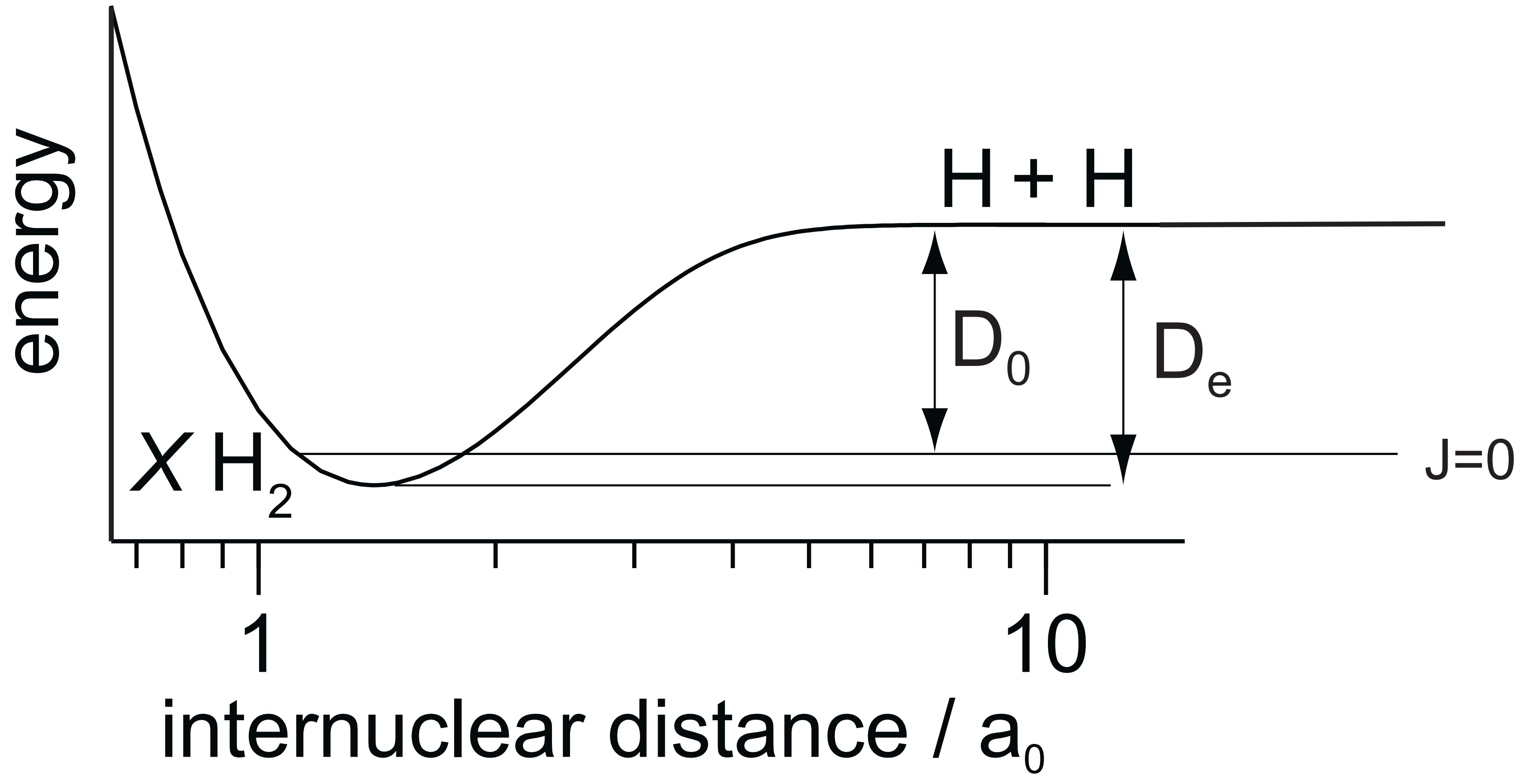
Zeeman deceleration on
Laser cooling on



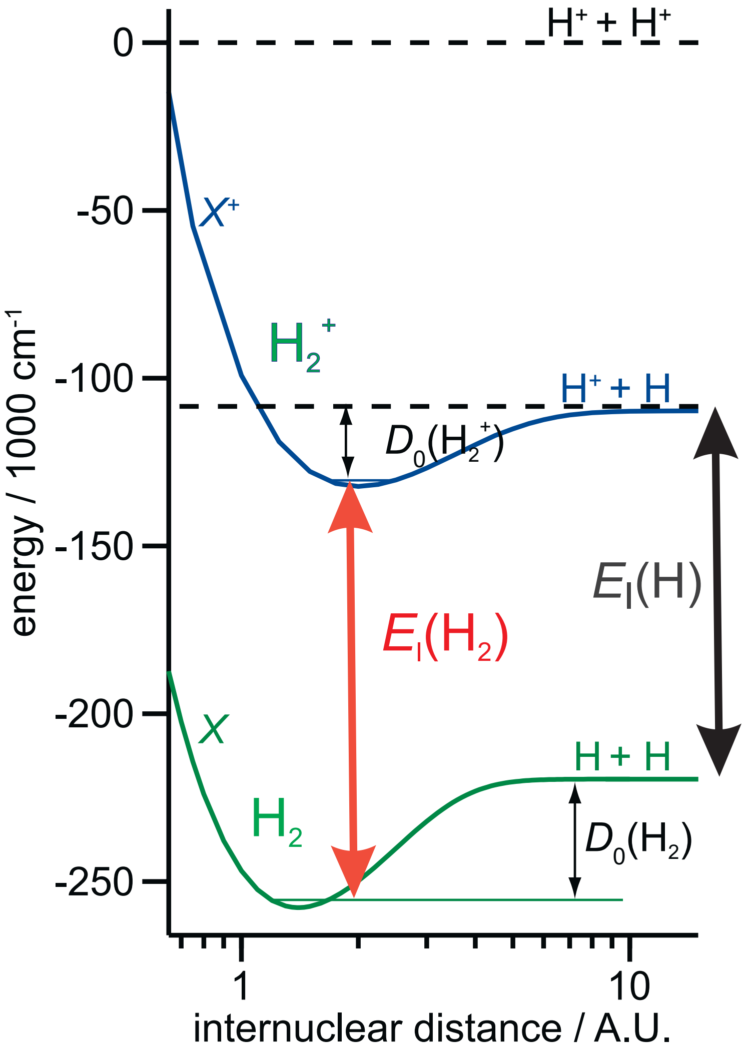
IV. The ionization and dissociation energies of H_2

D_0: Minimal energy required to break a molecule in its energetic ground state into two fragment, both in the energetic ground state

D_e: Energy difference between the dissociation limit and the minimum energy of the Born-Oppenheimer potential function



Ionization and dissociation energies of H_2



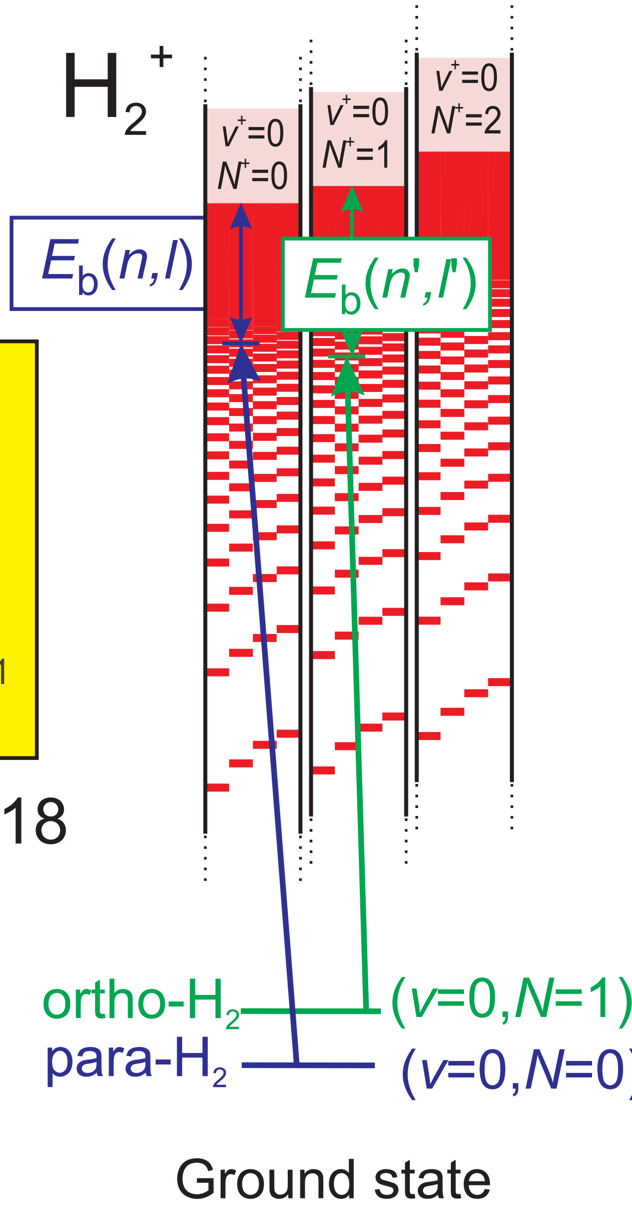
Measure ionization energy

$$D_o(H_2) = E_I(H_2) + D_o^+(H_2^+) - E_I(H)$$

$D_o^+(H_2^+)$: 21'379.350'249'6(6) cm^{-1}

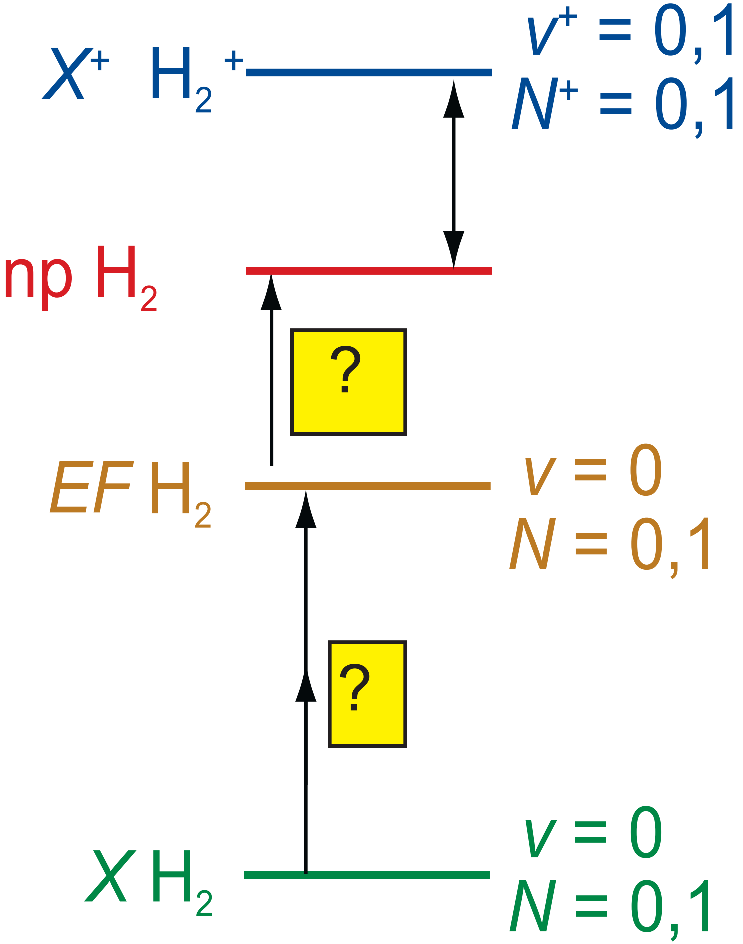
$E_I(H)$ = 109'678.771'743'07(10) cm^{-1}

