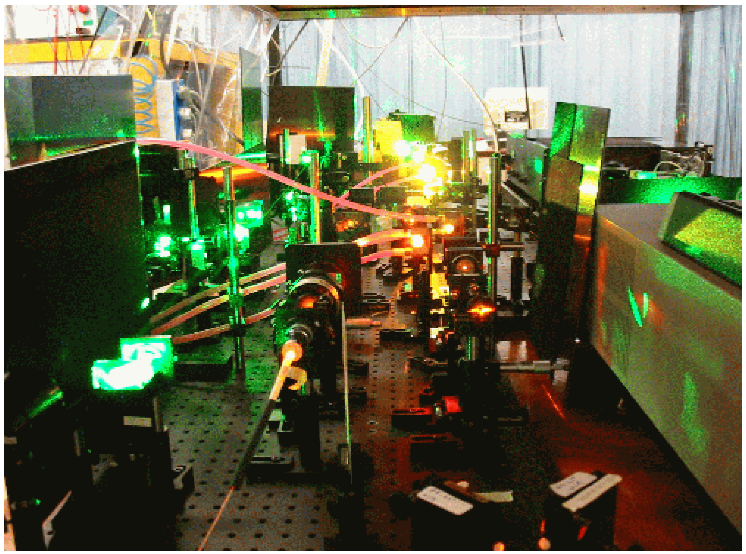
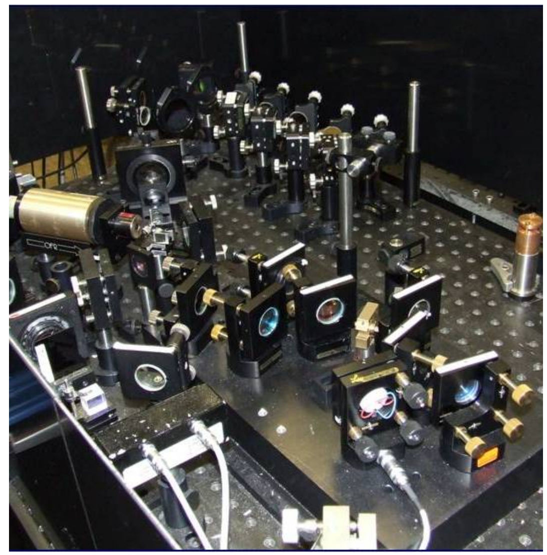
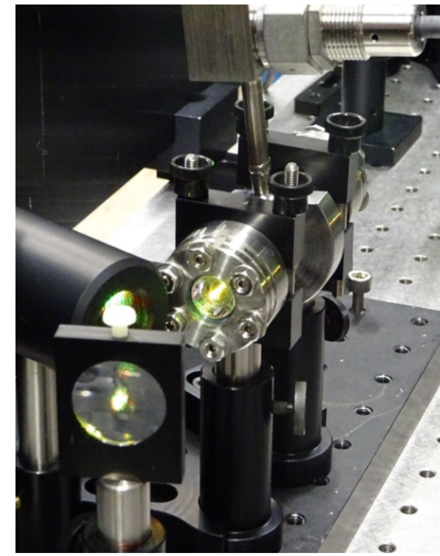
Physics beyond the Standard Model from hydrogen molecules







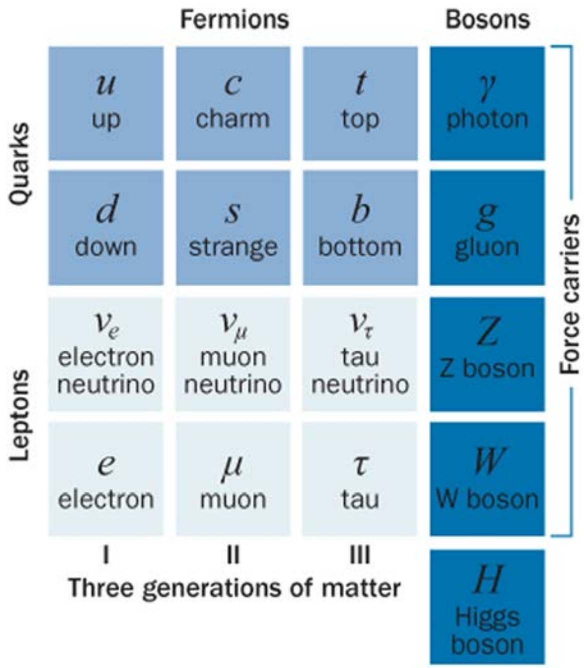
LaserLaB Amsterdam

Wim Ubachs
Vrije Universiteit Amsterdam

Nikhef Colloquium
Amsterdam
22 Nov 2019

The Standard Model of Physics

What do we know ?



What do we not know ?

- Dark Matter
- Dark Energy
- How does Gravity fit to SM ?
- Why is Gravity so weak ?
- Are there only 3+1 dimensions ?
- Are there only 4 forces ?
- Amount of CP violation

Beyond SM ?

- Variation of fundamental constants
- Space-time dependence of physical law (breakdown of GR)

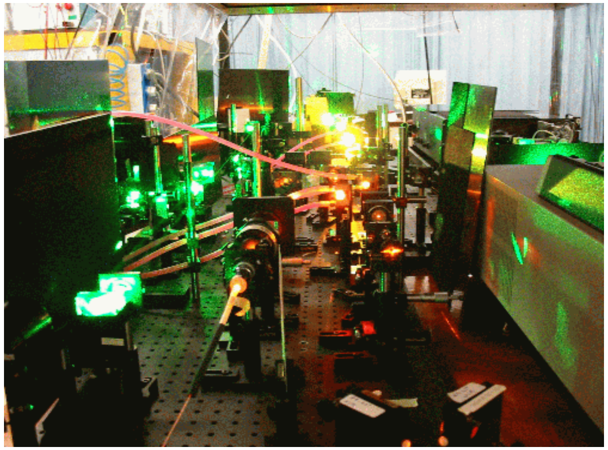
→ There is a precision molecular spectroscopy approach to these questions

Prelude

Empirical search for a drift of the Proton-Electron mass ratio μ

Compare H_2 in different epochs

Lab	QSO
today	12 Gyr ago
90-112 nm	~275-350 nm

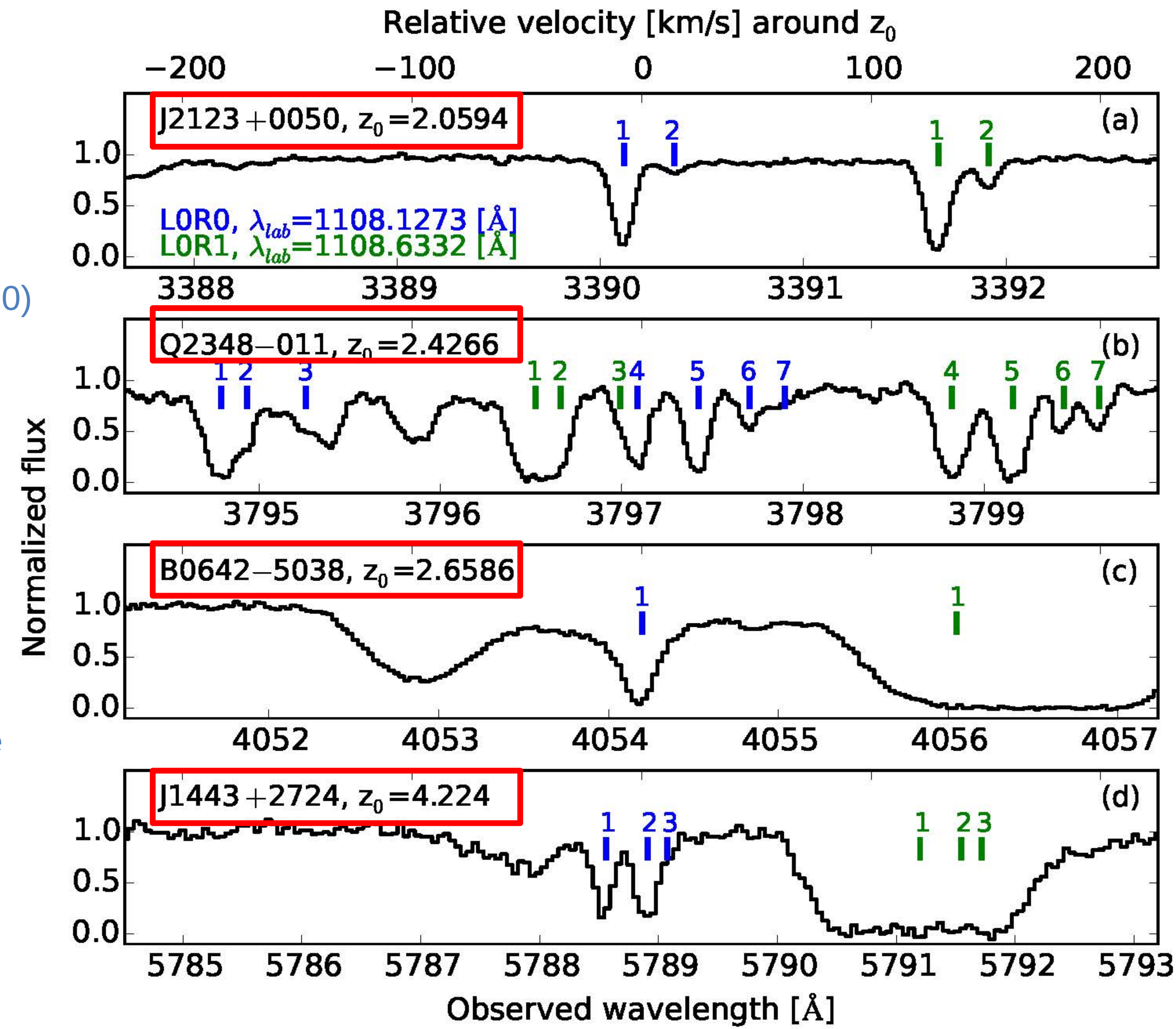


$$\frac{\lambda_i^z}{\lambda_i^0} \equiv 1 + z_i$$

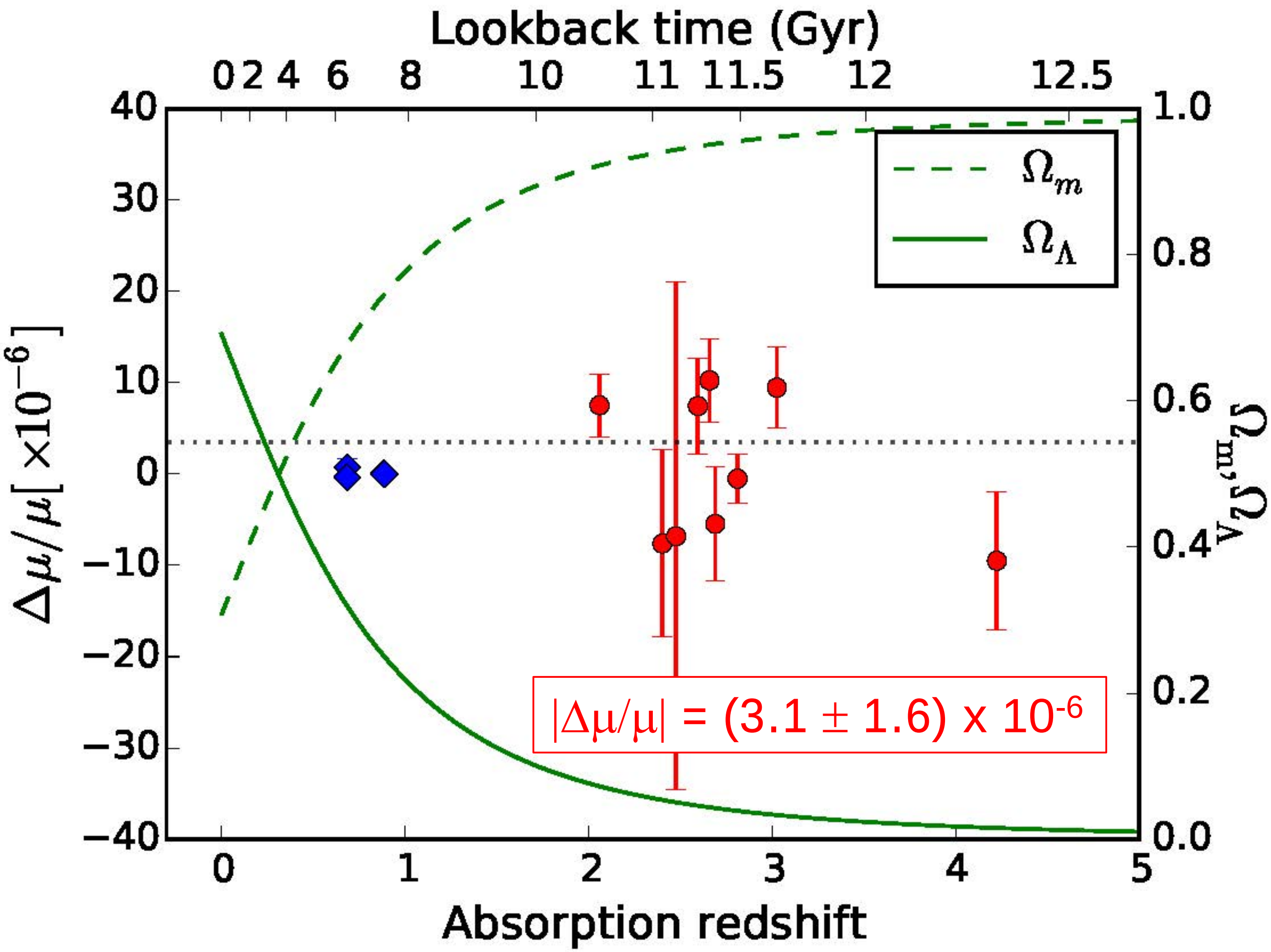
Cosmological redshift

Various (10) systems observed

Determine $\Delta\mu/\mu$



Status/Review: Varying Proton-electron mass ratio



W. Ubachs, J. Bagdonaite, E.J. Salumbides, M.T. Murphy, L. Kaper
Search for a drifting proton-electron mass ratio from H_2
Rev. Mod. Phys. 88, 021003 (2016)

