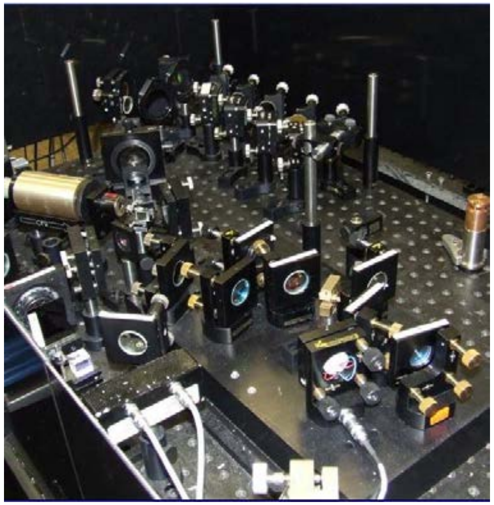
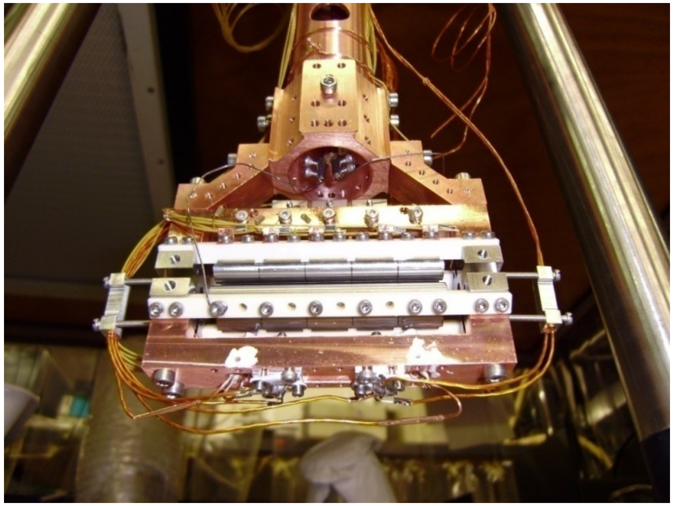
Precision spectroscopy of molecular hydrogen and the search for new physics





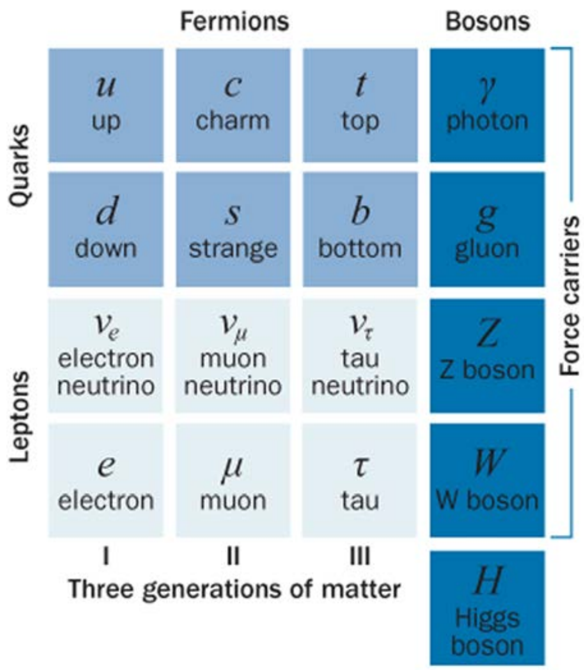
LaserLaB Amsterdam

Wim Ubachs
Vrije Universiteit Amsterdam

International Symposium on Molecular Spectroscopy
Urbana-Champaign
22 June 2017

The Standard Model of Physics

What do we know ?



What do we not know ?