CODATA 2006/2014/2018



The ionization energies of para and ortho H_2

Frequency combs, cw lasers, supersonic beams
Calibration: Rb GPS reference



Extrapolation $\Delta\nu = 300$ kHz

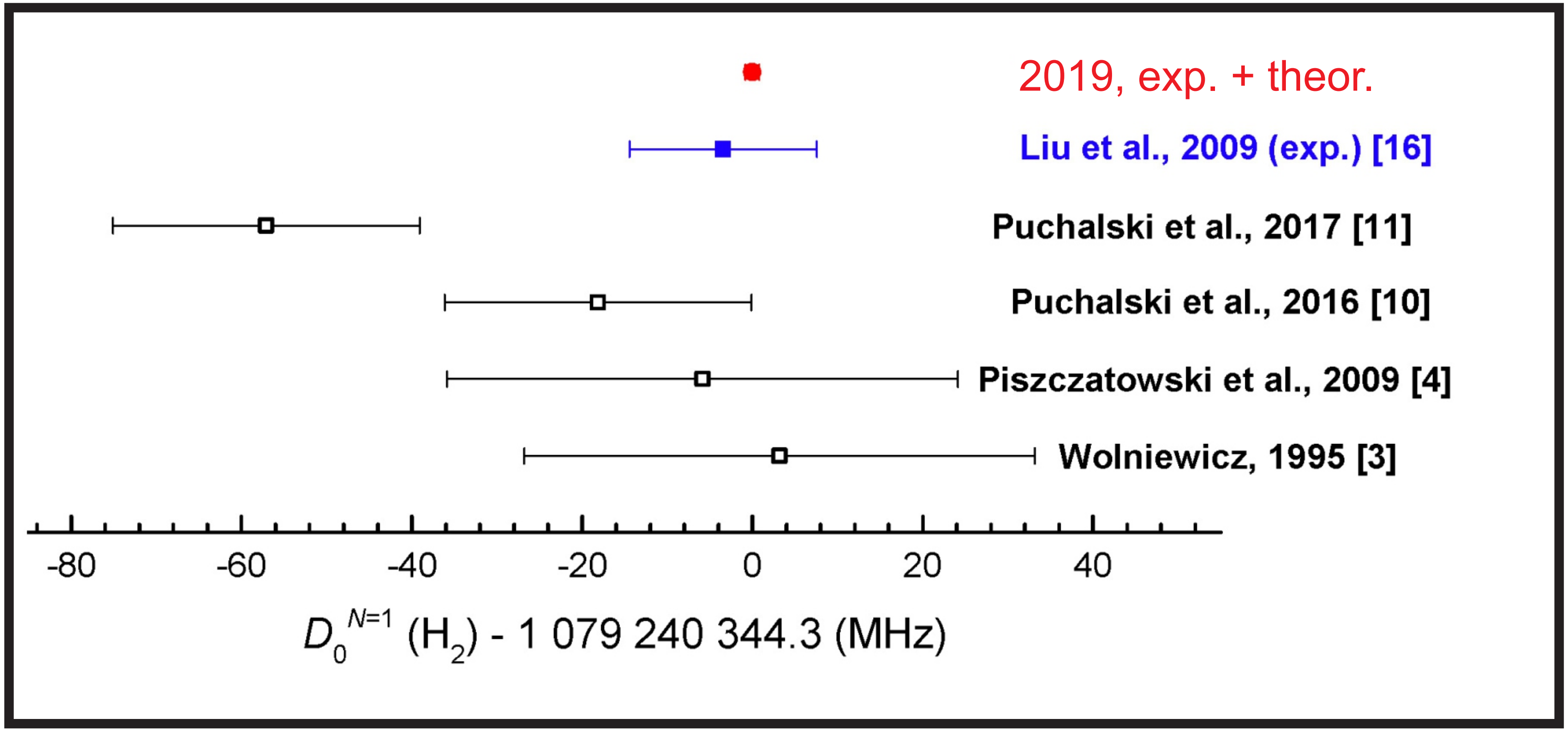
Zurich: single-photon, Doppler-limited, cw lasers $\Delta\nu = 150$ kHz[1]

[1] Hölsch et al., PRL **122**, 013001 (2019)

Amsterdam: Ramsey-comb, two-photon, Doppler-free $\Delta\nu = 75$ kHz[2,]
31 kHz[3]

[2] Altmann et al., PRL **120**, 043204 (2018)
[3] PREN2022 Talk by Elmer Gründeman

The dissociation energy of H_2 (in cm^{-1}): 2009 vs 2019

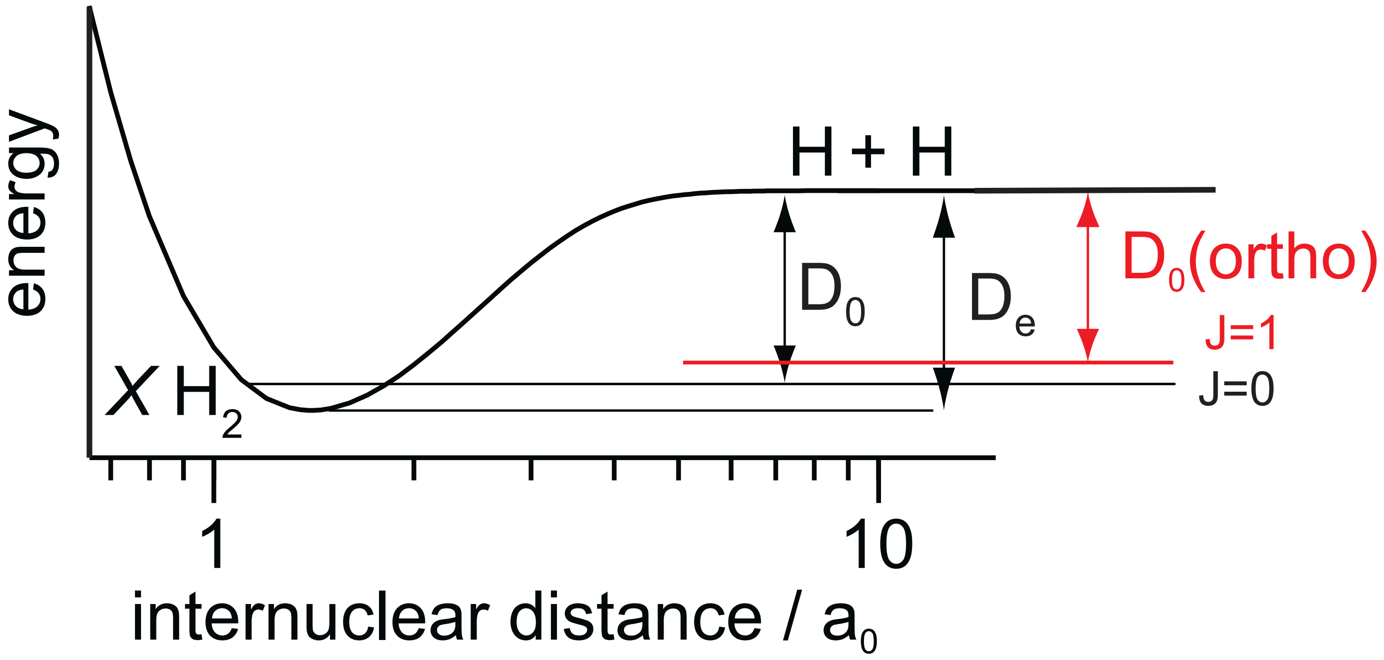


2019:

Relativistic correction with nonadiabatic wavefunction:
M. Puchalski, J. Komasa, P. Czachorowski and
K. Pachucki, Phys. Rev. Lett. **122**, 103003 (2019)
36'118.069'632(26) cm^{-1} (uncertainty 780 kHz)

Experiment:
Hölsch et al., Phys. Rev. Lett. **122**, 103002 (2019)
36'118.069'647(11) cm^{-1} (uncertainty 330 kHz)

The (J=1) - (J=0) ortho-para interval of H_2



Energy-level structures of para- and ortho-H_2 have never been connected. Global shift?

D_0(para-H_2): (1) = 36 118.069 605(31) cm^{-1}
D_0(ortho-H_2) (2) = 35 999.582 834(26) cm^{-1}
Ortho-para interval [a]: (1)-(2) = 118.486 771(50) cm^{-1}
Theory [b]: 118.486 812 7(11) cm^{-1} (without global shift)

Global shift [a]: 0.000041(50) cm^{-1} = 1.2(1.5) MHz

[a] Beyer et al., PRL **123**, 163002 (2019)
[b] Puchalski et al., PRL **122**, 103003 (2019)

What is next?

- He: Experiment has to be checked.

  Zurich: measurement of the ionization energy of He 2 $^3S_1$

- H_2: Theory has to be checked

  Warsaw: Higher-order QED correction

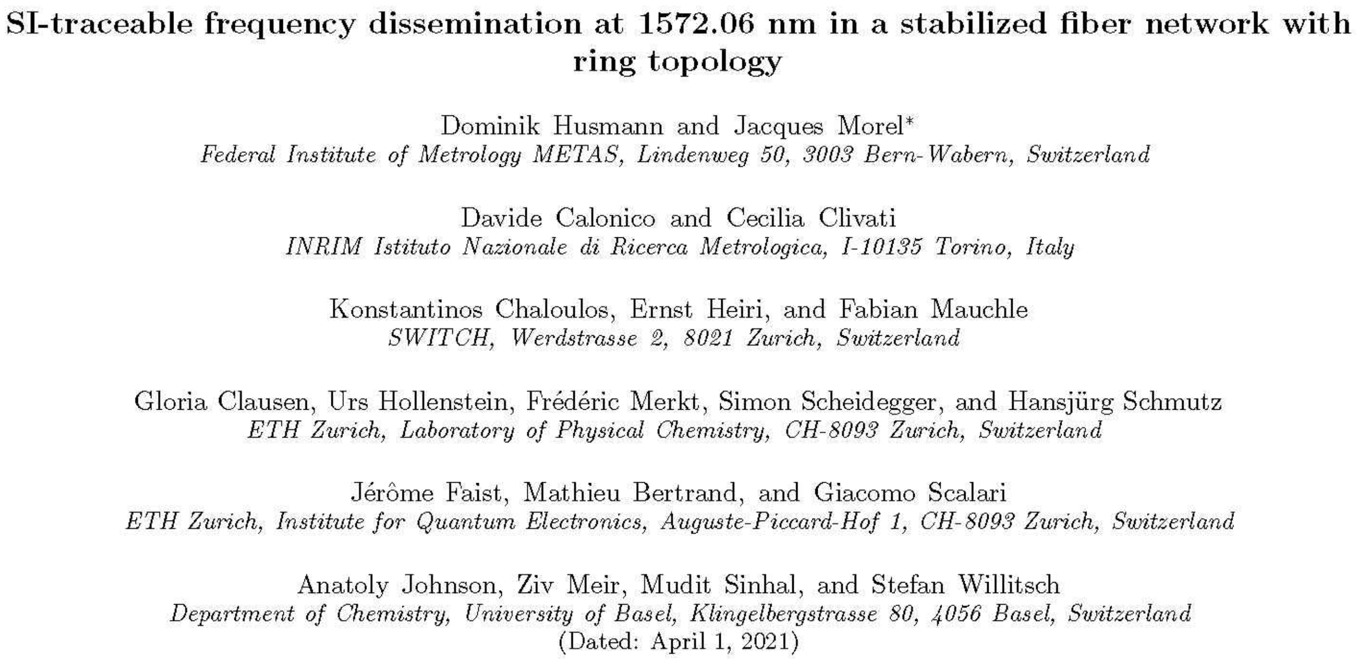
- Next generation of experiments is underway

  Amsterdam: Ramsey-Comb measurement in para H_2, HD and D_2

  Zurich: SI-traceable frequency calibration (Cs primary standard)

  Zurich: Rydberg extrapolation using zero-quantum-defect positions

Connection to Swiss Cs primary frequency standard



SI-traceable frequency dissemination at 1572.06 nm in a stabilized fiber network with ring topology

Dominik Husmann and Jacques Morel*
Federal Institute of Metrology METAS, Lindenweg 50, 3003 Bern-Wabern, Switzerland

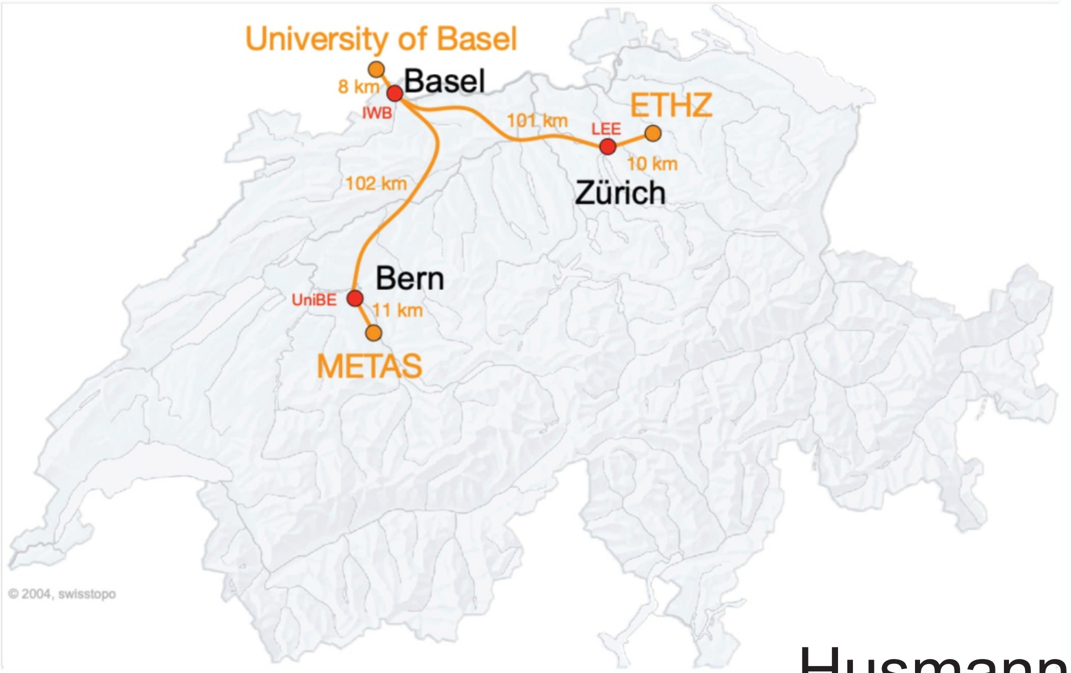
Davide Calonico and Cecilia Clivati
INRIM Istituto Nazionale di Ricerca Metrologica, I-10135 Torino, Italy