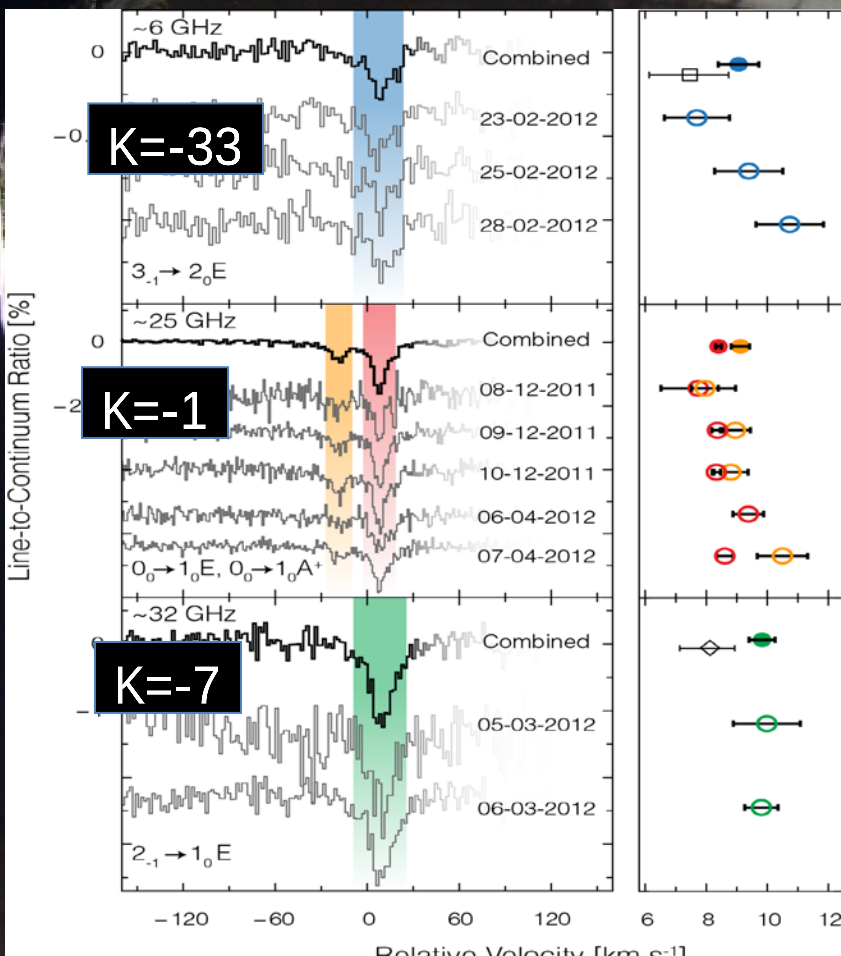
A Stringent Limit on a Drifting Proton-to-Electron Mass Ratio from Alcohol in the Early Universe

Bagdonaite, Jansen, Henkel, Bethlem, Menten, Ubachs,
Science 339 (2013) 46

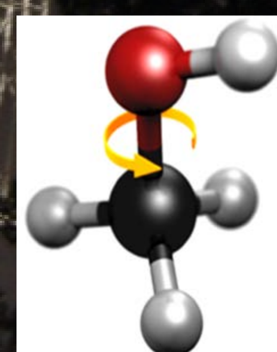
Effelsberg Radio Telescope

PKS-1830-211
“molecular factory”

at z=0.88582
(7.5 Gyrs look-back)



$$\left|\frac{\Delta\mu}{\mu}\right| < 10^{-7}$$



Methanol observations ongoing at ALMA

(Hydrogen) Molecules as a metrology test system

Search for BSM-physics from laboratory spectroscopy experiment

$$\Delta E = E_{\exp} - E_{theory}$$

$$\delta E = \sqrt{\delta E_{\exp}^2 + \delta E_{theory}^2}$$

$\Delta E < \delta E$ Validate theory (QED/SM)

$\Delta E > \delta E$ New Physics:

Discover new physics $\langle \Delta V_{new} \rangle > \delta E$

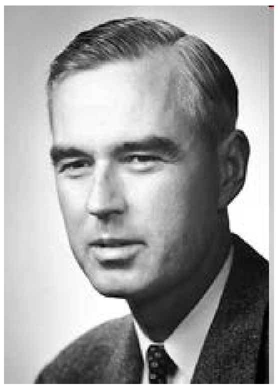
Constrain new physics $\langle \Delta V_{new} \rangle < \delta E$

Theory is needed – this works for "calculable" systems

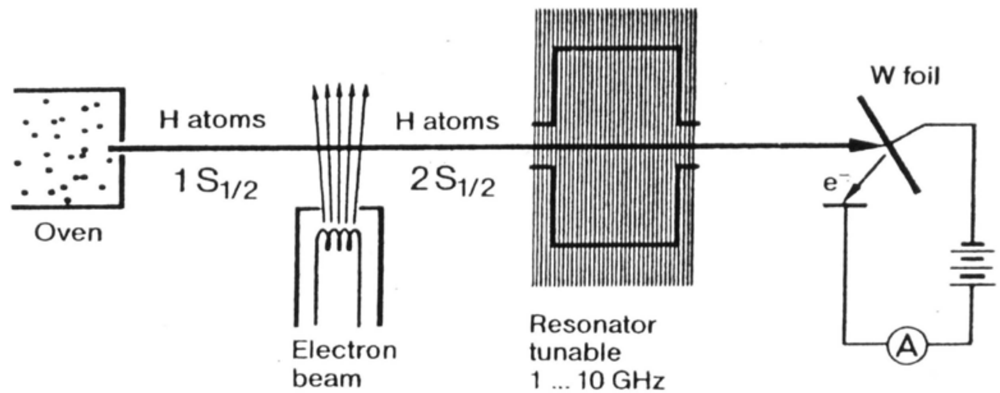
H_2 – Krzystof Pachucki, Jacek Komasa, Mariusz Puchalski

H_2^+/HD^+ - Vladimir Korobov, Jean-Philippe Karr, Laurent Hilico,

Historical Inspiration



Willis E Lamb



Measurement of the tiny $2S_{1/2} - 2P_{1/2}$ splitting

Breakdown of the Dirac theory of the electron
The advent of Quantum Electro Dynamics

Molecules as a metrology test system

1) Test of QED in molecules
H_2, HD, D_2, T_2

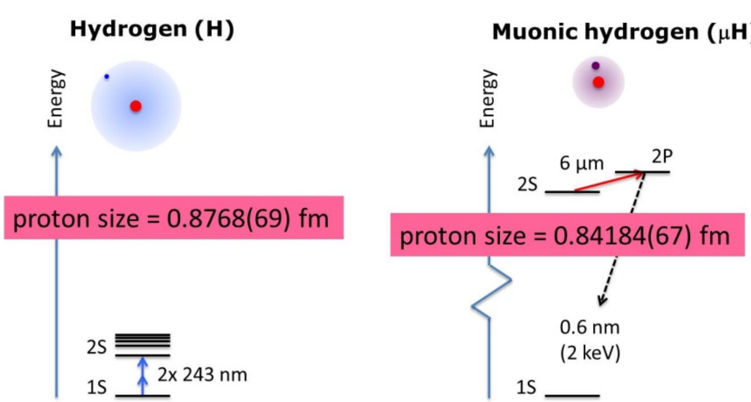
Born-Oppenheimer
Adiabatic corrections
Non-adiabatic corrections
or Full Nonadiabatic
Relativistic effects
QED effects up to order: $m\alpha^n$

2) The values
of fundamental constants

m_p / m_e m_d / m_e

m_t / m_e R_∞ α

3) The proton charge radius



4) New Physics

5th forces

Extra dimensions

Etc.

The proton size puzzle

$$E(n,l,j)/h = -\frac{Z^2 c R_\infty}{n^2}\frac{m_{\text{red}}}{m_e} + \frac{E_{NS}}{n^3}\delta_{l0} + \Delta(n,l,j)$$

$$E_{\text{NS}}^{(0)} = \frac{2}{3h}\left(\frac{m_{\text{red}}}{m_e}\right)^3 (Z\alpha)^4 m_e c^2 \left(\frac{r_N}{\lambda\!\!\!^{-}_C}\right)^2$$

$\propto (Z\alpha)^6$

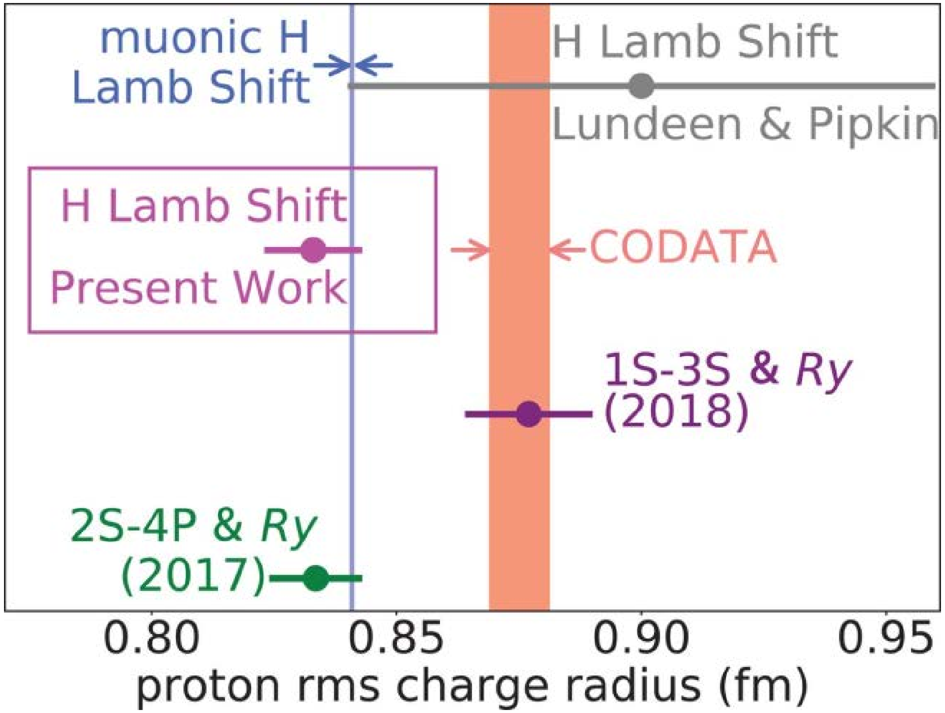
1s-2s in H
(15-digit accuracy)
= exact

+ 2s-2p Lamb shift

+ ns, np, nd states

+ molecular trans
(H2, HD, HD+, H2+)

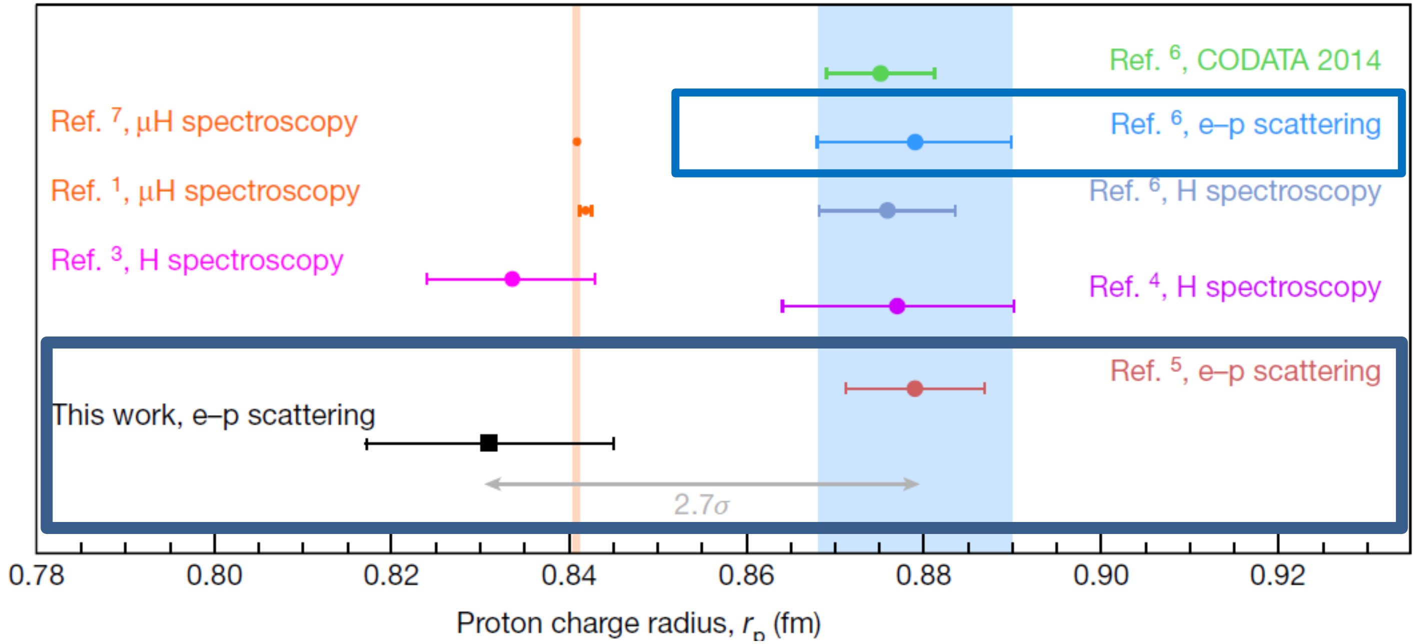
+ μH



The proton size puzzle

Remeasurement of e-p scattering (Jefferson Lab, Nature, Nov 2019)