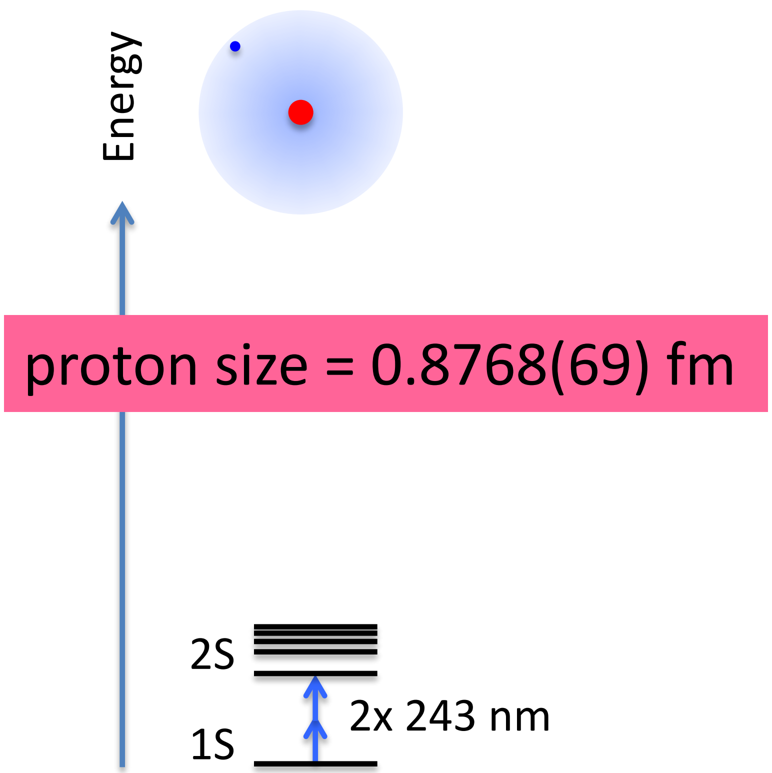
- Dark Matter
- Dark Energy
- How does Gravity fit to SM ?
- Why is Gravity so weak ?
- Are there only 3+1 dimensions ?
- Are there only 4 forces ?

Fundamental constants drift ?

- Variation on cosmological scale
- Dependencies on fields as indicators ?

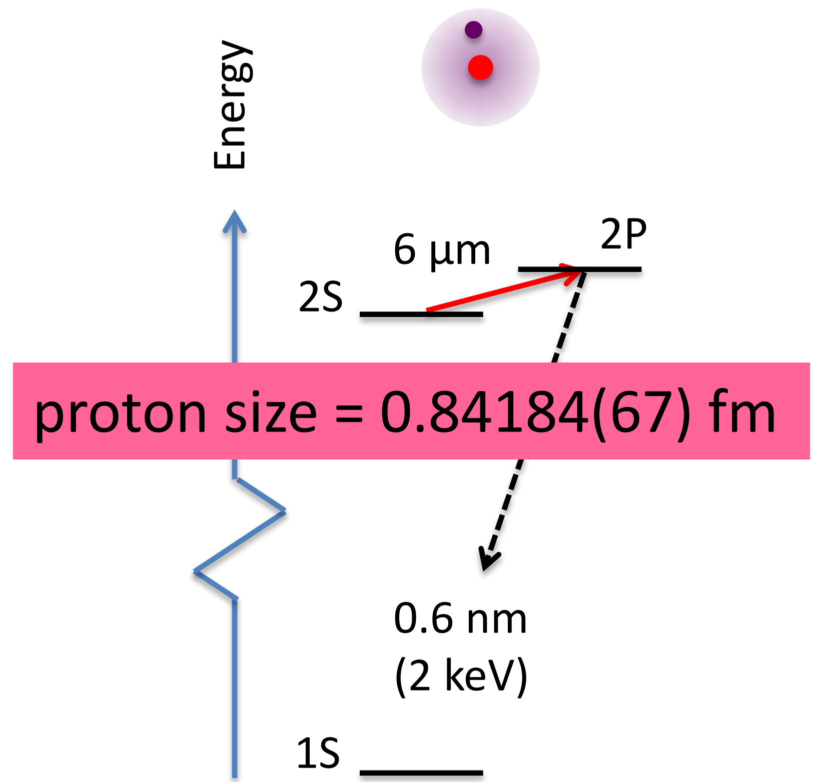
New urgent question: proton-radius puzzle

Hydrogen (H)



C.G. Parthey et al.,
PRL **107**, 203001 (2011)

Muonic hydrogen (μH)

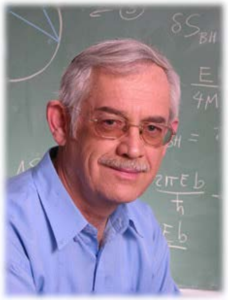


R. Pohl et al,
Nature, vol. **466**, pp. 213-216 (2010)
Science **339**, 417-420 (2013).

Varying Constants of Nature ?