Konstantinos Chaloulos, Ernst Heiri, and Fabian Mauchle
SWITCH, Werdstrasse 2, 8021 Zurich, Switzerland

Gloria Clausen, Urs Hollenstein, Frédéric Merkt, Simon Scheidegger, and Hansjürg Schmutz
ETH Zurich, Laboratory of Physical Chemistry, CH-8093 Zurich, Switzerland

Jérôme Faist, Mathieu Bertrand, and Giacomo Scalari
ETH Zurich, Institute for Quantum Electronics, Auguste-Piccard-Hof 1, CH-8093 Zurich, Switzerland

Anatoly Johnson, Ziv Meir, Mudit Sinhal, and Stefan Willitsch
Department of Chemistry, University of Basel, Klingelbergstrasse 80, 4056 Basel, Switzerland
(Dated: April 1, 2021)



Telecommunication data traffic: C-band (1530-1565 nm)

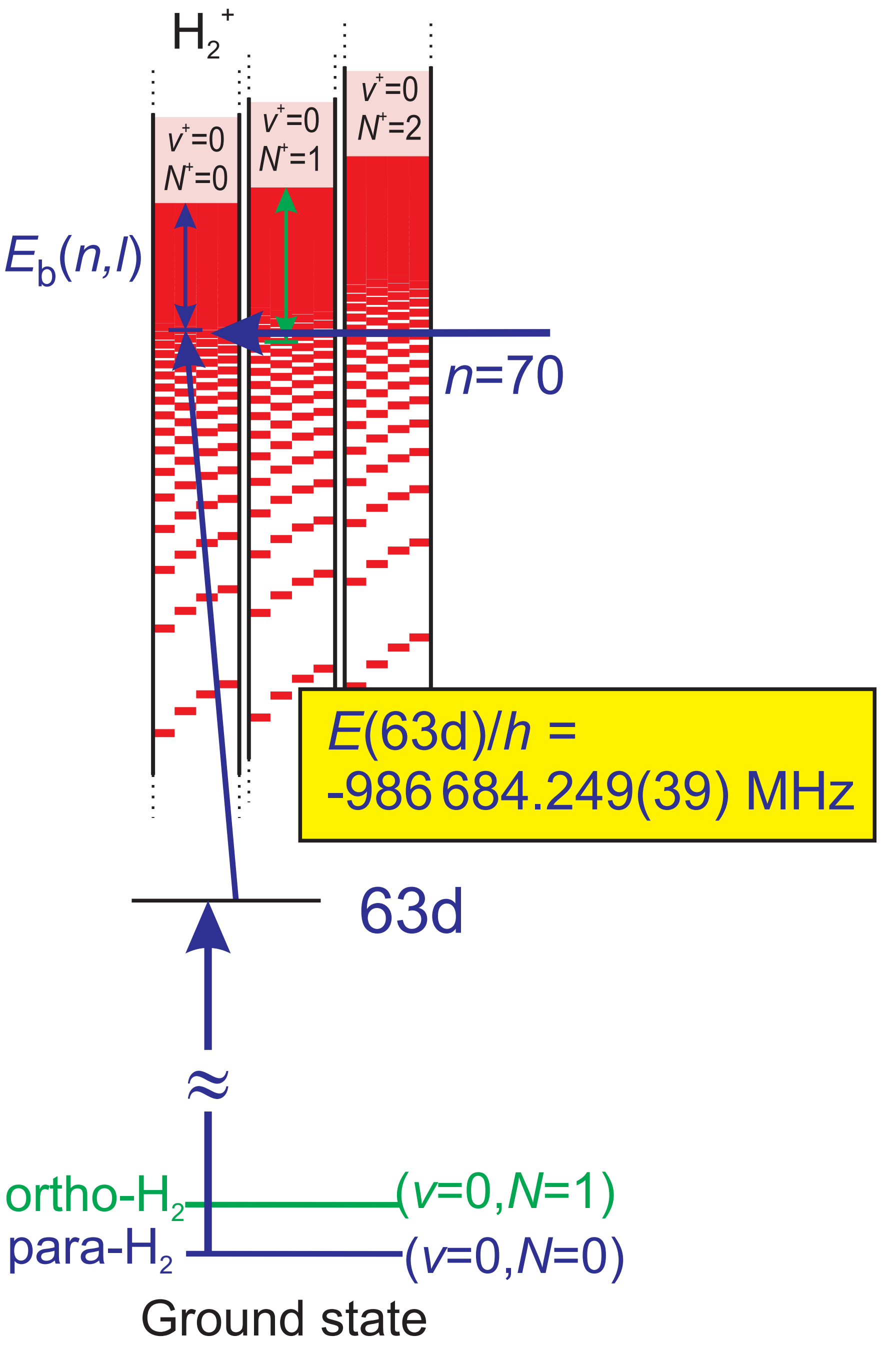
Our network: L-Band (1572.06 nm)

Closed-loop distribution of Cs primary frequency standard from METAS via a fibre network (Switch)

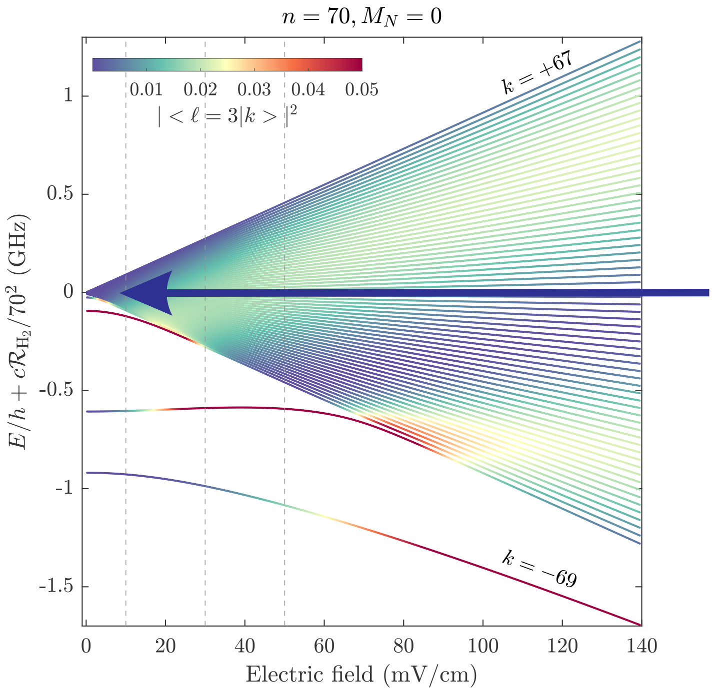
Link instability: 4.7×10^{-16} at 1 s

Husmann et al., Optics express **29**, 24592 (2021)