+ 2s-4p
+ 1s-3s
Munich



→ That seems to be settled, finally !
→ So we trust the μH value (most accurate)

Fifth-force searches

Assume: Extra *hadron-hadron* interaction
Parametrize as:

Yukawa potential

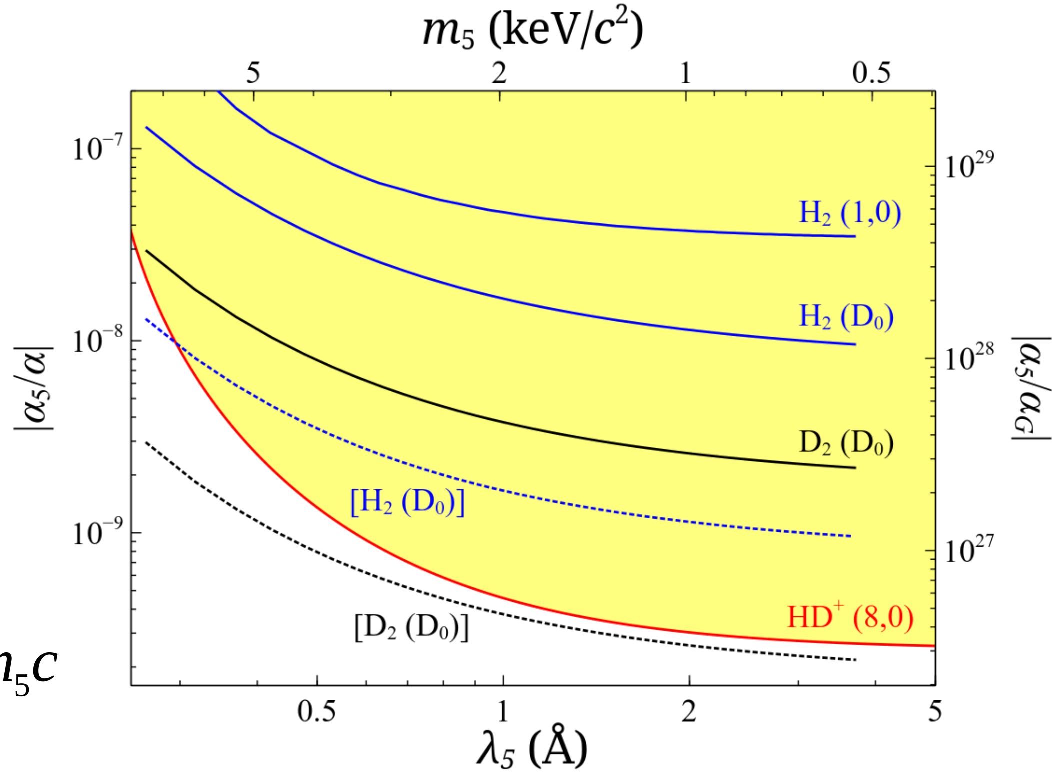
$$V_5(r) = N_1 N_2 \left\{ \alpha_5 \frac{\exp(-r/\lambda)}{r} \right\} \hbar c$$

Hideki Yukawa

Constraint:

$$\langle \Delta V_5 \rangle < \delta E$$

$$\lambda = \hbar / m_5 c$$



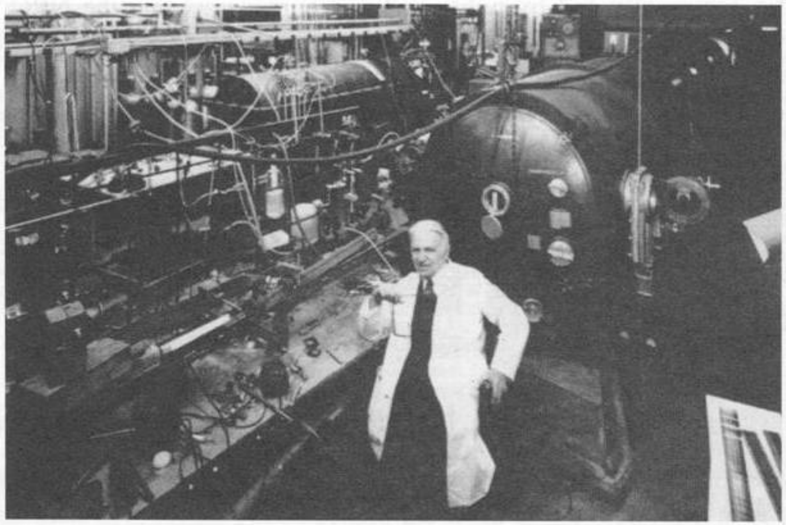
+ Search for higher Dimensions (ADD)

Salumbides
Gato-Rivera
Schellekens
Ubachs

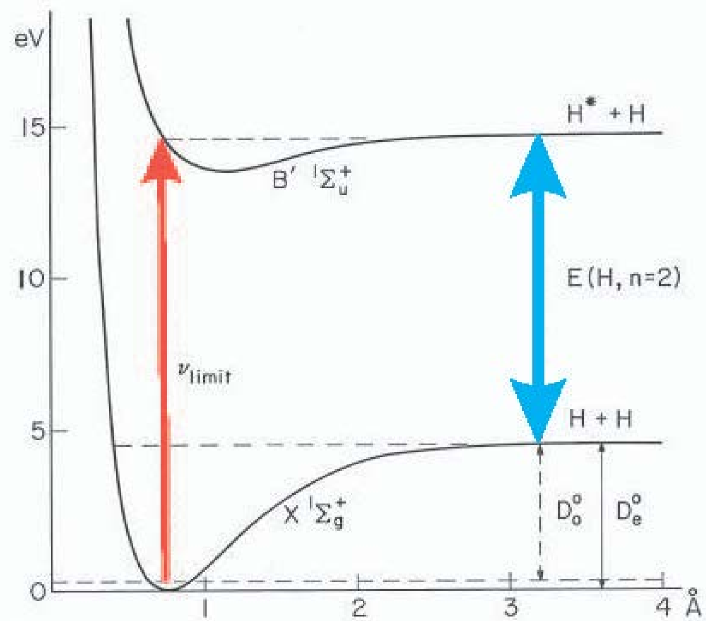
New. J. Phys 17, 033015 (2015)

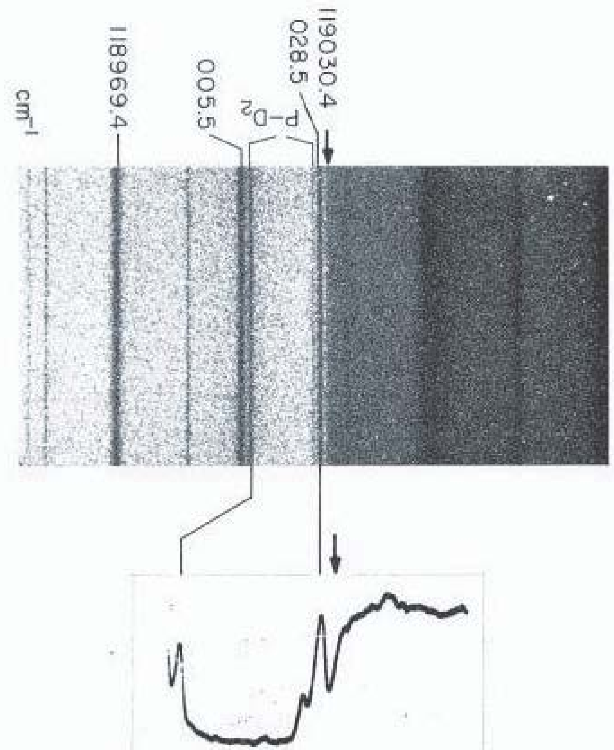
Salumbides, Koelemeij, Komasa, Pachucki, Eikema, Ubachs, *Phys Rev D* **87**, 112008 (2013).

H_2 Dissociation energy; benchmark

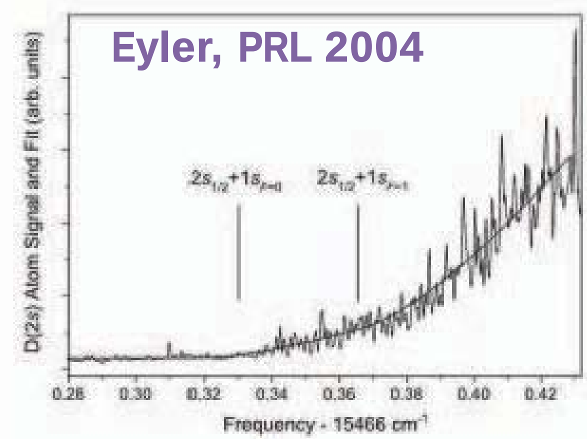


Herzberg in his laboratory.

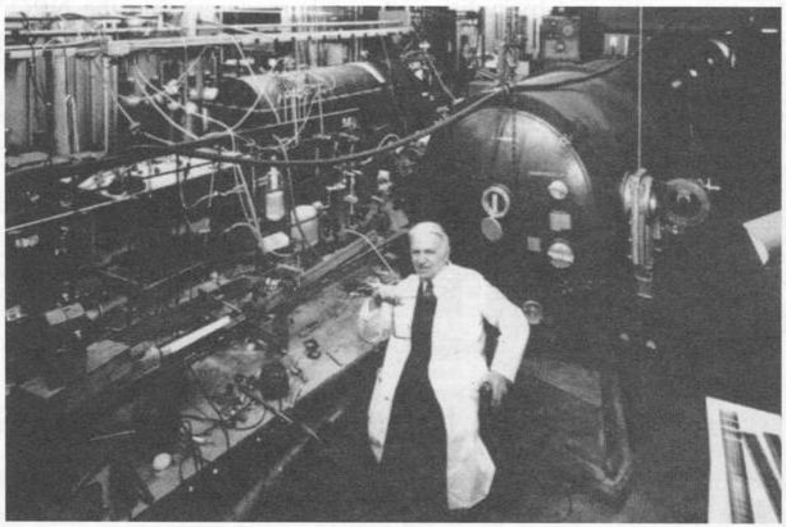




Herzberg Nobel Lecture

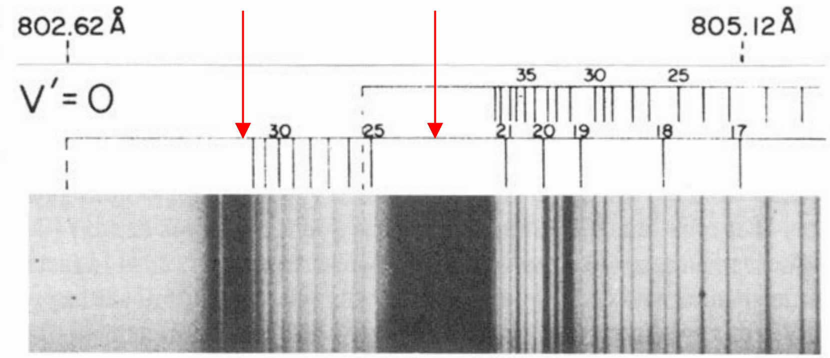


H_2 Dissociation energy; measurement of IP



Herzberg in his laboratory.

vibrational interlopers



Absorption spectrum of para-H_2 showing two Rydberg series, going to two different limits, after Herzberg and Jungen, 1972.