Coupling constants are free parameters in Standard Model
But cannot be varied at will

$$S = \int \left(L_{mat} + \frac{j_\mu}{c} A^\mu - \frac{\varepsilon_0}{4} F_{\mu\nu} F^{\mu\nu} e^{-2\phi} - \frac{\hbar c}{2l^2} \partial_\mu \partial^\mu \phi \right) d\Omega$$



Jacob Bekenstein

Bekenstein – Barrow – Flambaum : consistent models

$$\phi \rightarrow \Delta\alpha, \Delta\mu$$

1) Variation on cosmological time scales
"Connection to Dark Energy scenarios"

2) Coupling to environment
-> "chameleons"
Dependence on local density
Dependence on gravity

Empirical search for a change in μ

Compare H_2 in different epochs

Lab

today

QSO

12 Gyr ago

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

90-112 nm

~300-500 nm

Cosmological redshift

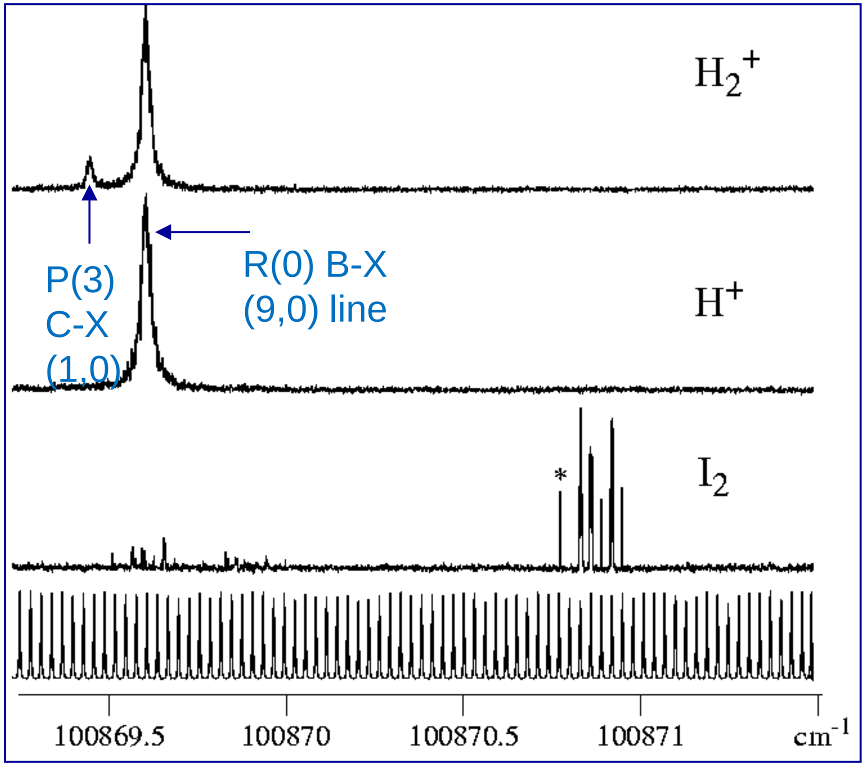
$$T = T_0 \left[1 - \frac{1}{(1 + z_{abs})^{3/2}} \right]$$

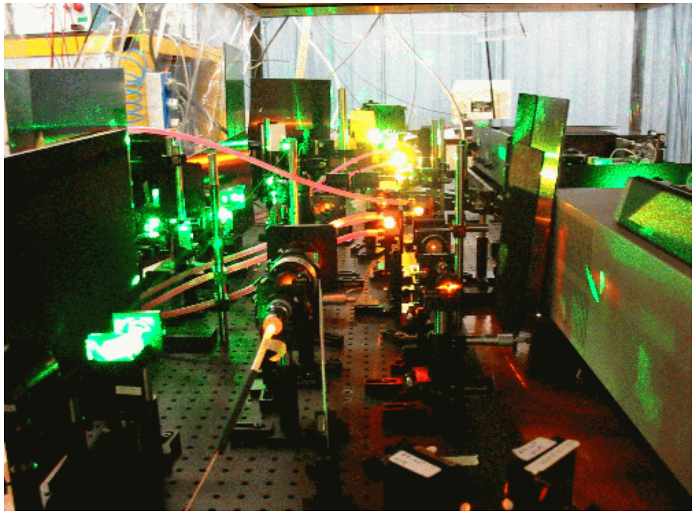
Practical: atmospheric transmission only for $z > 2$