Rydberg-series extrapolation with zero-quantum-defect positions

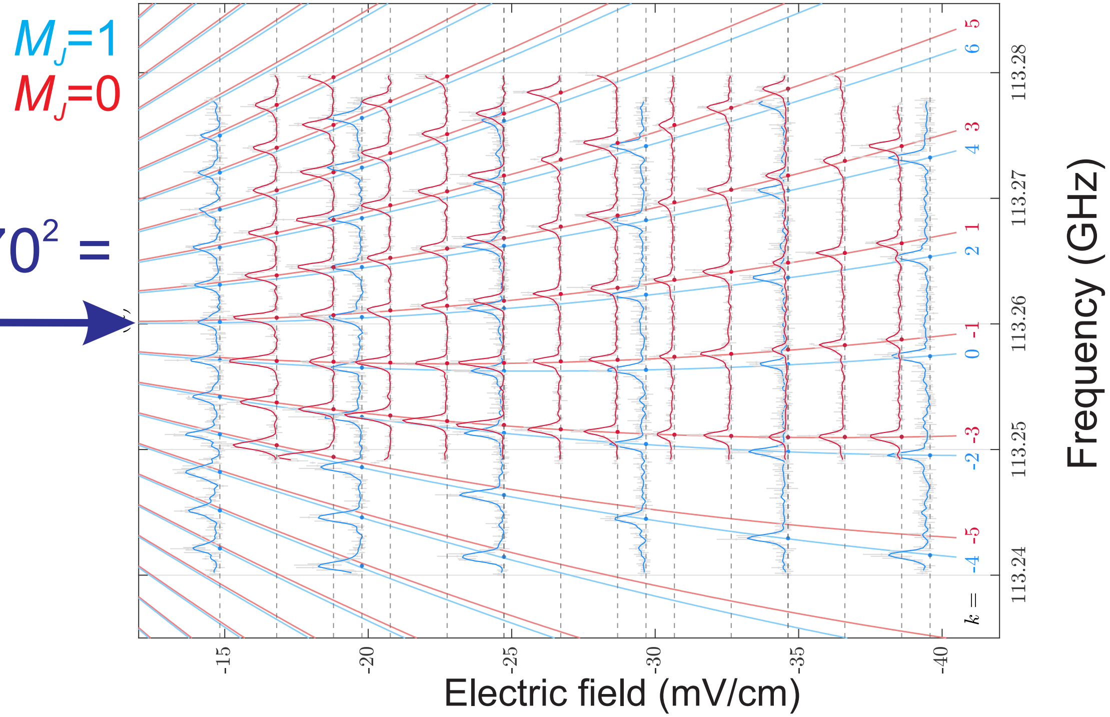


$E(63d)/h$ =
-986 684.249(39) MHz

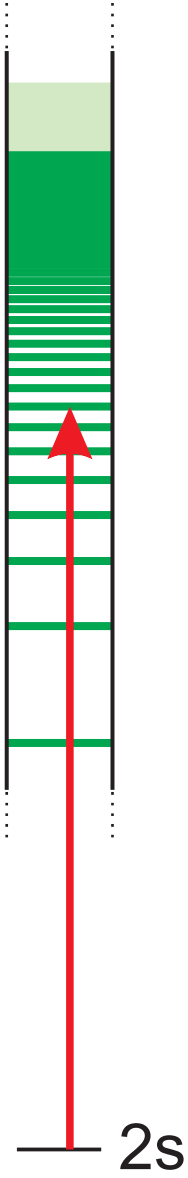


$E_b(n=70)=$
$-R_{H2}/70^2$

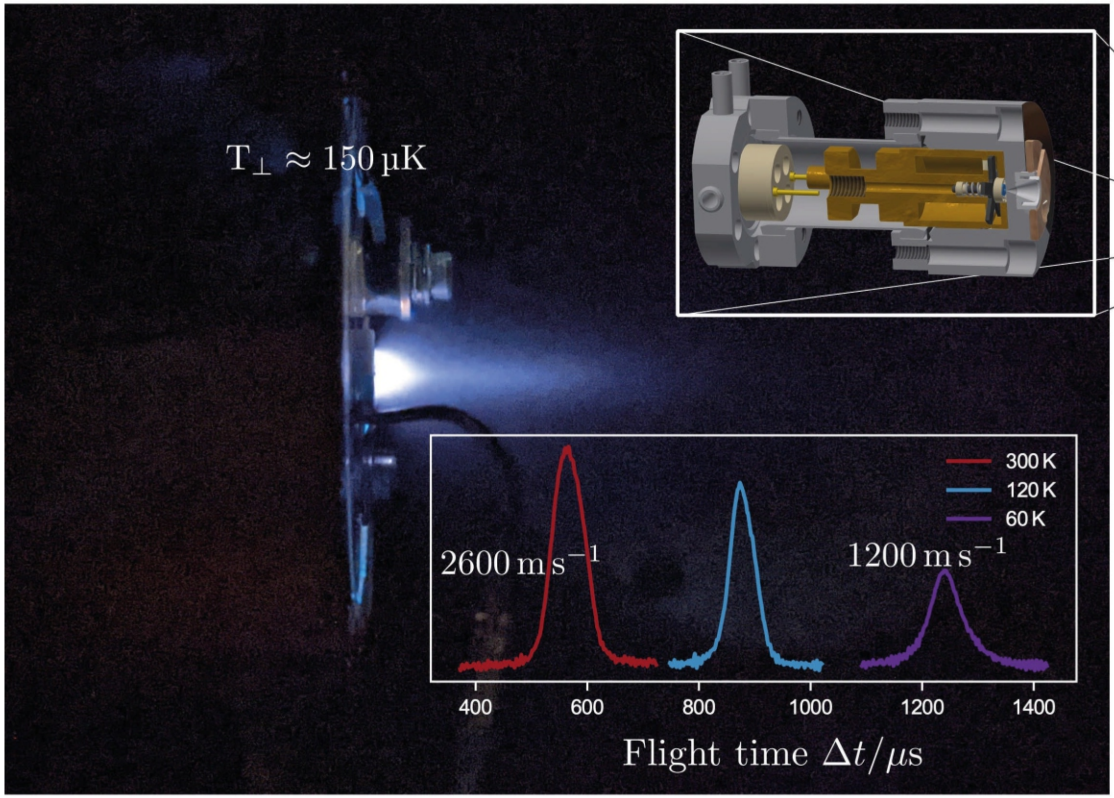
$-R_{H2}/70^2 =$

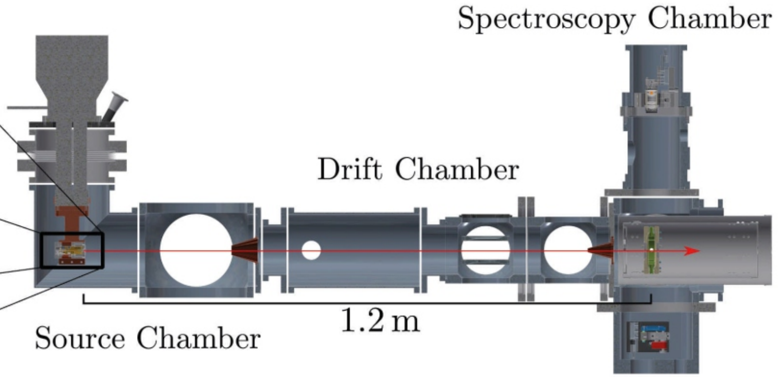


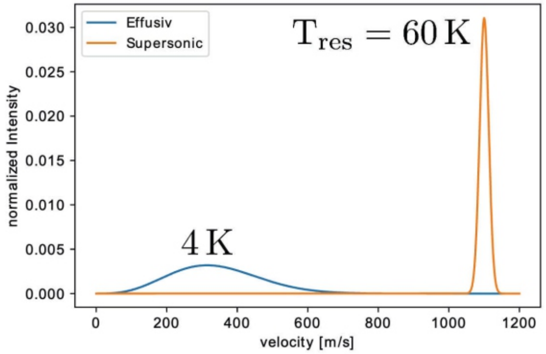
The ionization energy of H



Cryogenic pulsed H atom source

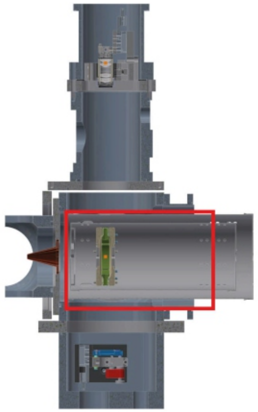


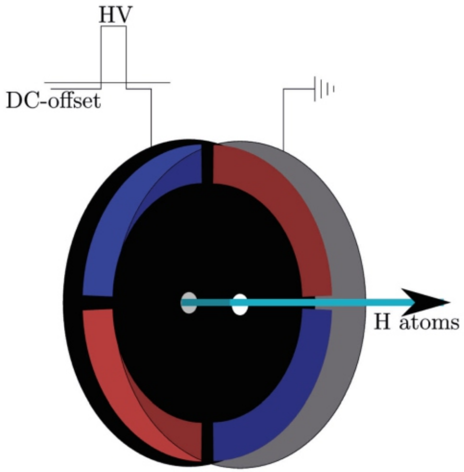




Field compensation

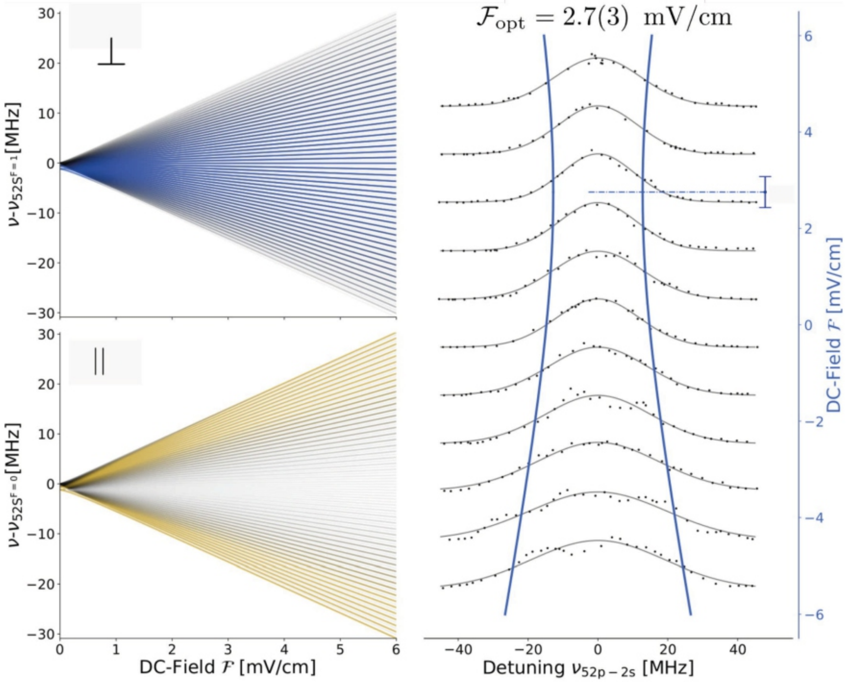
$$E = 1.92\mathcal{F}nk\,\frac{\mathrm{MHz}}{\mathrm{V/cm}}$$