Christian Jungen

Herzberg and Jungen 1972

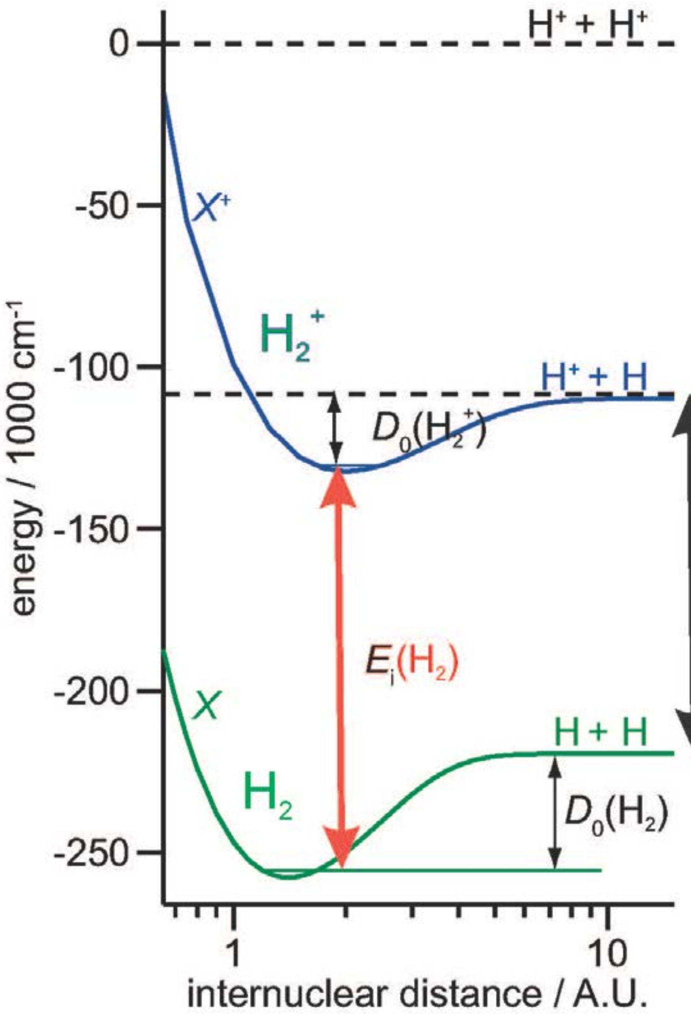
MQDT of molecules

$N^+=2$

$N^+=0$

Rydberg series interaction

Benchmark: Dissociation energy H_2



$$D_o(H_2) = E_{IP}(H_2) + D_o(H_2^+) - E_{IP}(H)$$

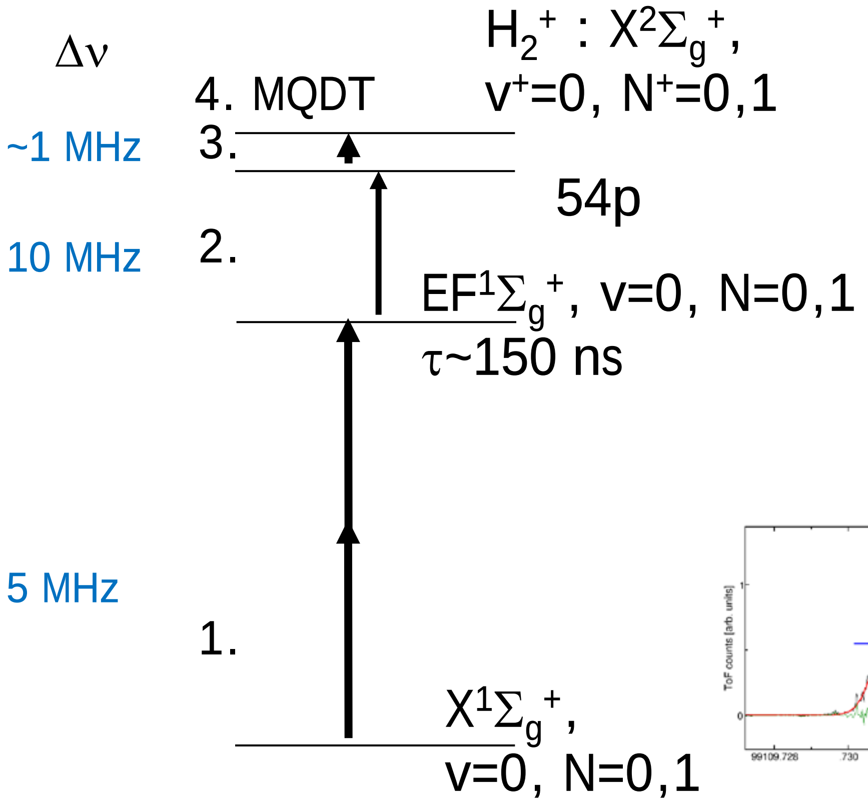
$$D_o(H_2^+) = 21379.350232(50)\ \mathrm{cm}^{-1}$$

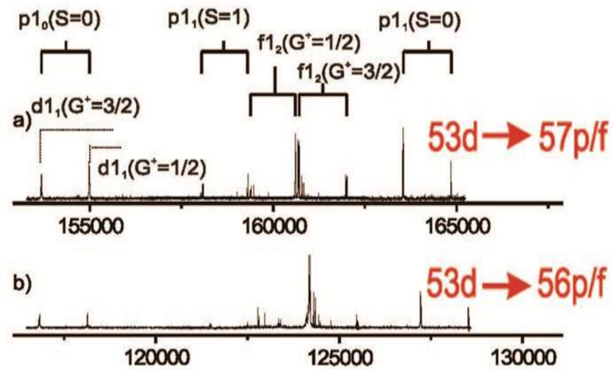
$$E_{IP}(H) = 109678.77174307(10)\ \mathrm{cm}^{-1}$$

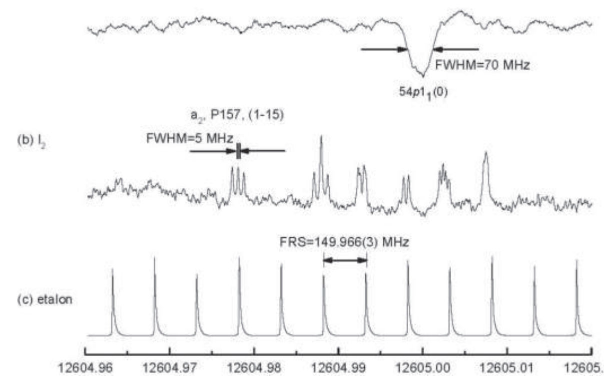
$$E_{IP}(H_2) \rightarrow D_o(H_2)$$

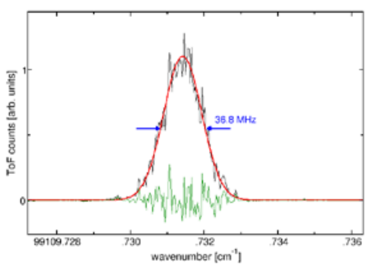
(2009 effort) Measurement of IP in H_2

3 step approach (Zürich-Amsterdam collaboration)









E_i (ortho) = 124 357.237 97 (36) cm^{-1}

E_i (para) = 124 417.491 13 (37) cm^{-1}

J. Liu et al, J. Chem. Phys. 130, 174306 (2009)

Comparison Theory/Experiment

(Theory: Pachucki, Komasa, et al.: 2010 values)

$D_0(H_2)$:	Experiment [1]	36118.0696(4) cm^{-1}
	Theory [2]:	
	Born–Oppenheimer	36112.5927(1) cm^{-1}
	adiabatic	+ 5.7711(1) cm^{-1}
	nonadiabatic	+ 0.4339(2) cm^{-1}
	total α^0	36118.7978(2) cm^{-1}
	α^2 all relativistic	– 0.5319(5) cm^{-1}
	α^3 all QED	– 0.1948(3) cm^{-1}
	α^4 one-loop term	– 0.0016(8) cm^{-1}
	Total theory	36118.0695(10) cm^{-1}
$D_0(D_2)$:	Total theory [2]	36748.3633(9) cm^{-1}
	Experiment [4]	36748.3629(7) cm^{-1}

QED

Towards measuring the ionisation and dissociation energies of molecular hydrogen with sub-MHz accuracy

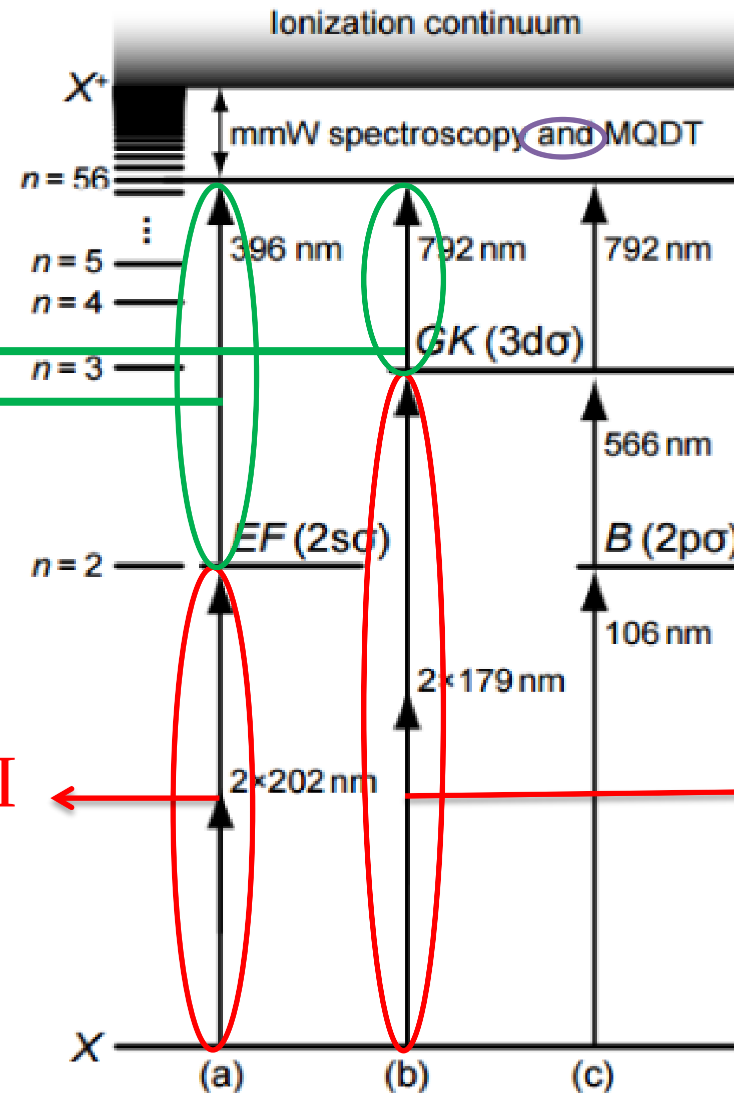
Faraday Meeting 2011

Daniel Sprecher,[a] Christian Jungen,†[b] Wim Ubachs[c] and Frédéric Merkt*[a]

Christian Jungen

Frederic Merkt

Zurich works
IR/UV CW
Laser excitation
+MMW



Further Rydberg MQDT-analyses

Direct frequency comb

II

I

2x VUV

Amsterdam works

Kjeld Eikema

Progress in theory;   NAPT and Full-NA

PHYSICAL REVIEW LETTERS **121**, 073001 (2018)

4-particle variational

Nonadiabatic Relativistic Correction to the Dissociation Energy of H_2, D_2, and HD

Mariusz Puchalski,[1] Anna Spyszkiewicz,[1] Jacek Komasa,[1] and Krzysztof Pachucki[2]
[1]*Faculty of Chemistry, Adam Mickiewicz University, Umultowska 89b, 61-614 Poznań, Poland*
[2]*Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland*

(Received 5 June 2018; published 14 August 2018)

Contribution	$D_0(H_2)$	$D_0(HD)$	$D_0(D_2)$
$\alpha^2 m$	36 118.797 746 10(3)	36 406.510 891 37(1)	36 749.090 990 99(2)
$\alpha^4 m$	−0.531 215 6(5)	−0.529 887 5(2)	−0.528 206 05(9)
$\alpha^5 m$	−0.194 8(2)	−0.196 4(2)	−0.198 2(2)
$\alpha^6 m$	−0.002 067(6)	−0.002 080(6)	−0.002 096(6)
$\mathcal{E}^{(2)}_{\rm rel} \sim \alpha^6 m$	0.000 008 5	0.000 008 6	0.000 008 6
$\alpha^7 m$	0.000 12(6)	0.000 12(6)	0.000 12(6)
FS	−0.000 031	−0.000 117	−0.000 204
Total	36 118.069 76(21)	36 405.782 54(21)	36 748.362 41(21)
Exp.	36 118.069 62(37)	36 405.783 66(36)	36 748.362 86(68)
	OK	2.7σ	OK