H_2 laboratory wavelengths

The Amsterdam “XUV-laser”

XUV-laser excitation (90-115 nm)





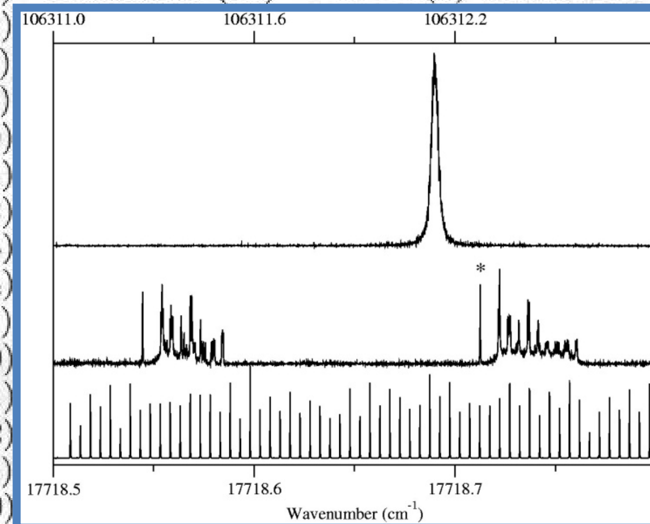
Ubachs, Phys. Rev. Lett. (2004)
Reinhold et al, Phys. Rev. Lett. (2006)

For HD

Ivanov et al., Phys. Rev. Lett. (2008)

TABLE I: Comprehensive list of measured transition wavelengths of the Lyman (L) and Werner (W) lines using the ultr narrowband XUV laser source in Amsterdam. Values in nm.

Line	λ_0	Line	λ_0	Line	λ_0	Line	λ_0
L0 P(1)	111.006 251 (6)	L8 P(3)	100.838 615 (6)	L13 R(3)	95.894 665 (6)	W1 P(3)	99.138 046 (8)
L0 R(0)	110.812 733 (7)	L8 R(0)	100.182 387 (5)	L13 R(4)	96.215 297 (6)	W1 Q(1)	98.679 800 (5)
L0 R(1)	110.863 326 (7)	L8 R(1)	100.245 210 (5)	L14 P(1)	94.751 403 (10)	W1 Q(2)	98.797 445 (6)
L1 P(1)	109.405 198 (6)	L8 R(2)	100.398 545 (5)	L14 R(0)	94.616 931 (10)	W1 Q(3)	98.972 929 (8)
L1 P(2)	109.643 894 (6)	L8 R(3)	100.641 416 (6)	L14 R(1)	94.698 040 (10)	W1 R(0)	98.563 371 (5)
L1 P(3)	109.978 718 (7)	L9 P(1)	99.280 968 (5)	L14 R(2)			5)
L1 R(0)	109.219 523 (6)	L9 R(0)	99.137 891 (5)	L15 P(1)			6)
L1 R(1)	109.273 243 (6)	L9 R(1)	99.201 637 (5)	L15 P(3)			9)
L1 R(2)	109.424 460 (6)	L9 R(2)	99.355 061 (9)	L15 R(0)			6)
L1 R(3)	109.672 534 (6)	L9 R(3)	99.597 278 (20)	L15 R(1)			7)
L2 P(1)	107.892 547 (5)	L10 P(1)	98.283 533 (5)	L15 R(2)			7)
L2 R(0)	107.713 874 (5)	L10 P(2)	98.486 398 (5)	L15 R(3)			5)
L2 R(1)	107.769 894 (5)	L10 P(3)	98.776 882 (6)	L15 R(4)			5)
L2 R(2)	107.922 542 (6)	L10 R(0)	98.143 871 (5)	L16 P(1)			7)
L2 R(3)	108.171 124 (7)	L10 R(1)	98.207 427 (5)	L16 R(0)			7)
L2 R(4)	108.514 554 (6)	L10 R(2)	98.359 107 (5)	L16 R(1)			8)
L3 P(1)	106.460 539 (5)	L10 R(3)	98.596 279 (6)	L16 R(2)			5)
L3 P(2)	106.690 068 (5)	L11 P(1)	97.334 458 (5)	L17 P(1)			5)
L3 R(0)	106.288 214 (5)	L11 P(2)	97.534 576 (5)	L17 R(0)			6)
L3 R(1)	106.346 014 (5)	L11 P(3)	97.821 804 (6)	L17 R(1)	92.464 326 (9)	W2 R(3)	96.678 035 (7)
L3 R(2)	106.499 481 (5)	L11 R(0)	97.198 623 (5)	L18 P(1)	91.841 331 (9)	W3 P(2)	94.961 045 (5)
L3 R(3)	106.747 855 (5)	L11 R(1)	97.263 275 (5)	L18 R(0)			36 (5)
L4 P(1)	105.103 253 (4)	L11 R(2)	97.415 791 (5)	L18 R(1)			38 (5)
L4 R(0)	104.936 744 (4)	L11 R(3)	97.655 283 (6)	L18 R(2)			33 (5)
L4 R(1)	104.995 976 (4)	L11 R(4)	97.980 512 (7)	L19 P(1)			73 (5)
L4 R(2)	105.149 857 (5)	L11 R(5)	98.389 896 (7)	L19 P(2)			57 (4)
L4 R(3)	105.397 610 (4)	L12 P(1)	96.431 064 (5)	L19 P(3)			75 (4)
L5 P(1)	103.815 713 (4)	L12 P(2)	96.627 550 (5)	L19 R(0)			39 (4)
L5 R(0)	103.654 581 (4)	L12 P(3)	96.908 984 (6)	L19 R(1)	[illegible]		57 (5)
L5 R(1)	103.714 992 (4)	L12 R(0)	96.297 800 (5)	L19 R(2)	91.295 107 (17)	W3 R(4)	95.031 536 (5)
L5 R(2)	103.869 027 (4)	L12 R(1)	96.360 800 (5)	L19 R(3)	91.521 225 (17)	W4 P(2)	93.260 468 (10)
L5 R(3)	104.115 892 (4)	L12 R(2)	96.504 574 (5)	W0 P(2)	101.216 942 (6)	W4 P(3)	93.479 006 (10)
L6 P(1)	102.593 517 (8)	L12 R(3)	96.767 695 (6)	W0 P(3)	101.450 423 (6)	W4 Q(1)	93.057 708 (10)
L6 R(0)	102.437 395 (8)	L12 R(4)	97.083 820 (8)	W0 Q(1)	100.977 088 (5)	W4 Q(2)	93.178 086 (10)
L6 R(1)	102.498 790 (8)	L12 R(5)	97.488 649 (9)	W0 Q(2)	101.093 845 (6)	W4 Q(3)	93.357 794 (10)