$$\mathcal{H} = \mathcal{H}_{\mathrm{atom}} + e\mathcal{F}z$$

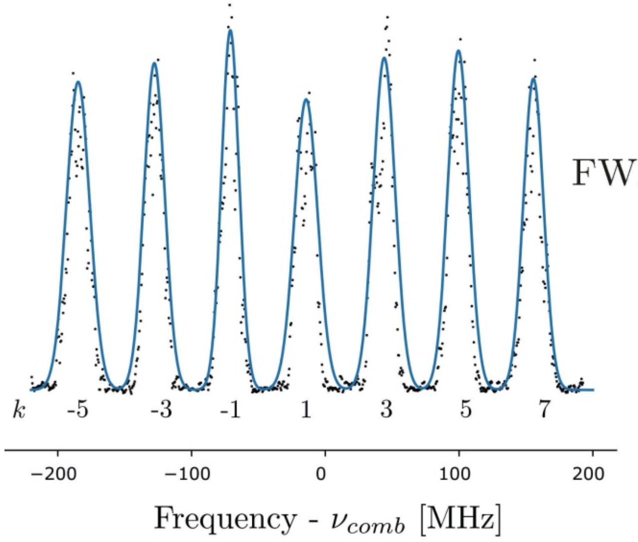
$52\mathrm{p} \leftarrow 2\mathrm{s}$



Rydberg spectra with and without fields

$\mathcal{F}_z \approx 0.83\,\mathrm{V\,cm^{-1}}$

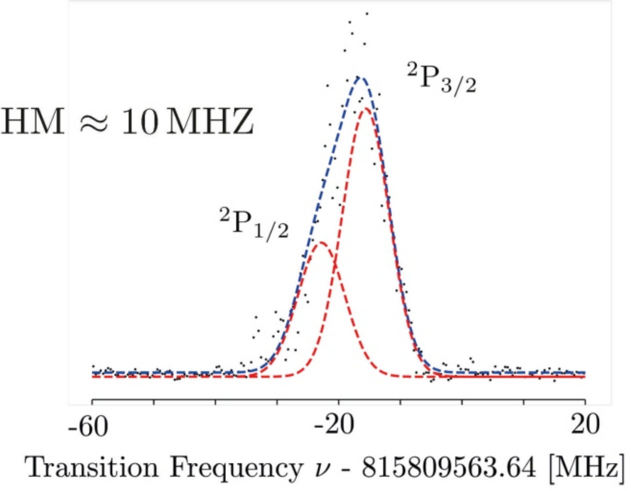
$n = 35, m = 1$



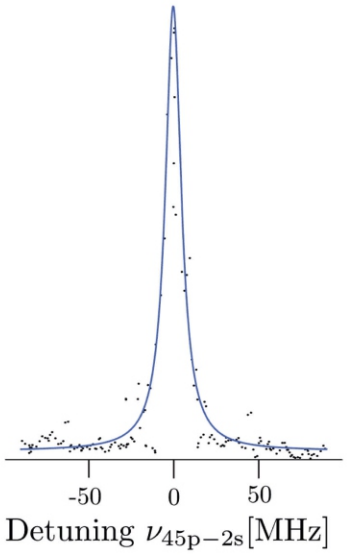
FWHM ≈ 10 MHZ

$\mathcal{F} \approx 0.0(3)\,\mathrm{V\,cm^{-1}}$

$n = 23$



$n = 45$

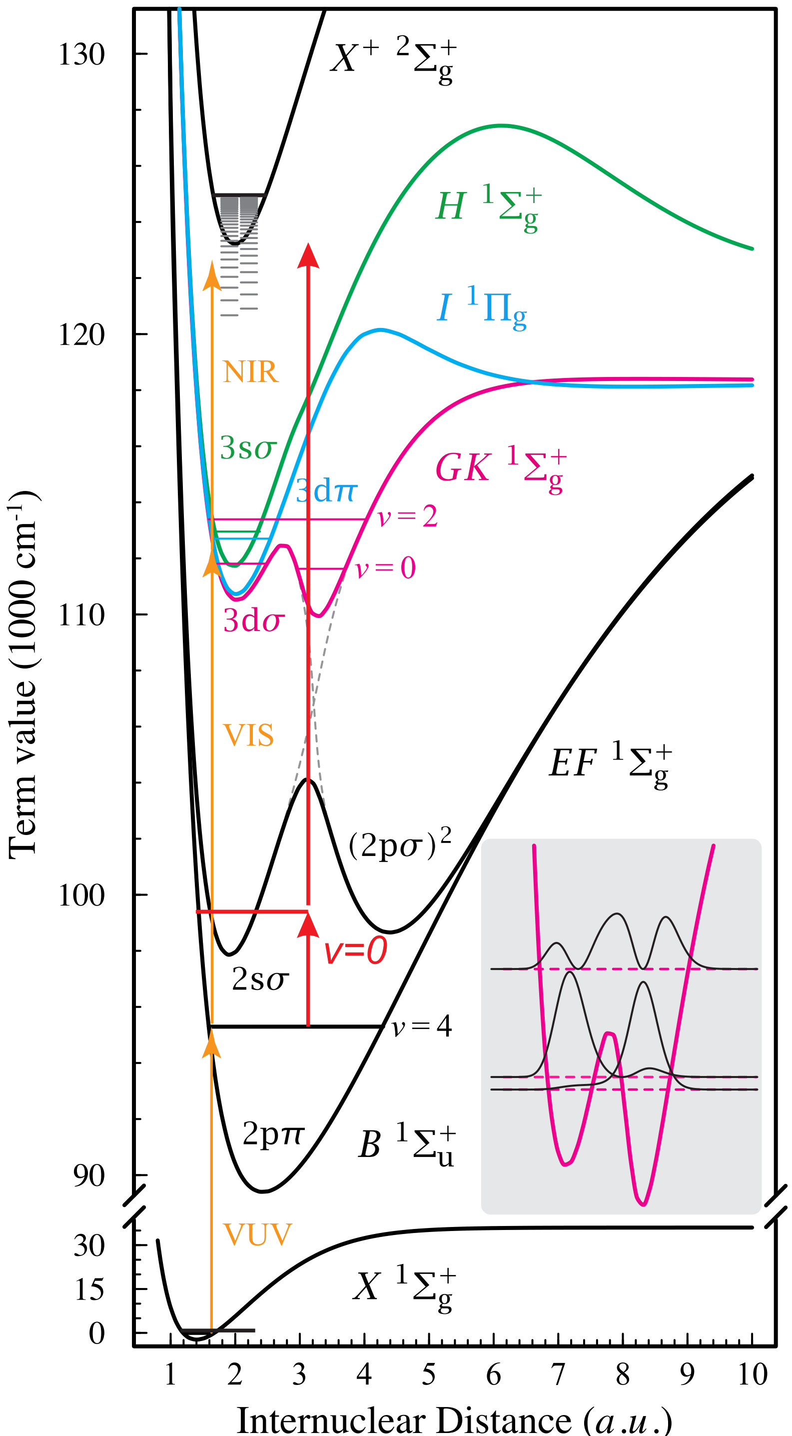


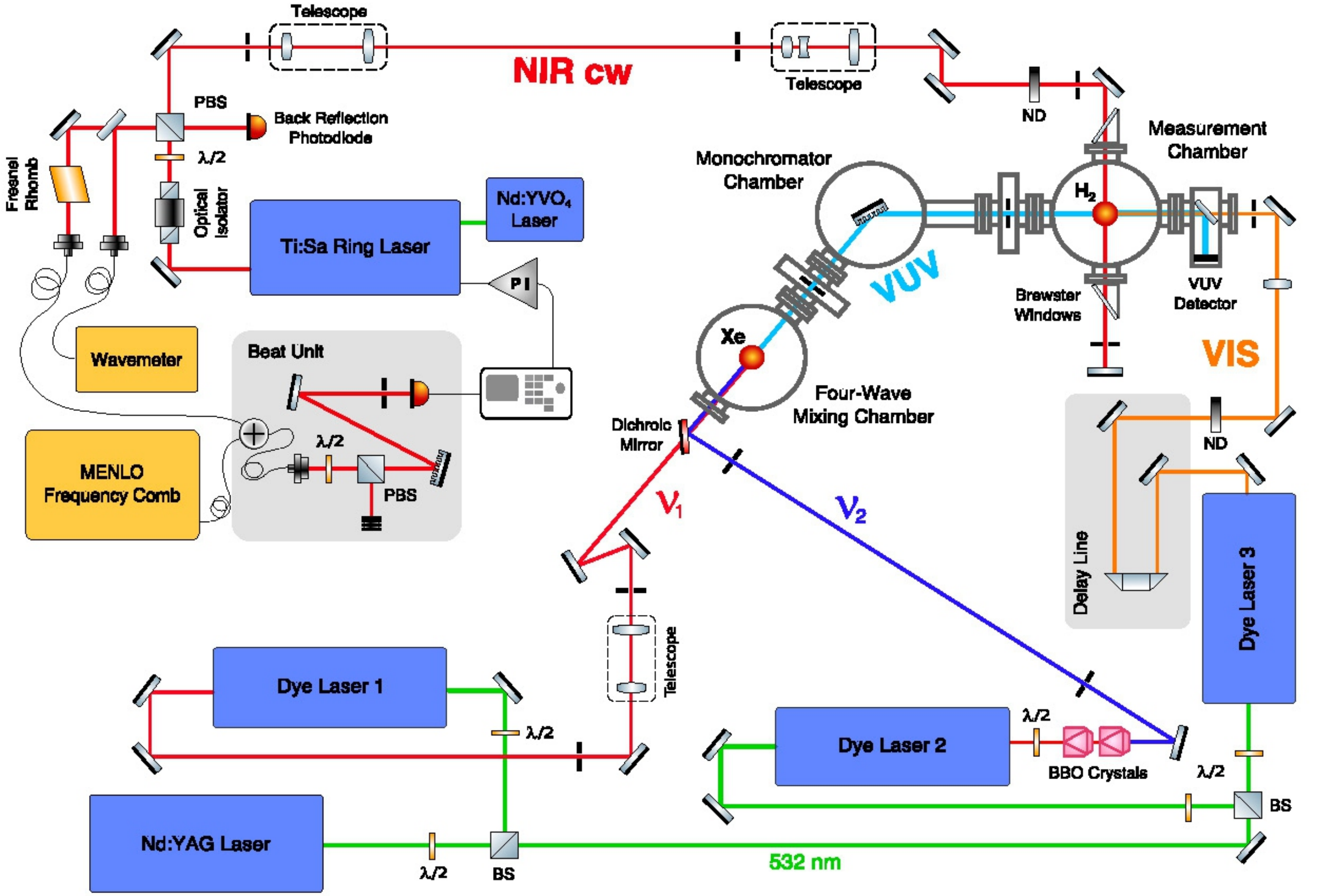
March 2022

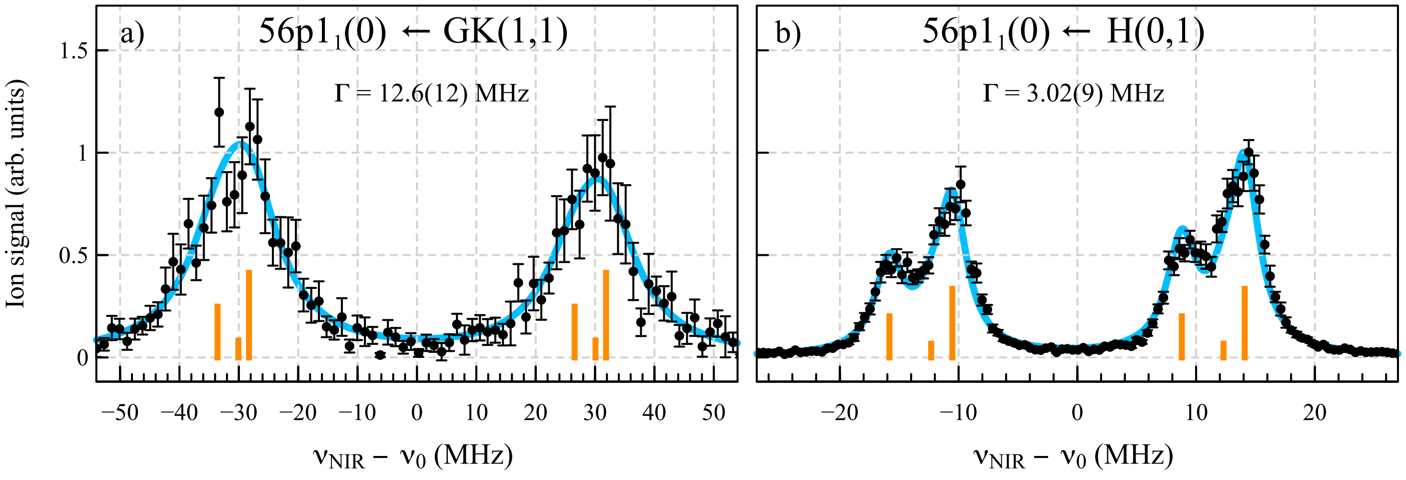
Financial support: Swiss National Science Foundation, ERC advanced Grant Programme

Collaborations: Wim Ubachs and Kjeld S. E. Eikema, Amsterdam
Christian Jungen, Orsay

Experiment (H_2)







Projects in my group:

H atom: $2\mathrm{s} \longrightarrow n\mathrm{p}$ ($n > 20$)	Simon Scheidegger (WI-02)
He atom: $1\mathrm{s}2\mathrm{s}\ {}^1\mathrm{S}_0 \longrightarrow n\mathrm{p}$ ($n > 20$)	Gloria Clausen (WI-03)
H_2 /D_2: E_I and D_0	Nicolas Hölsch (WI-05) Joël Hussels (WI-06)
He_2 and He_2^+	Paul Jansen Luca Semeria

The H atom and muonic hydrogen

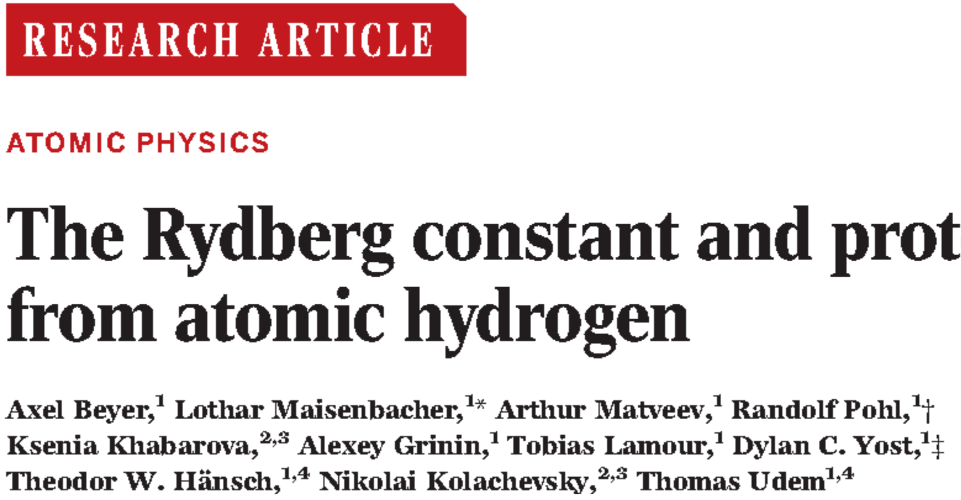
Electronic structure (Lyman, Balmer, ...): QM

Fine structure: relativistic QM, QED

Lamb shift: QED

Nuclear-size effects, hyperfine structure

Experimental H spectra (world data) ↔ R, α, m_p/m_e, magnetic moments, proton radius, ...

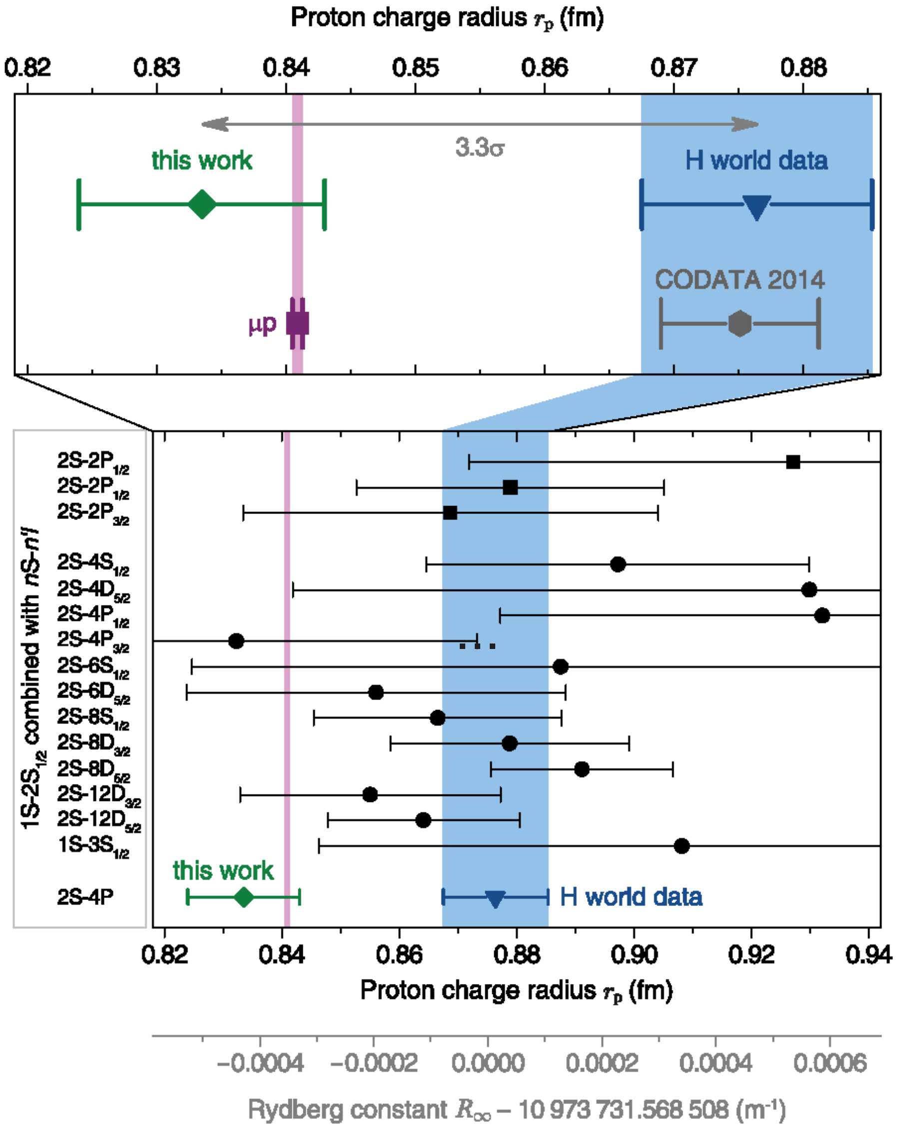


RESEARCH ARTICLE

ATOMIC PHYSICS

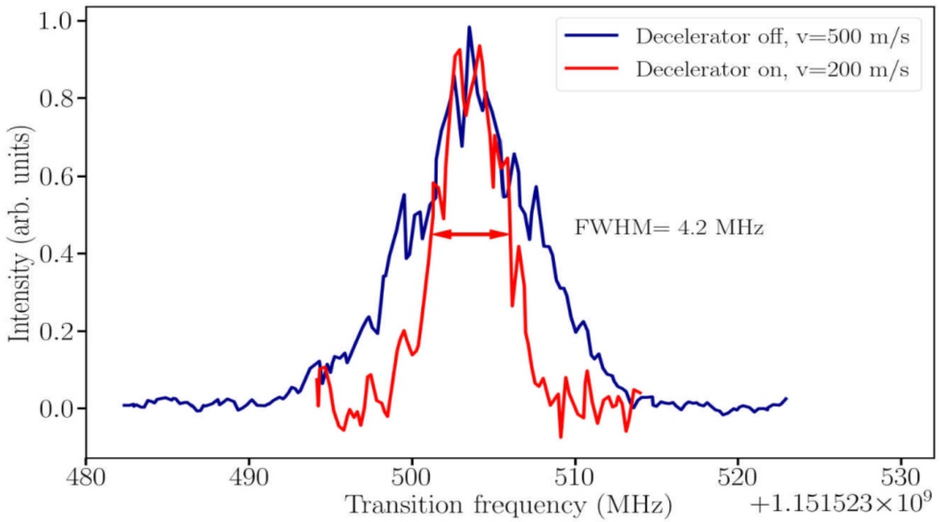
The Rydberg constant and proton size from atomic hydrogen

Axel Beyer,[1] Lothar Maisenbacher,[1*] Arthur Matveev,[1] Randolf Pohl,[1†] Ksenia Khabarova,[2,3] Alexey Grinin,[1] Tobias Lamour,[1] Dylan C. Yost,[1‡] Theodor W. Hänsch,[1,4] Nikolai Kolachevsky,[2,3] Thomas Udem[1,4]