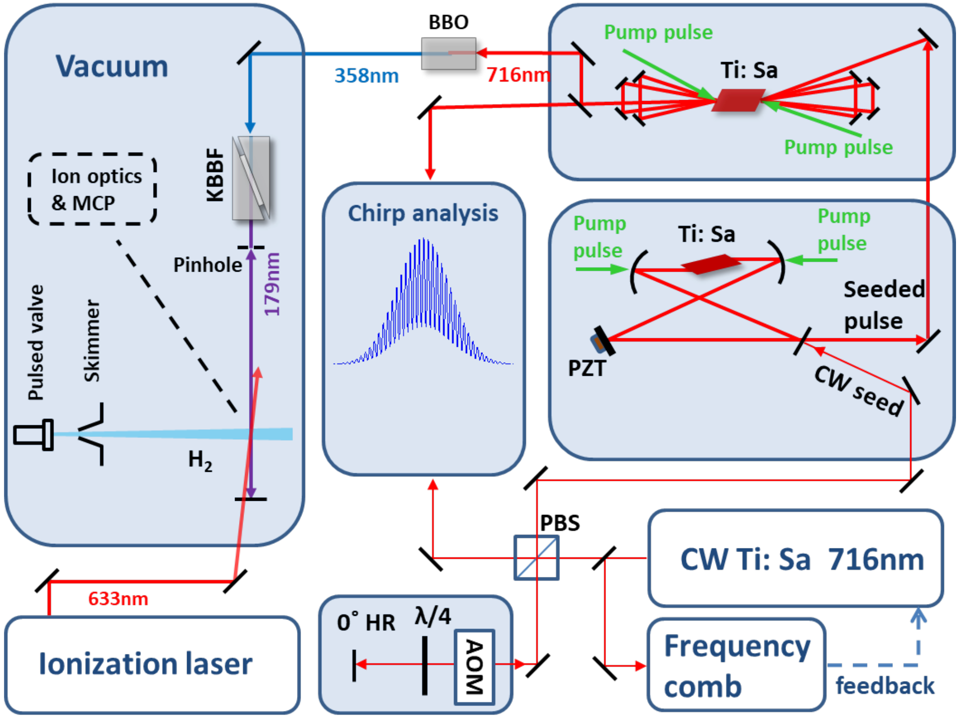
theory

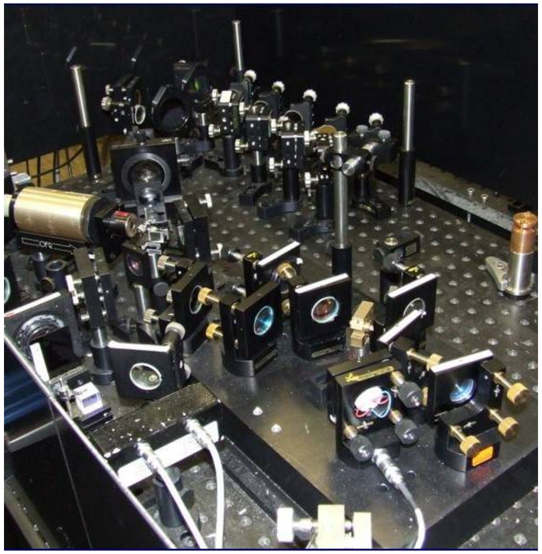
Ams+Zur 2010

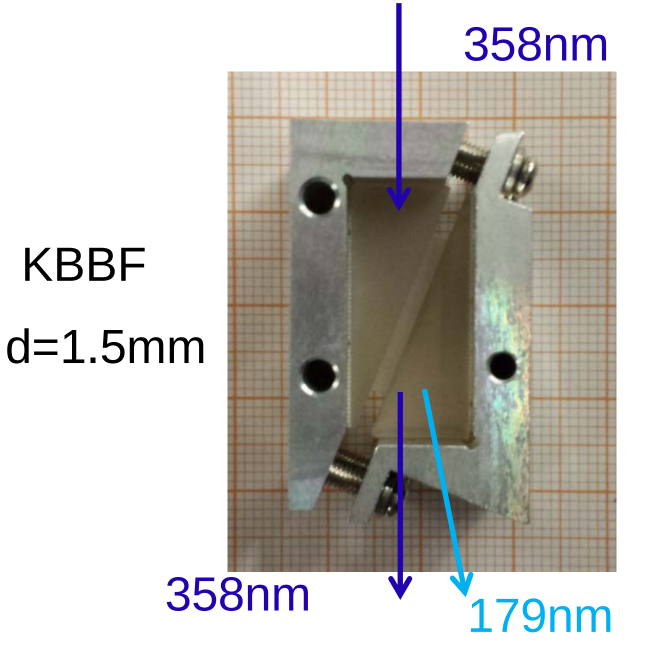
Path I

Two-photon Doppler-free at λ = 179 nm

Experimental Scheme







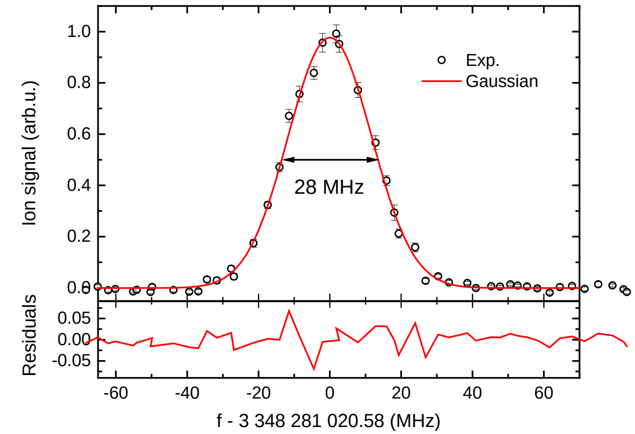
Path I

PHYSICAL REVIEW LETTERS **121**, 013001 (2018)

Featured in Physics

Ortho-H_2 ↑

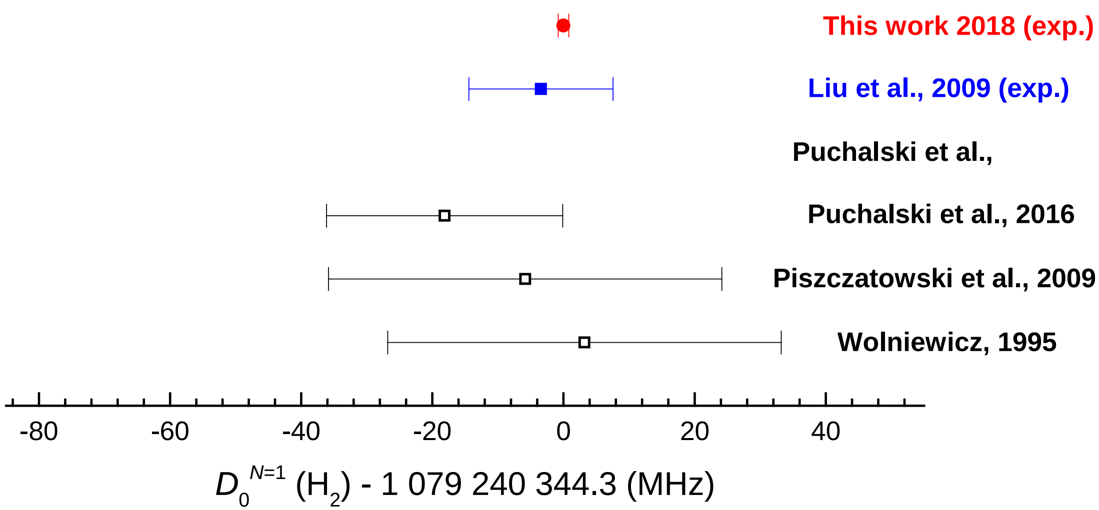
Dissociation Energy of the Hydrogen Molecule at 10^{-9} Accuracy



GK-X (N=1): 3348281018.35(49)$_{stat}$(43)$_{sys}$ MHz (2 x 10^{-10})

$E_i(H_2^{ortho})$ = 124 357.238 062(25) cm^{-1}

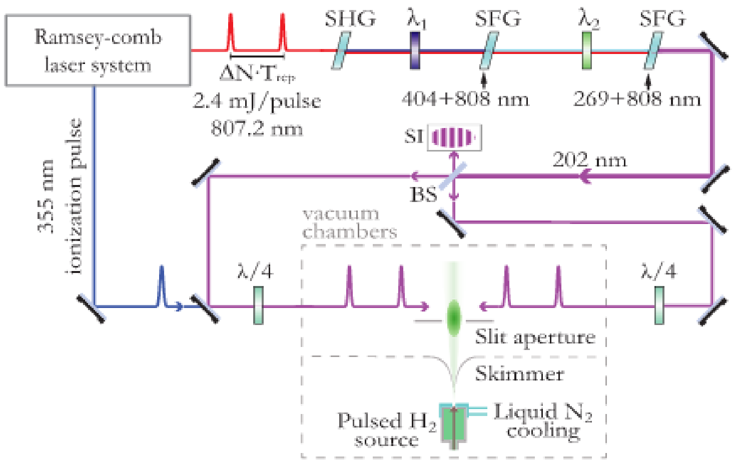
$D_0(H_2^{ortho})$ = 1 079 240 344.3(8) MHz (8 x 10^{-10})

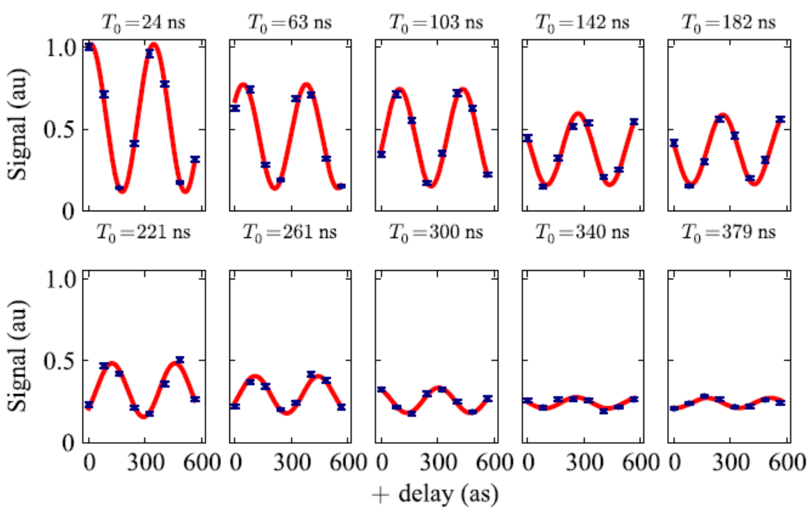


13 times better

Path II (direct frequency comb)

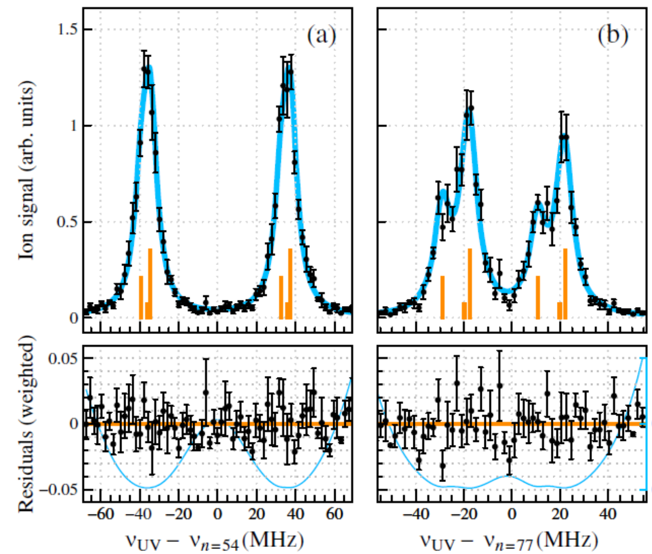
Amsterdam: EF-X(0,0) Q1
Direct Frequency-comb excitation;
Time-domain Ramsey ($\Delta\nu$= 70 kHz)





Altman et al, Phys. Rev. Lett. 120, 043204 (2018)

Zurich:
CW UV-laser excitation of Rydberg States; EF- np



$54p1_1 \leftarrow EF(0,1)$ $77p1_1 \leftarrow EF(0,1)$

Hölsch et al, Phys. Rev. Lett. 122, 123002 (2019)

Exp (2019):
$D_0(H_2)$ = 35999.582834 (11) cm^{-1}
340 kHz uncertainty
Theory (state-of-the-art):
$D_0(H_2)$ = 35999.582820 (26) cm^{-1}
1 MHz uncertainty

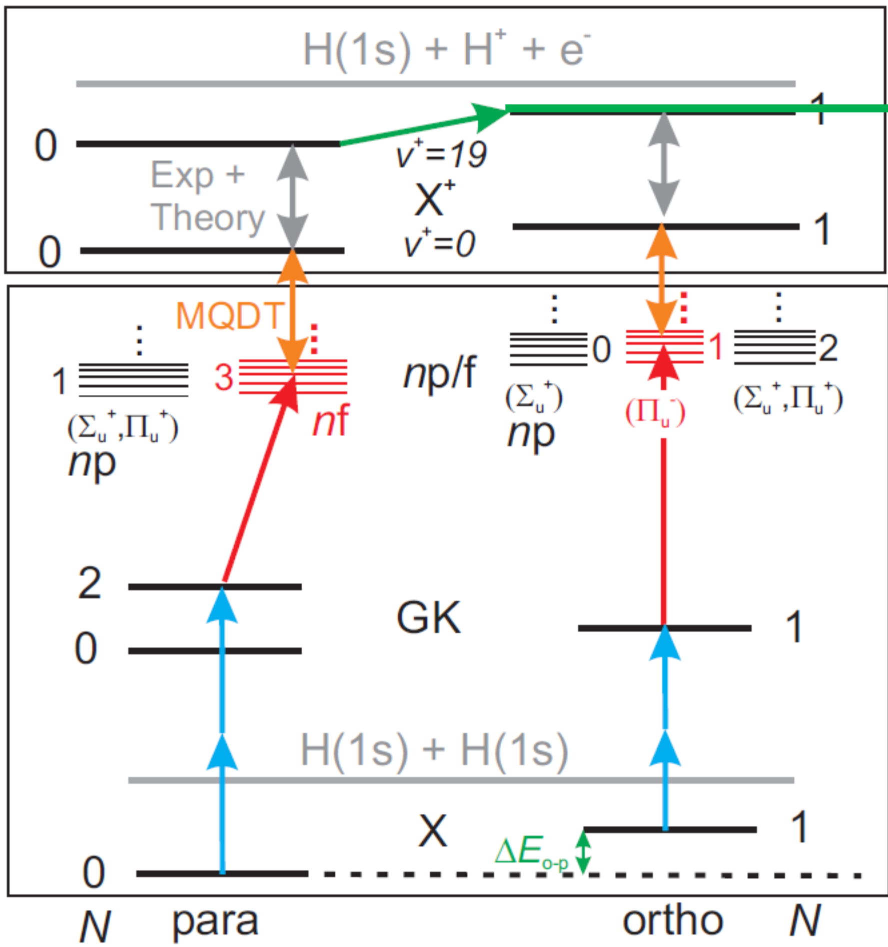
Puchalski et al, Phys. Rev. Lett. 122, 1230023 (2019)

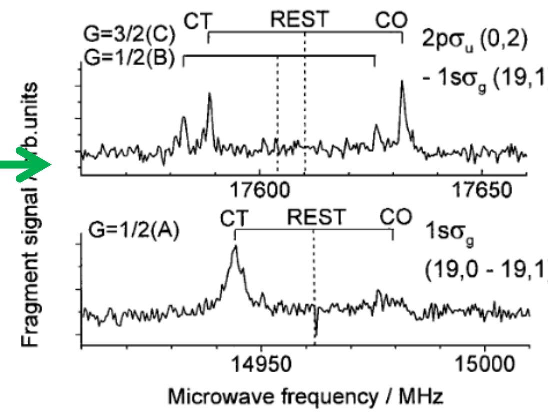
PHYSICAL REVIEW LETTERS **123**, 163002 (2019)

Editors' Suggestion

Determination of the Interval between the Ground States of Para- and Ortho-H_2

M. Beyer,[1,*] N. Hölsch,[1] J. Hussels,[2] C.-F. Cheng,[2,†] E. J. Salumbides,[2] K. S. E. Eikema,[2]
W. Ubachs,[2] Ch. Jungen,[3] and F. Merkt[1]