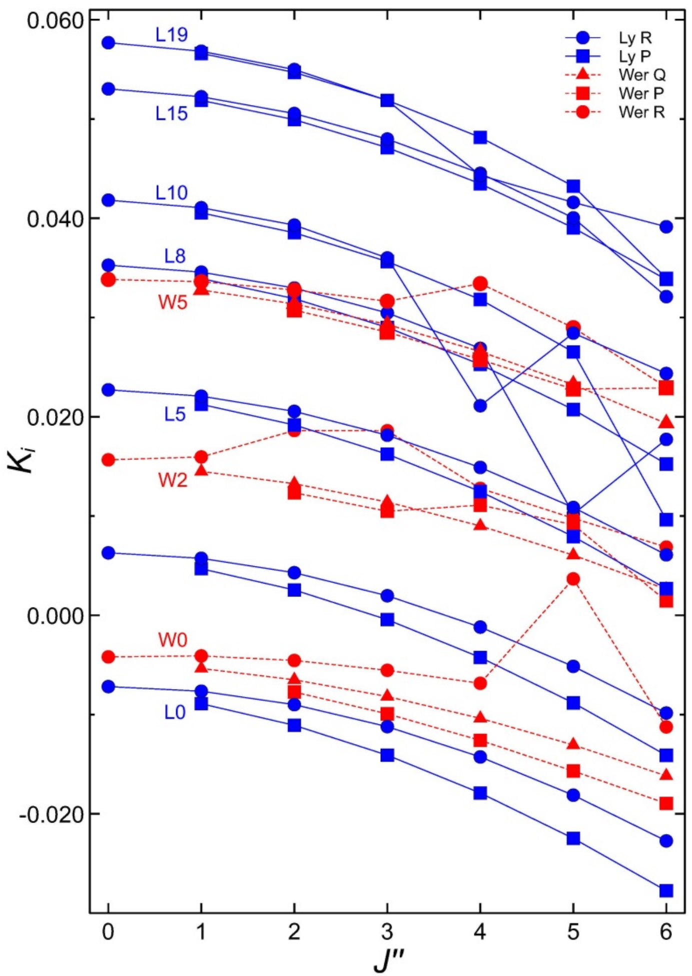


>160 lines measured at ~ 5 x 10^{-8}

Some lines at < 1 x 10^{-8}

“Sensitivity”