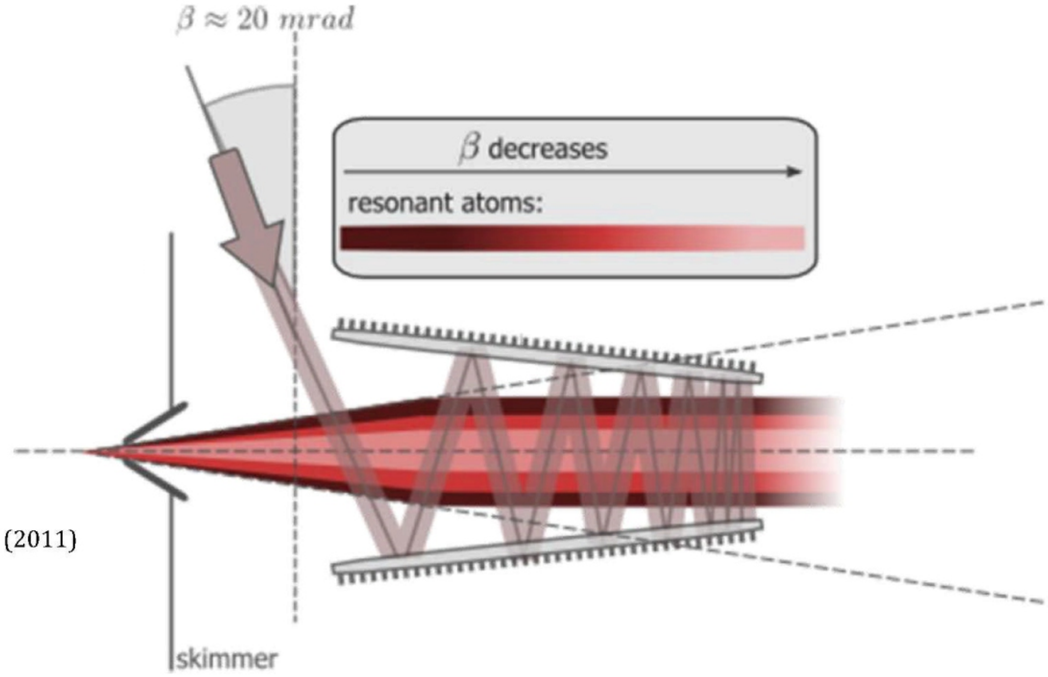


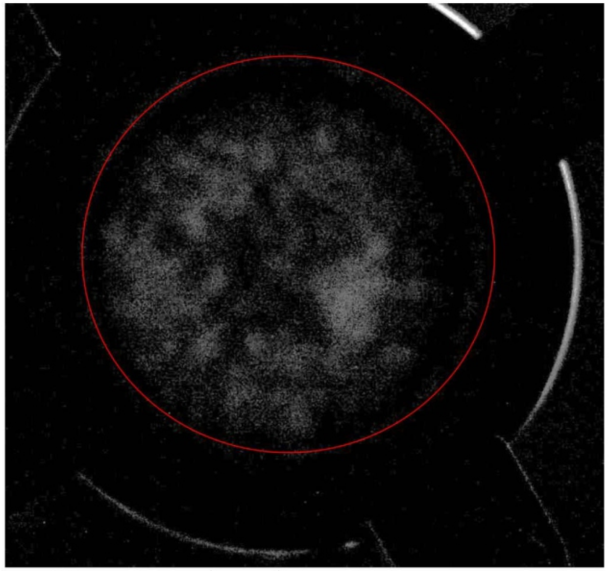
R. Pohl, A. Antognini et al., Nature, **466**,213 (2010)
Beyer et al., Science, **358**, 79 (2017)

Measurement in He 2s $^3S_1$

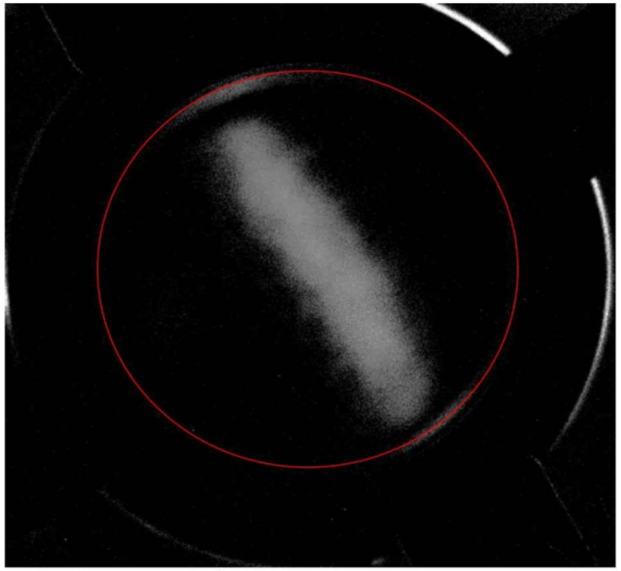


- LKB Paris, BEC Subgroup
  J. Simonet Optical traps for Ultracold Metastable Helium atoms, (2011)
- Zeilinger group, Vienna
  M. Keller *et al.* PRA **90**, 063607 (2014)
- M. D. Hoogerland *et al.* Appl. Phys. B **62**, 323 (1996)
- Wallraff group ETH Zürich (T. Thiele, A. Hambitzer, D. Friese, L. Gerster, M. Melchner)

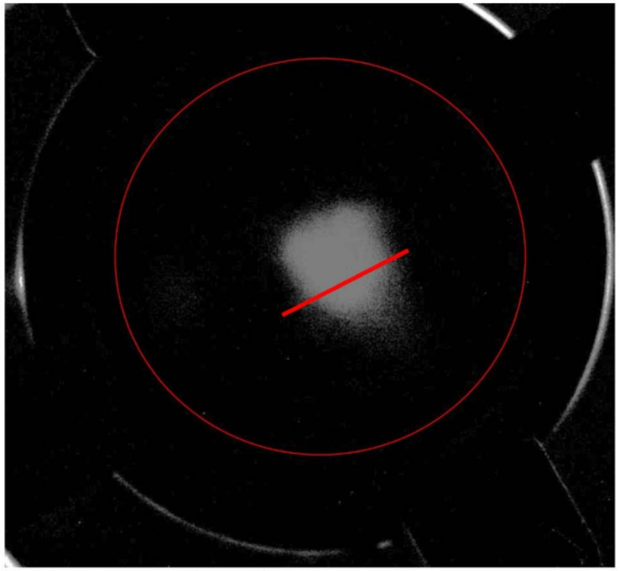




Zeeman deceleration on
Laser cooling off

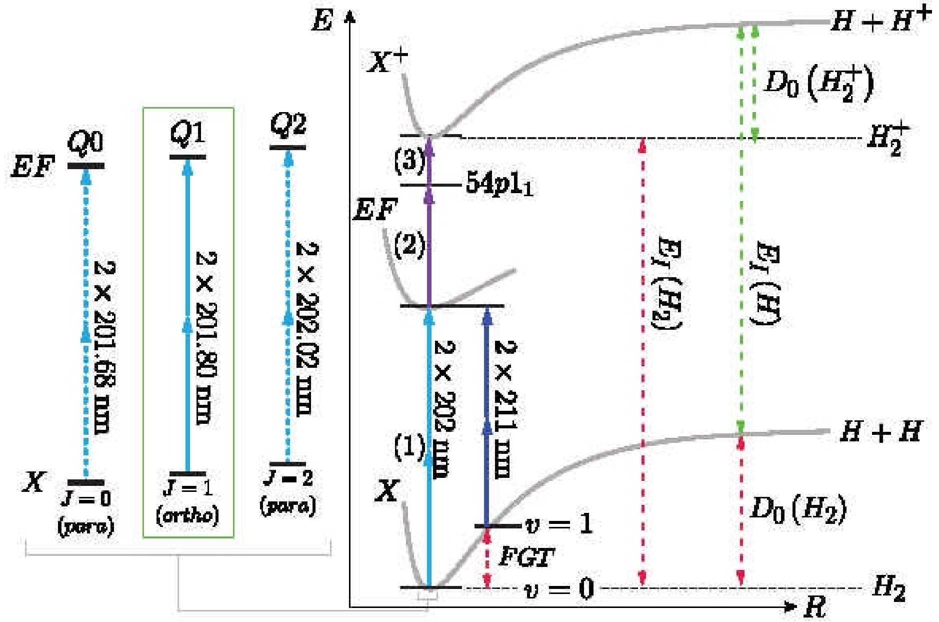


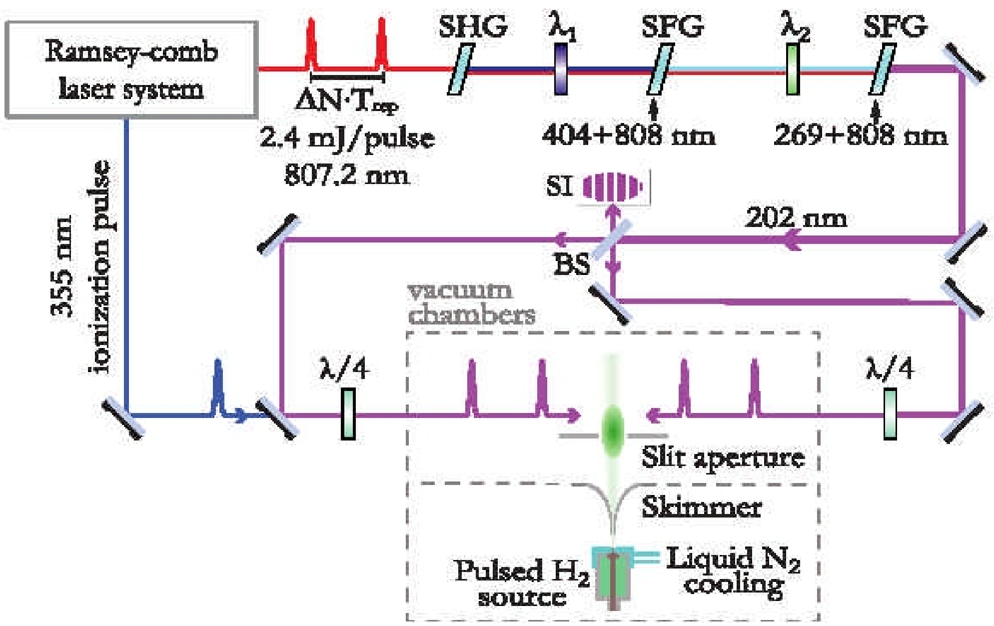
Zeeman deceleration on
Laser cooling on one direction