PRL
2001

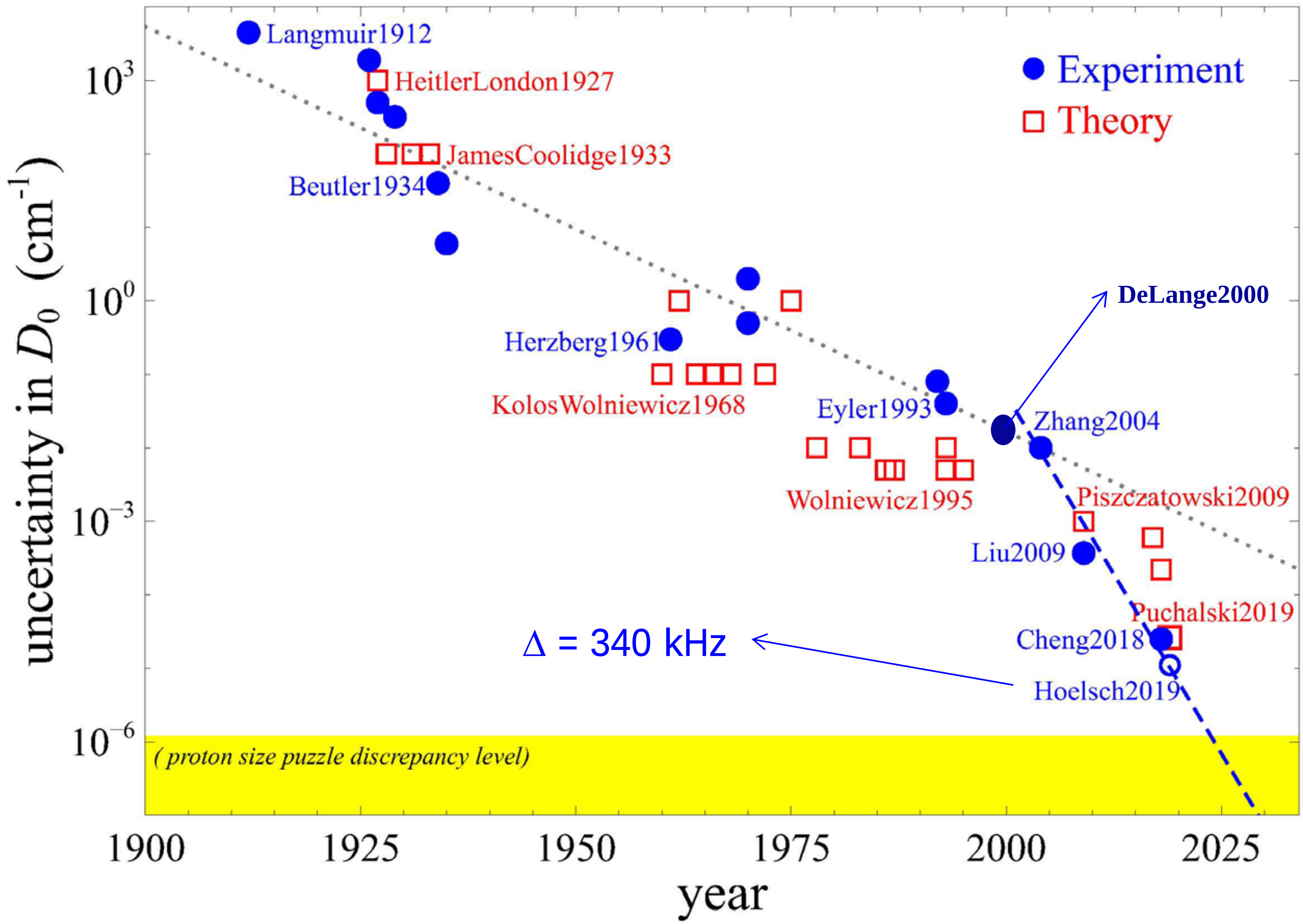
Para-H_2
- I=0 ; no hyperfine
- problem with Q(0)
- problems with np series

Ortho-para splitting in H_2

$\Delta_{o\text{-}p}$ = 118.486773(33) cm^{-1}
$\Delta_{o\text{-}p}^{th}$ = 118.4868127(11) cm^{-1}

Bound on spin-dependent forces ?

Pushing the precision frontier; history of $D_0(H_2)$



This is all pulsed lasers; can we do better ?

No. 4222 September 30, 1950 NATURE 563

Rotation-Vibration Spectrum of the HD Molecule

As is well known, the hydrogen molecule (H_2) has no ordinary dipole infra-red spectrum. Its quadrupole rotation-vibration spectrum is exceedingly weak, and has only recently been found[1]. In the case of HD, on account of the asymmetry, there is no longer a distinction between symmetric and antisymmetric rotational levels, and a dipole rotation-vibration spectrum can occur at least in principle. However, the change of dipole moment associated with the vibration of HD is obviously very small. The main contribution to this change is due to the fact that the electrons lag slightly behind the nuclei during the vibrational motion. Wick[2] has calculated according to wave mechanics the intensity of the fundamental of HD. From his data it can be estimated that the minimum absorbing path required for an observation of the fundamental of HD is 30 m. atm. For the overtones, correspondingly longer path-lengths would be required.

With the technique of long optical paths recently developed[3], it appeared promising to attempt an observation of the HD spectrum in the photographic infra-red. A glass absorption tube 5 metres long was filled with HD of 1 atm. pressure. Using approximately 140 and 200 traversals, that is, absorbing paths of 700 and 1,000 metres, seven and six lines respectively were found of the 3–0 and 4–0 bands of HD (second and third overtone) near 9650 and 7400 A. The accompanying table lists the observed

$$B_v = 45{\cdot}638_5 - 1{\cdot}9503(v+\tfrac{1}{2}) + 0{\cdot}0140_0\,(v+\tfrac{1}{2})^2.$$
$$D_v = 0{\cdot}02590 - 0{\cdot}00084(v+\tfrac{1}{2}) + 0{\cdot}00004_4\,(v+\tfrac{1}{2})^2.$$
$$G(v) = 3809{\cdot}7_{45}(v+\tfrac{1}{2}) - 89{\cdot}7668(v+\tfrac{1}{2})^2 + 0{\cdot}36567(v+\tfrac{1}{2})^3.$$

A value $H_v = 0{\cdot}0000219$ cm.$^{-1}$ was assumed. The differences between the observed wave-numbers and those calculated from the new constants are given in the last column of the table.

If a sufficient amount of hydrogen and deuterium were present in the atmospheres of the major planets, the 4–0 band of HD might be used for their detection[7]. However, this would require the highest possible resolution, because of the small width of these lines.

It is hoped to observe the fundamental and first overtone of HD in the near future with the aid of a new high-dispersion infra-red spectrometer which is being built in this laboratory.

G. HERZBERG

Division of Physics,
National Research Council,
Ottawa, Ontario, Canada.
May 30.

[1] Herzberg, G., *Nature*, **163**, 170 (1949); *Can. J. Res.*, A, **28**, 144 (1950).

[2] Wick, G. C., *Atti Reale Accad. Lincei*, **21**, 708 (1935).

[3] White, J. U., *J. Opt. Soc. Amer.*, **32**, 285 (1942). Bernstein, H. J., and Herzberg, G., *J. Chem. Phys.*, **16**, 30 (1948).

[4] Jeppesen, C. R., *Phys. Rev.*, **45**, 480 (1934).

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FORBIDDEN TRANSITIONS IN DIATOMIC MOLECULES

V. THE ROTATION–VIBRATION SPECTRUM OF THE HYDROGEN-DEUTERIDE (HD) MOLECULE[1]

(1960)

HD (2-0) band

R. A. DURIE[2] AND G. HERZBERG

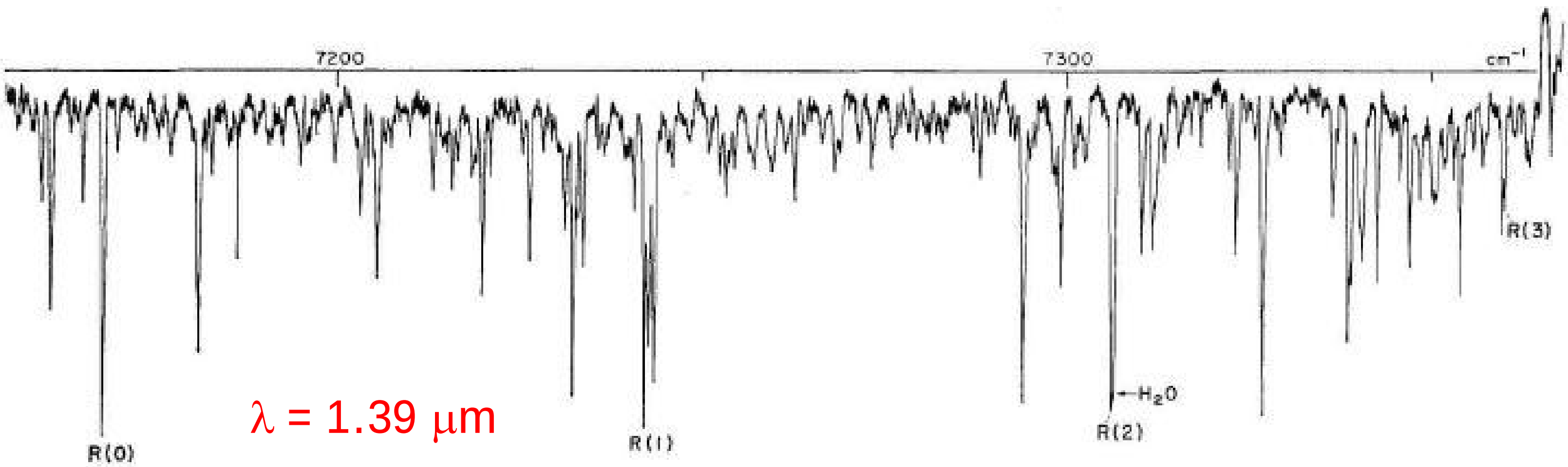
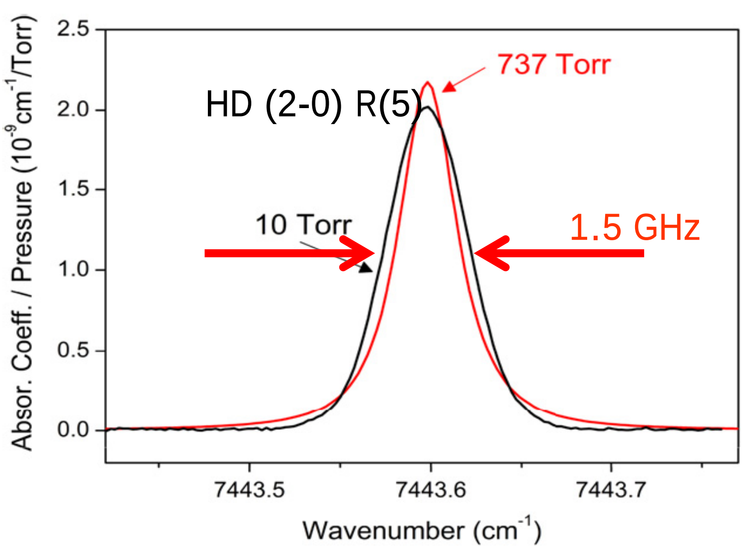


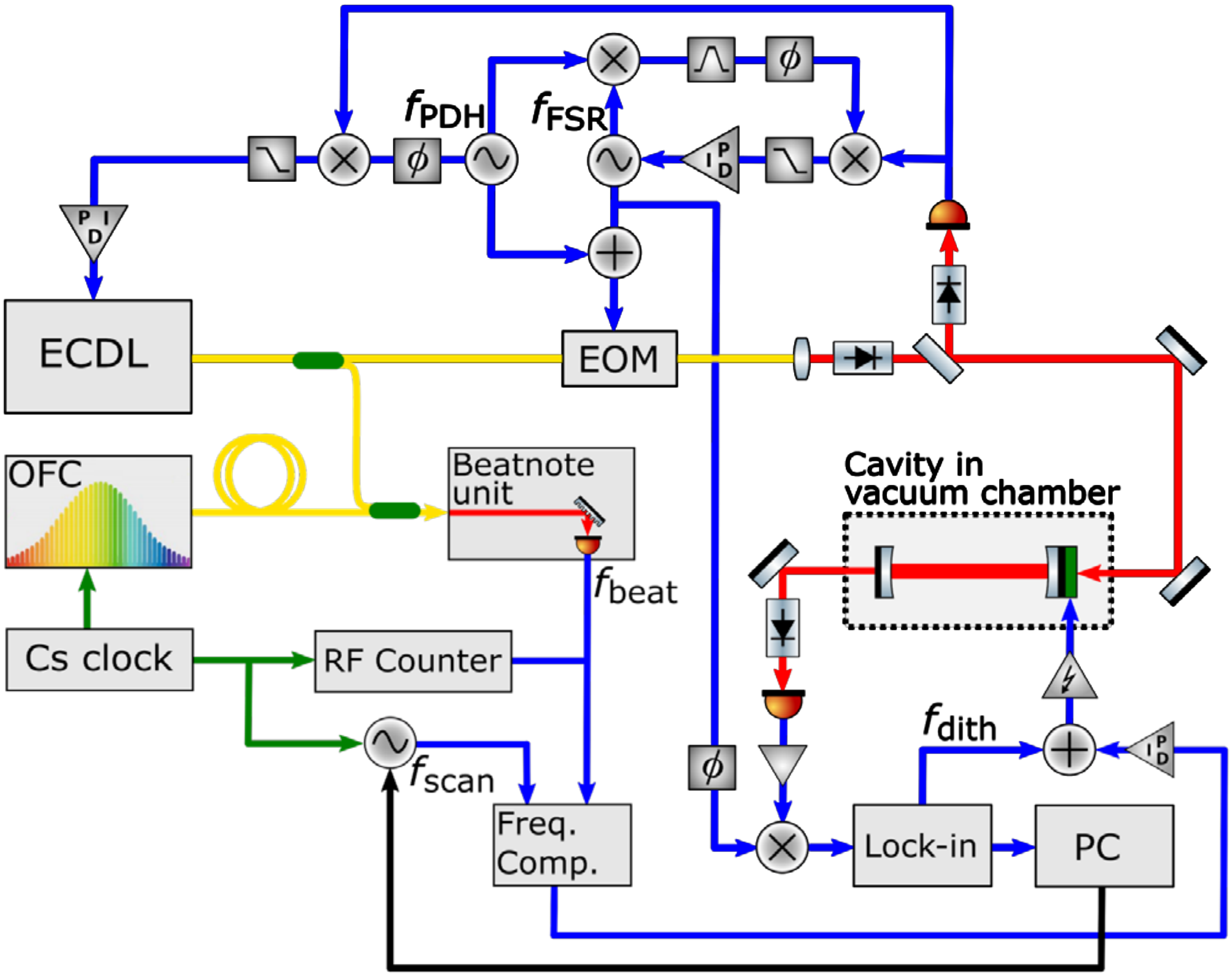
FIG. 2. *R* branch of 2–0 band of HD.
Absorbing path 200 m atm. Rapid scan in 2nd order of 7200 lines/inch grating. The unmarked absorption lines are due to H_2O.