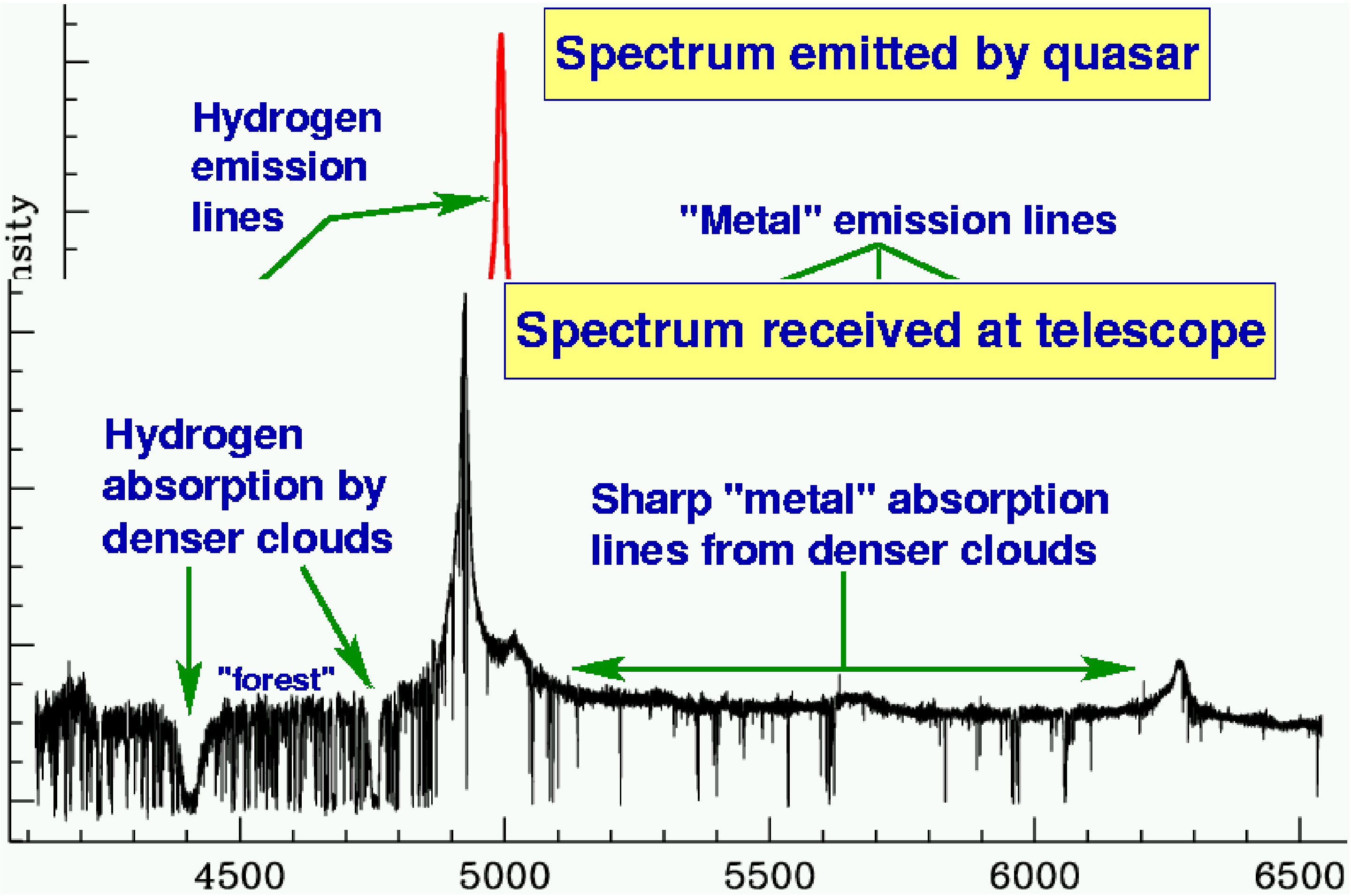
$$K_i = \frac{d \ln \lambda_i}{d \ln \mu}$$