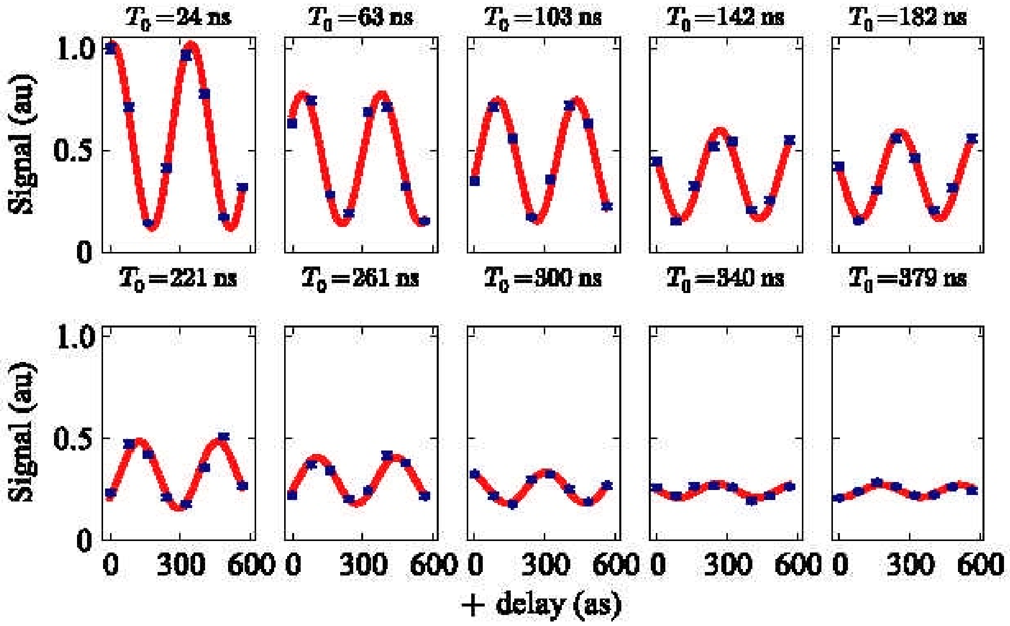


Zeeman deceleration on
Laser cooling on

Amsterdam experiment



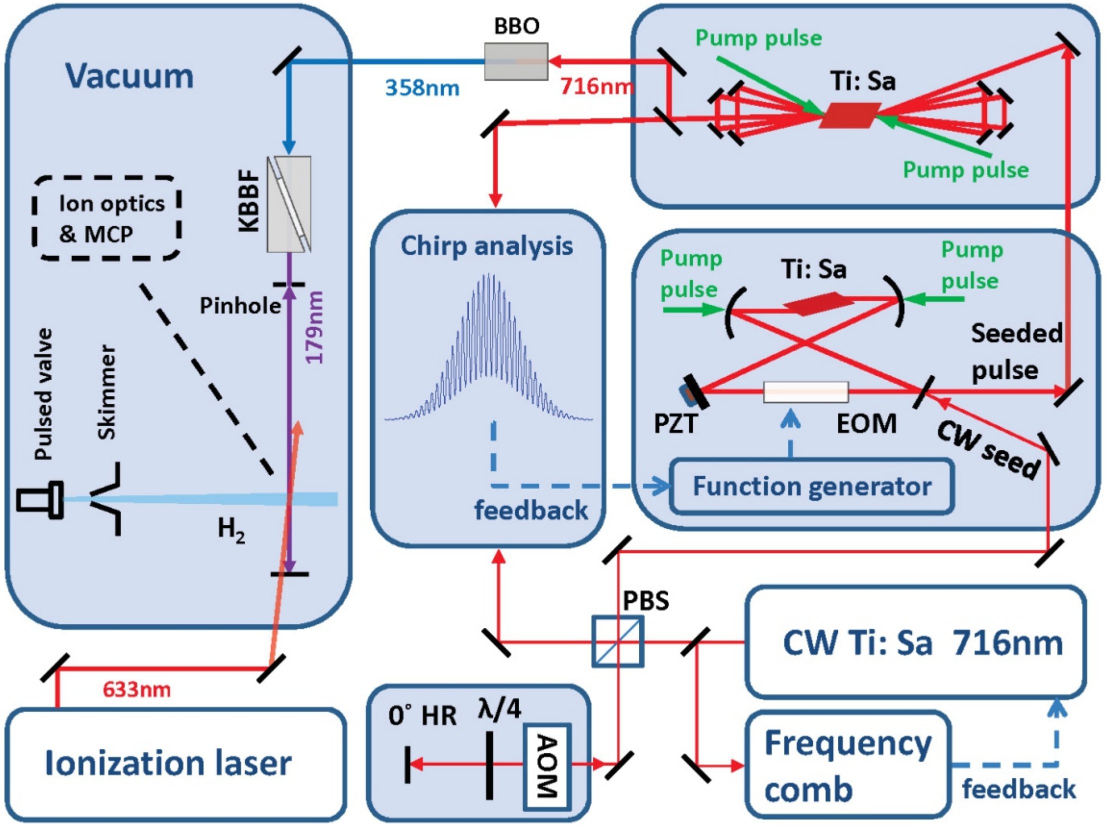


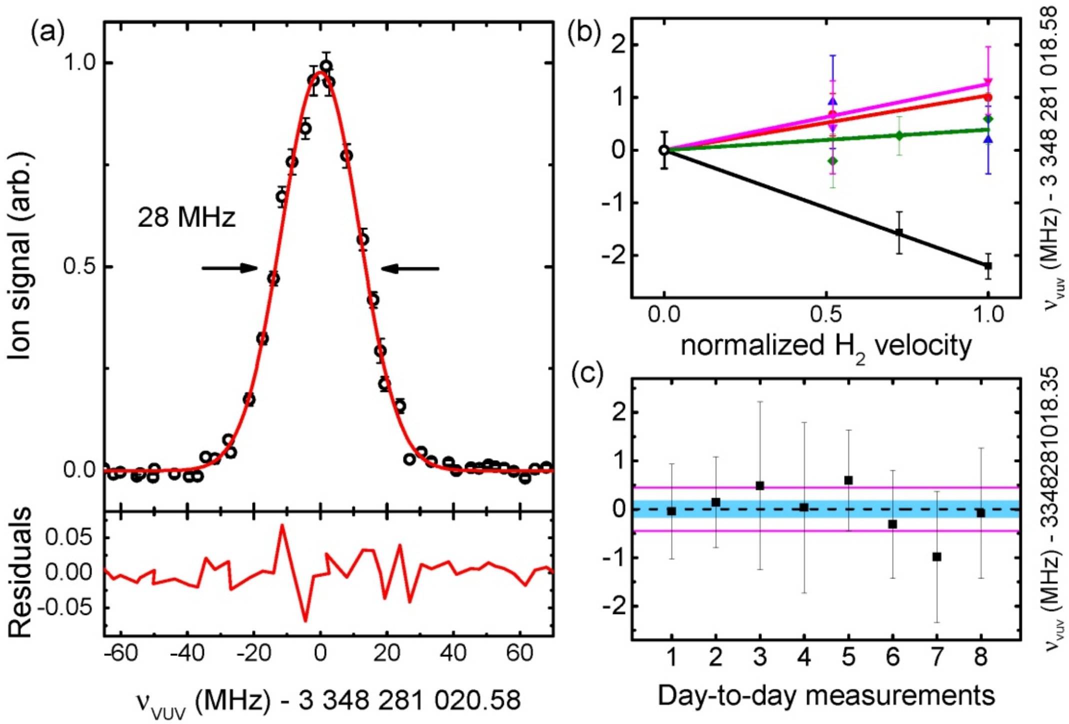


Altmann et al., PRL 120, 043204 (2018)

Result of Amsterdam experiment:

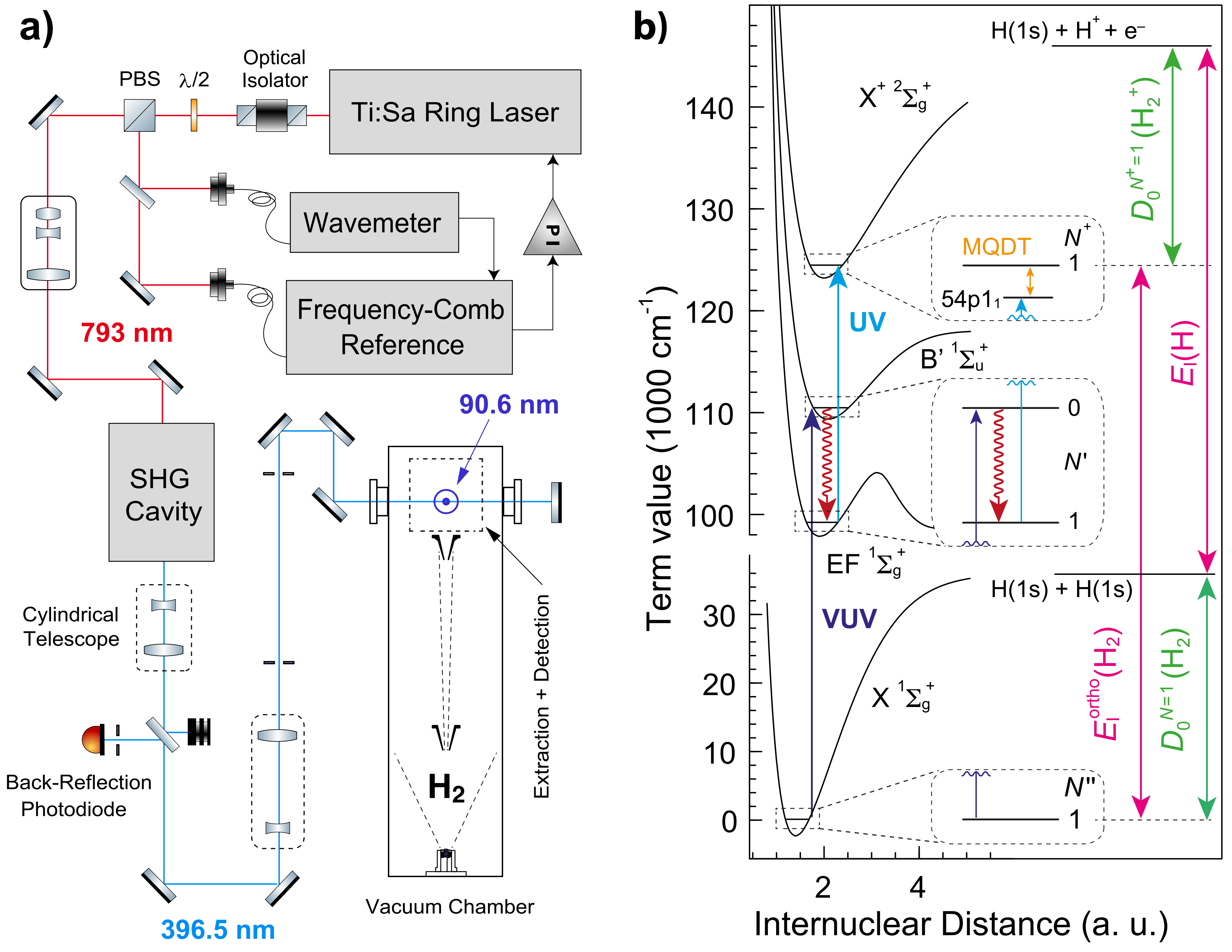
X(v=0,N=1) - GK(v=1,N=1): $\nu = 3\ 348\ 281\ 018.35(49)_{stat}(43)_{sys}$ MHz