Kassi & Campargue, Grenoble

Journal of Molecular Spectroscopy 267 (2011) 36–42

Frequency comb referenced NICE-OHMS



Cavity
- 130,000 finesse
- 40 km length
- ~ 100 W power

Diode laser
- Locked to cavity
- And to Comb

Detection
- Lock-in

OFC lock
- Stabilized to CS clock

NICE-OHMS; J. Ye, L.S. Ma, J. Hall; J Opt. Soc. Am. B (1998)

Sub-Doppler Frequency Metrology in HD for Tests of Fundamental Physics

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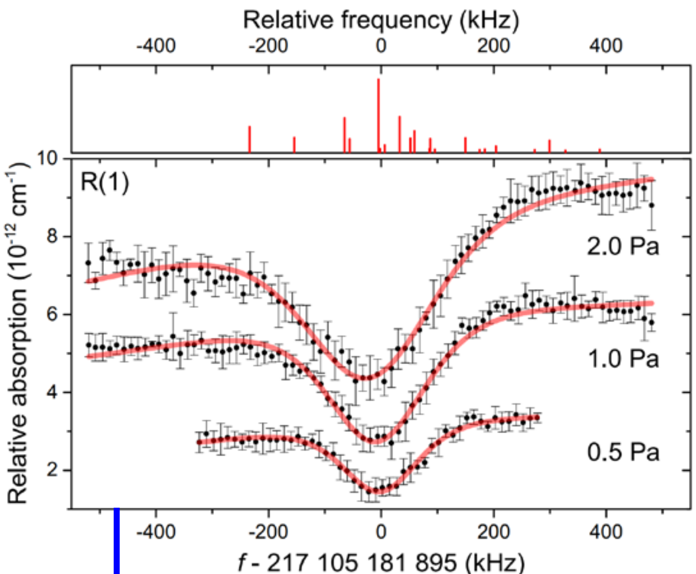
(Received 22 December 2017; published 9 April 2018)



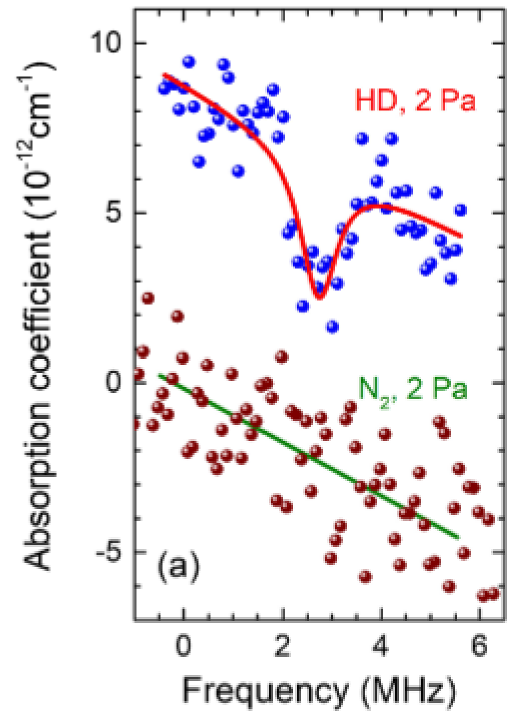
R(1) [2-0]

AMS

Hefei

$\Delta_{\text{AMS-Hefei}}$ = 900 kHz

(Discussed Opt. Lett. 2019)



Lines too narrow:
- transit time
- hyperfine
- recoil doublet

Section of cold molecules
(100 W intra / sat 10 kW)

Toward a Determination of the Proton-Electron Mass Ratio from the Lamb-Dip Measurement of HD

L.-G. Tao,[1] A.-W. Liu,[1,2] K. Pachucki,[3] J. Komasa,[4] Y. R. Sun,[1,2] J. Wang,[1] and S.-M. Hu[1,2,*]
[1]*Hefei National Laboratory for Physical Sciences at Microscale, iChem center, University of Science and Technology of China, Hefei, 230026 China*
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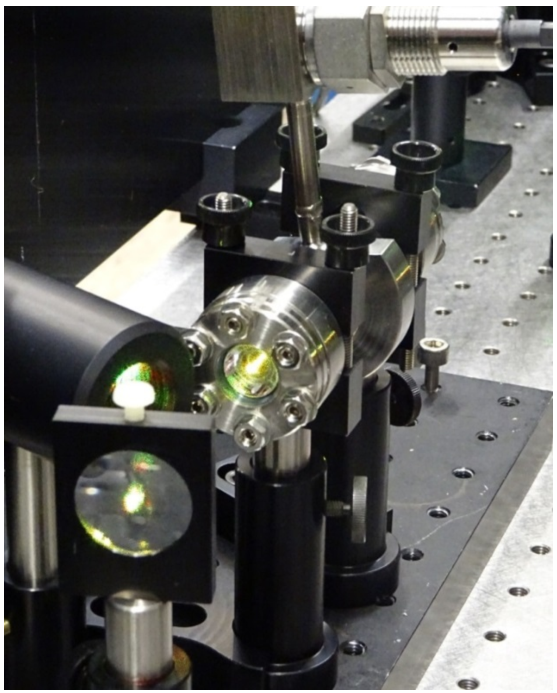
(Received 22 December 2017; published 9 April 2018)

Pushing the experimental frontier : include Tritium

TLK Tritium Laboratory Karlsruhe

KIT Karlsruhe Institute of Technology

LaserLaB Amsterdam



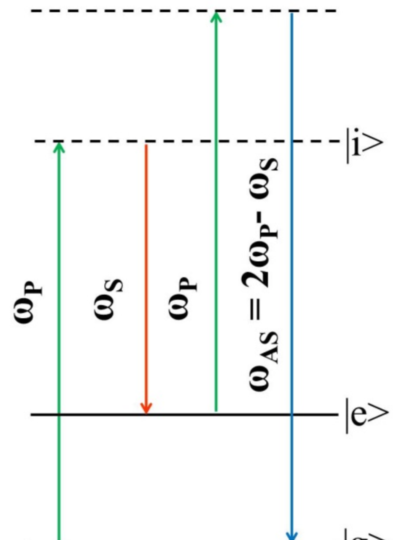
<1 GBq (15 mbar x cm^3)

All optical experiment

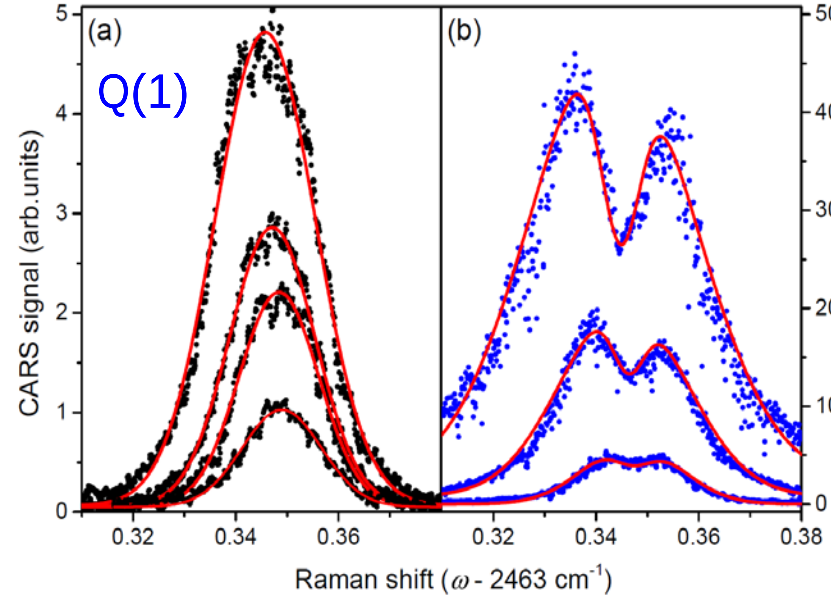
CARS (saturated CARS)

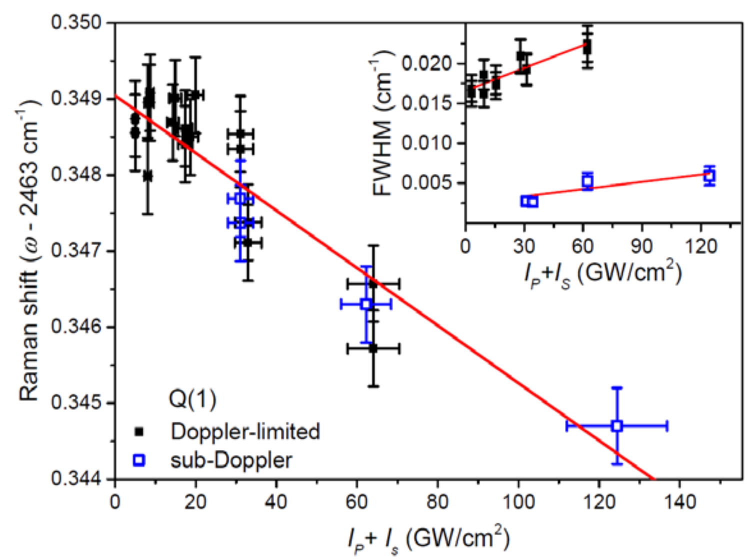
Phys. Rev. Lett. 163002 (2018)