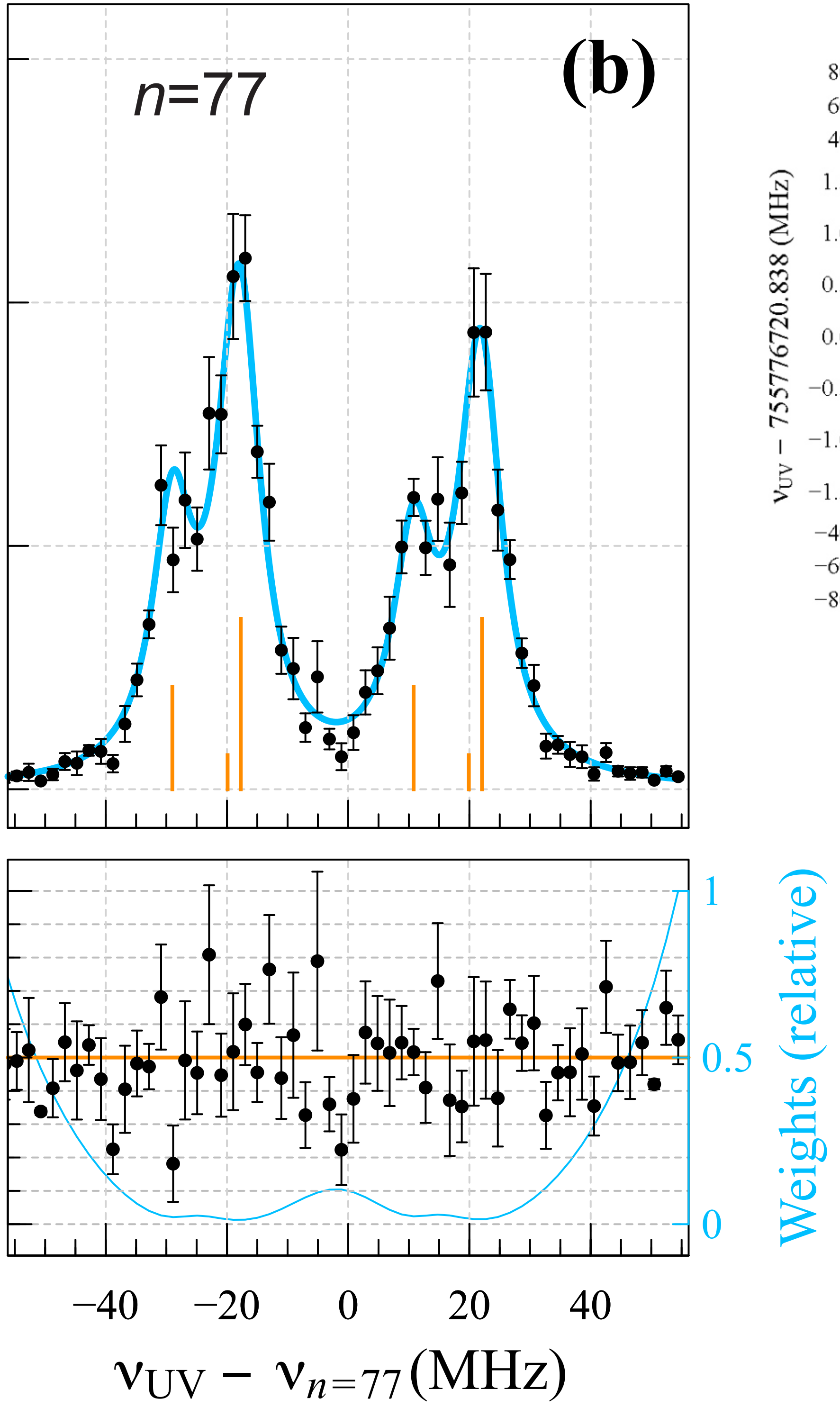


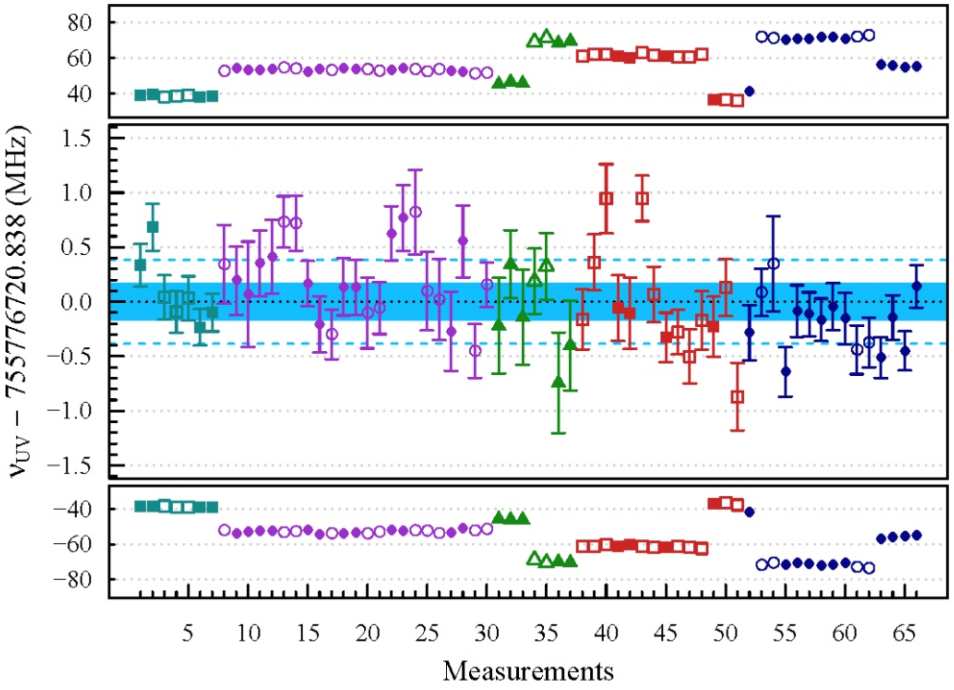


C. Cheng, J. Hussels, M. Niu, H.L. Bethlem, K.S.E. Eikema, E. J. Salumbides and W. Ubachs, 2018

Zurich experiment







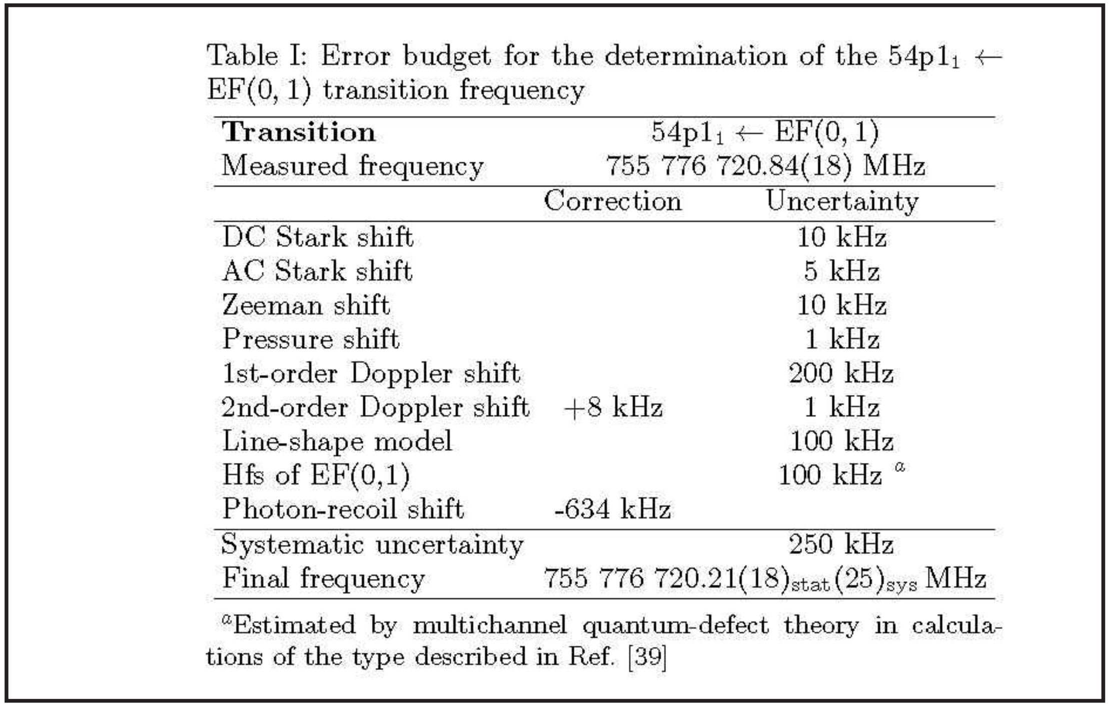


Table I: Error budget for the determination of the $54p1_1 \leftarrow EF(0,1)$ transition frequency

Transition	$54p1_1 \leftarrow EF(0,1)$	
Measured frequency	755 776 720.84(18) MHz	
	Correction	Uncertainty
DC Stark shift		10 kHz
AC Stark shift		5 kHz
Zeeman shift		10 kHz
Pressure shift		1 kHz
1st-order Doppler shift		200 kHz
2nd-order Doppler shift	+8 kHz	1 kHz
Line-shape model		100 kHz
Hfs of EF(0,1)		100 kHz [a]
Photon-recoil shift	-634 kHz	
Systematic uncertainty		250 kHz
Final frequency	755 776 720.21$(18)_{\text{stat}}(25)_{\text{sys}}$ MHz	

[a] Estimated by multichannel quantum-defect theory in calculations of the type described in Ref. [39]

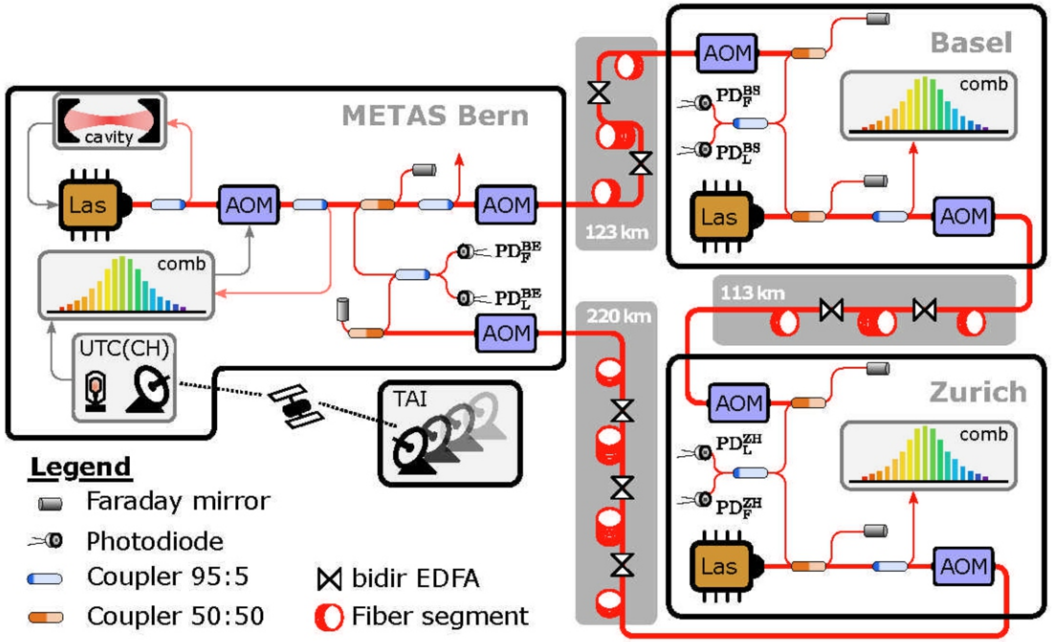
Hölsch et al., Phys. Rev. Lett. **122**, 013001 (2019)

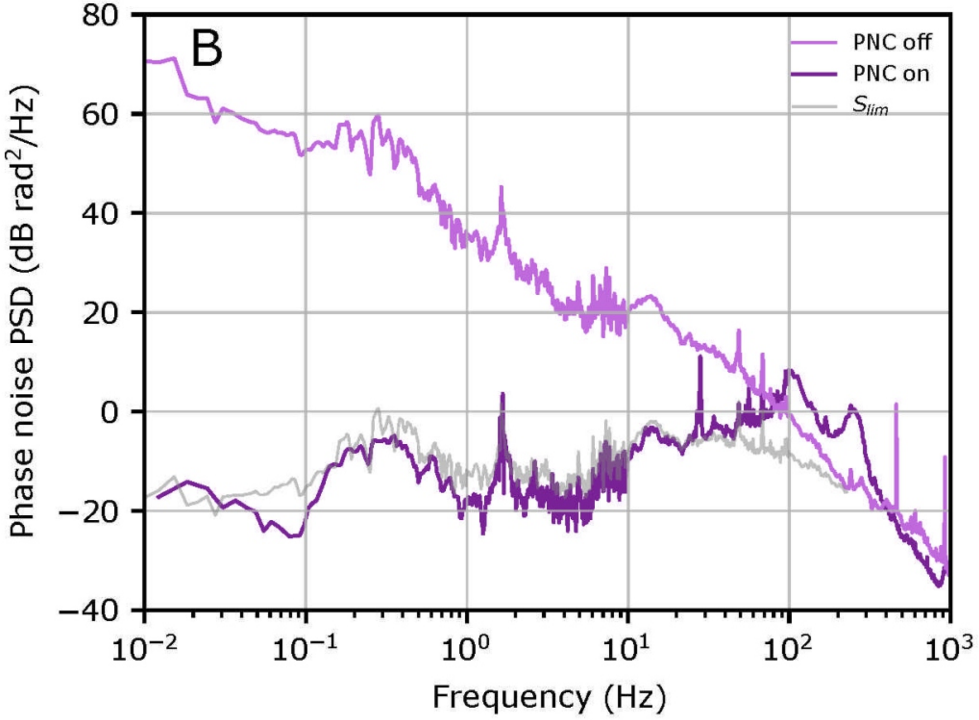
Current status

	Experiment	Theory
H_2:	36'118.069 647(11) cm^{-1} (1)	36'118.069 632(26) cm^{-1} (2)
D_2:	36 748.362 282(26) cm^{-1} (3)	36748.362 342(26) cm^{-1} (4)
HD:	36 405.783 66(36) cm^{-1} (5)	36405.782 477(26) cm^{-1} (4)

2022: Discrepancy in HD is about to be resolved

(1) Hölsch et al., Phys. Rev. Lett. **122**, 013002 (2019)
(2) Puchalski et al., Phys. Rev. Lett. **122**, 103003 (2019)
(3) Hussels et al., Phys. Rev. A **105**, 022820 (2022)
(4) Puchalski et al., Phys. Rev. A **100**, 020503(R) (2019)
(5) Sprecher et al., J. Chem. Phys. **133**, 111102 (2010)

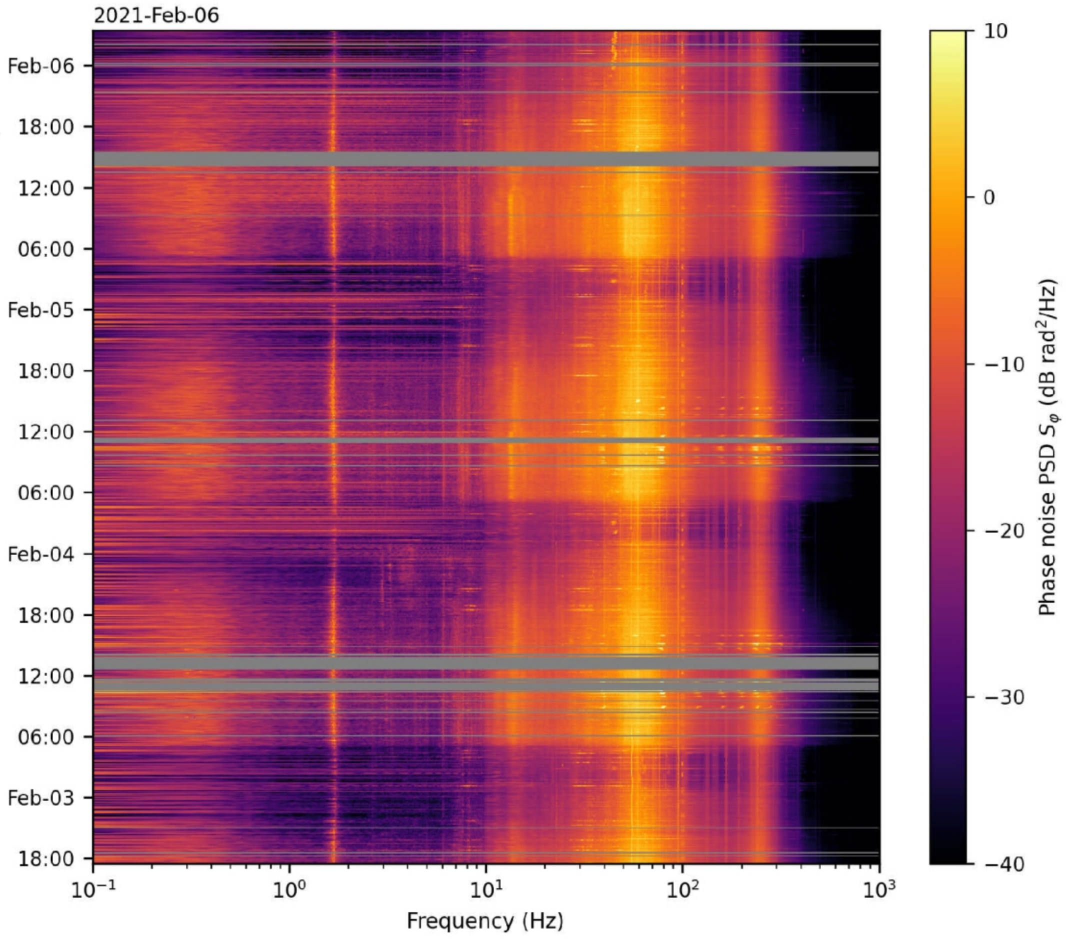




Link instability:

4.7 x 10^{-16} at 1 s

Monitoring human activity through phase noise:



Husmann et al., Optics express **29**, 24592 (2021)