CARS scheme

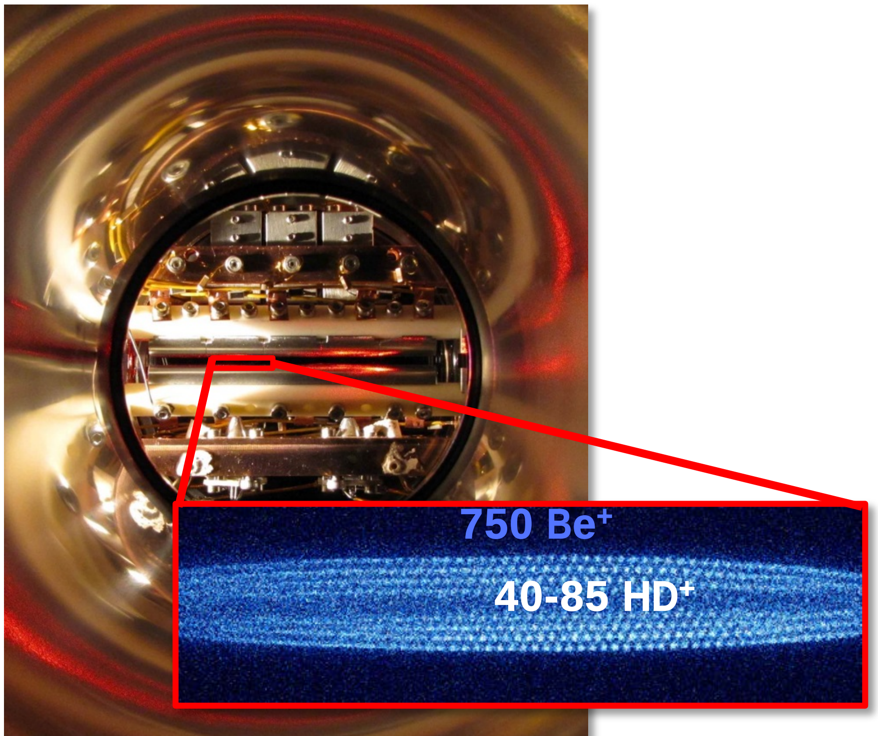


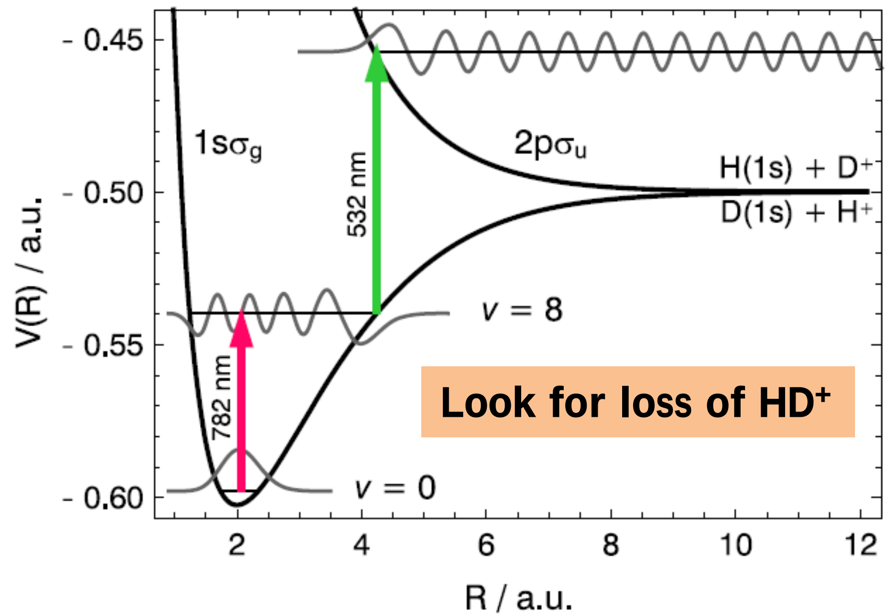
T_2

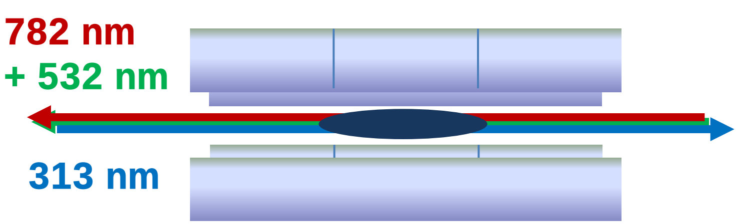




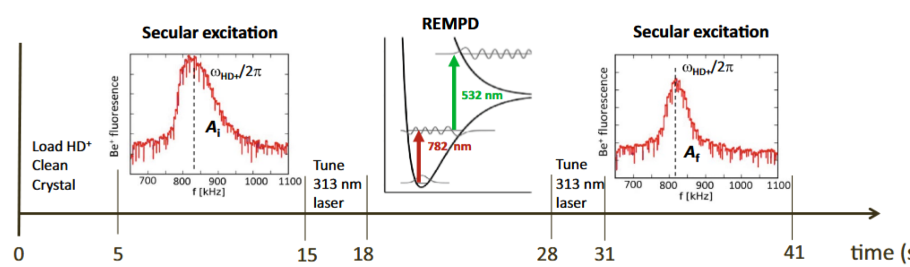
HD^+ ions in a trap; measurement of (8,0)



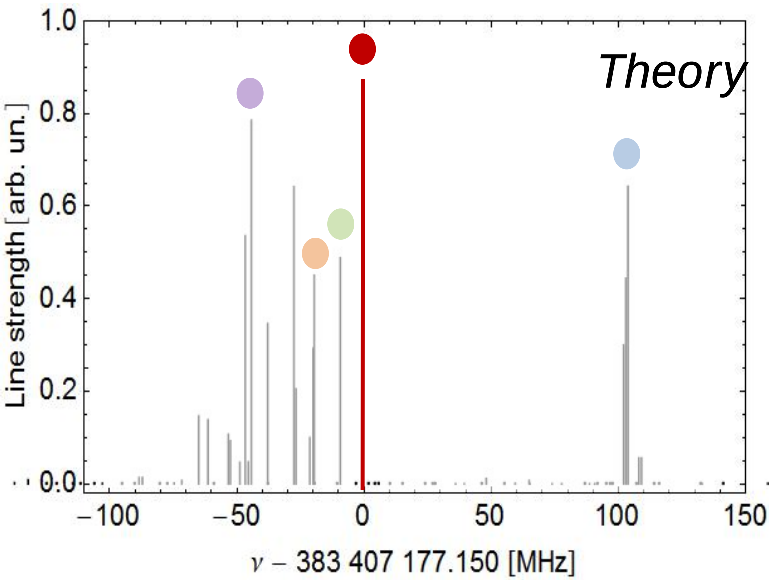


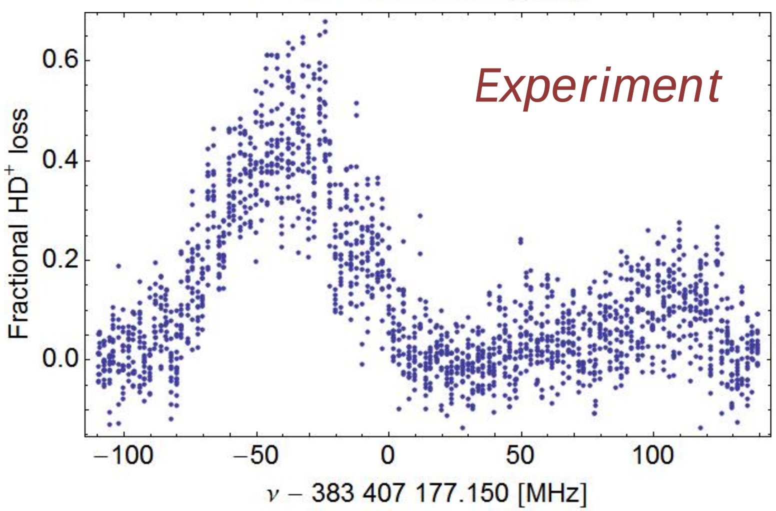


Signal detection by REMPD

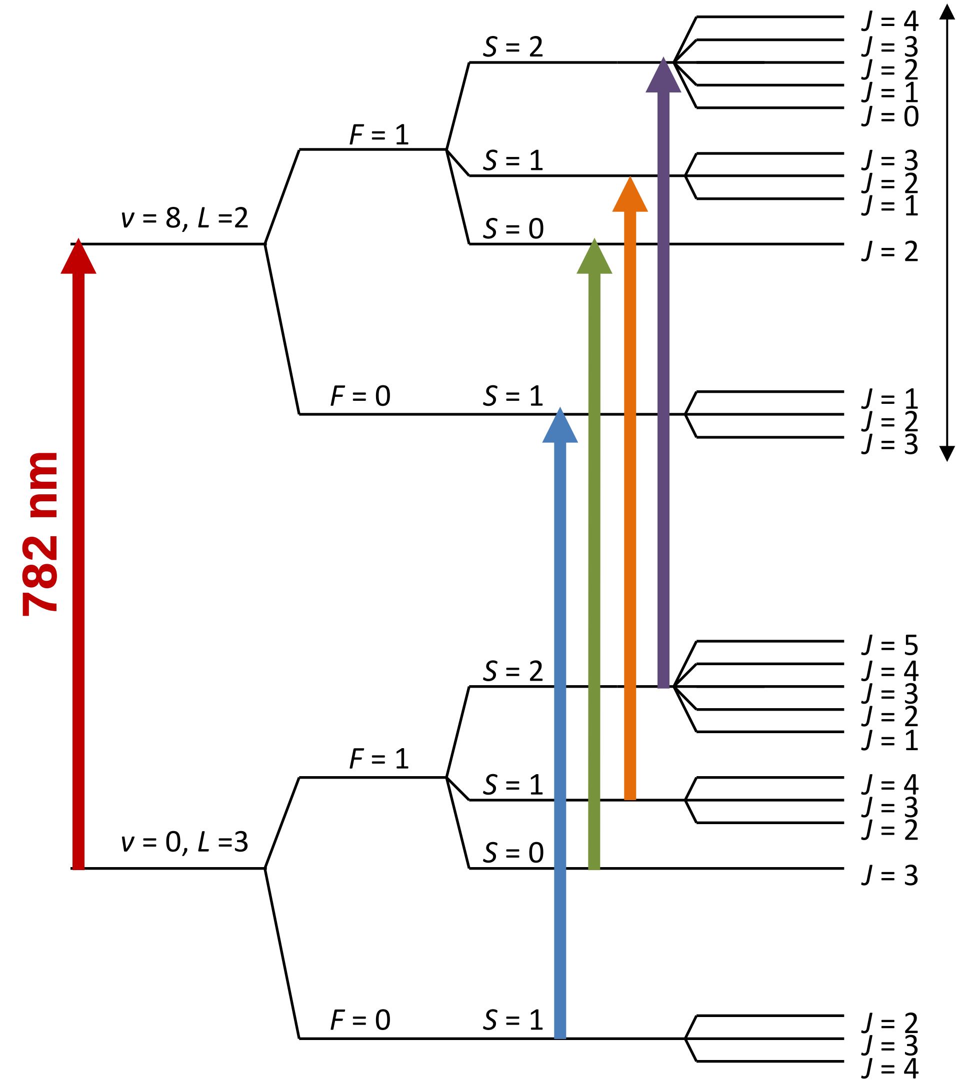


HD^+ spectrum





Biesheuvel et al. Nat. Comm. 7 (2016) 10385



Experiment: 383,407,177.38(41) MHz

Theory*: 383,407,177.150(15) MHz

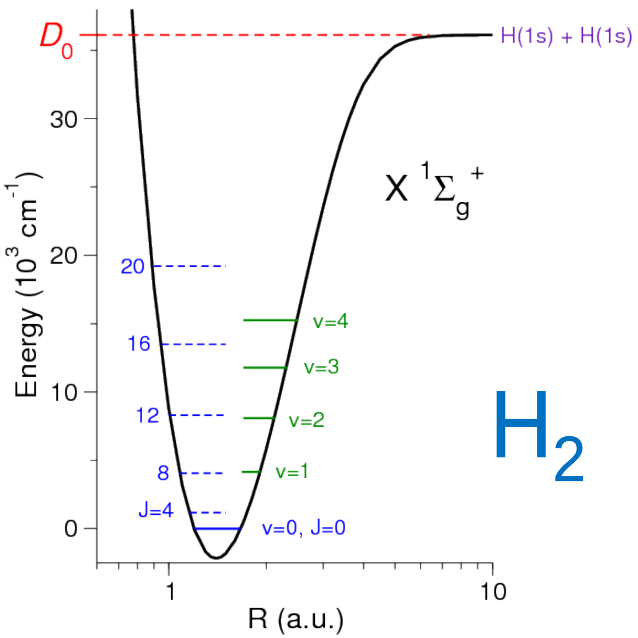
*Korobov, Hilico, Karr, Phys. Rev. A **89**, 032511 (2014)

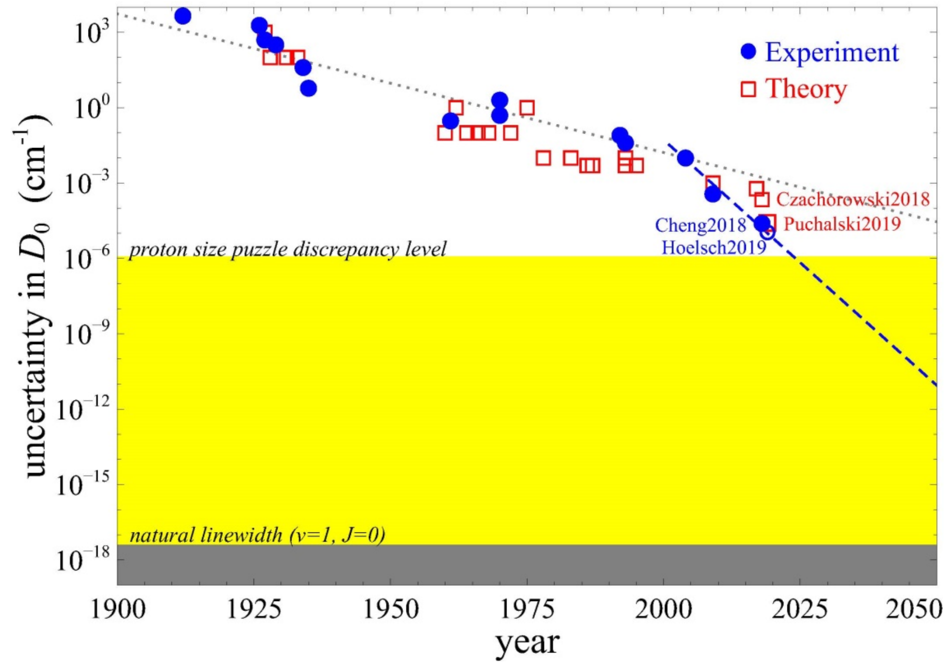
Conclusion:

Molecular Spectroscopy for Fundamental Physics

OUTLOOK:

A future molecular test system for physics





Lifetimes 10^6 seconds (!)

Quadrupole transitions ~ 10^{14} Hz

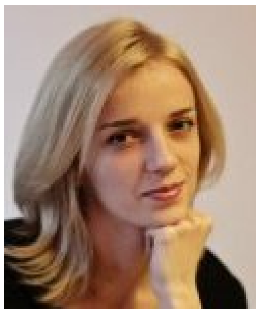
Possible precision 20-digit

There is room at the bottom

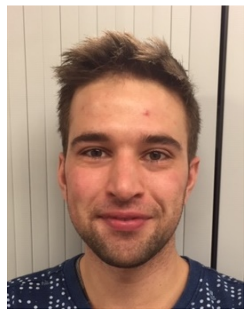
Thanks & Acknowledgement

LaserLaB Amsterdam

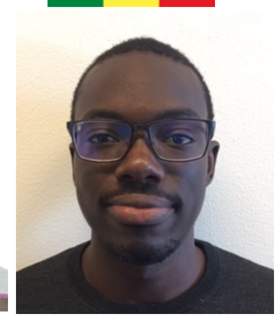
erc European Research Council


Julija Bagdonaite

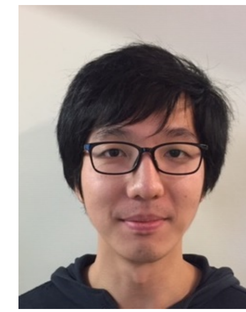

Edcel Salumbides


Joel Hussels


Madhu T Trivikram


Meissa Diouf


Frank Cozijn


Kin Fung Lai


Kjeld Eikema


Jeroen Koelemeij


Matthias Germann


Frederic Merkt


Krzysztof Pachucki


Magnus Schloesser