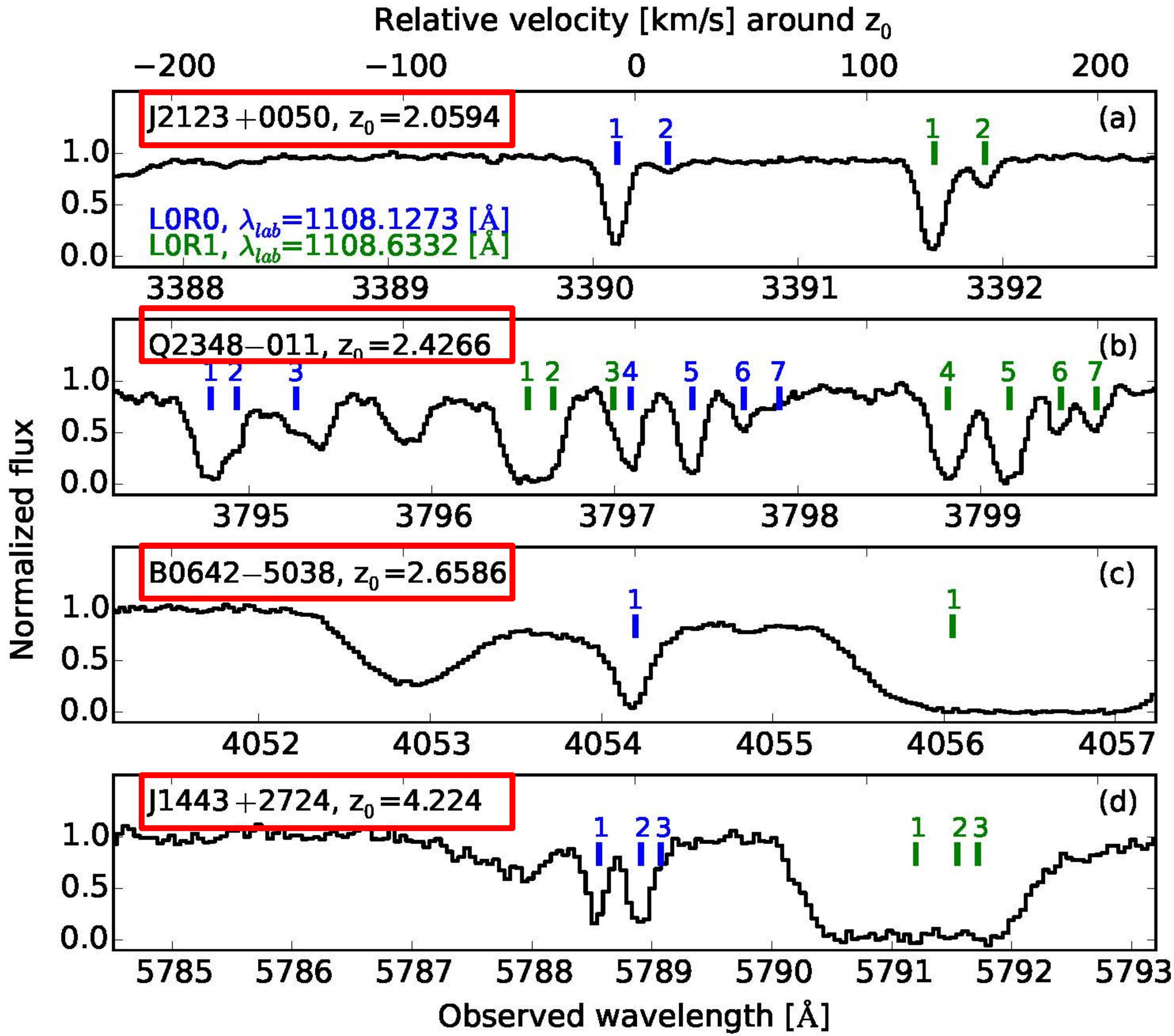
$$\frac{\lambda_i^z}{\lambda_i^0} \equiv 1 + z_i = (1 + z_{abs})\left(1 + K_i \frac{\Delta\mu}{\mu}\right)$$

VLT – UVES
Paranal, Chili

Keck – HIRES
Hawaii


Spectrum emitted by quasar
Hydrogen
emission
lines
"Metal" emission lines
nsity
Spectrum received at telescope
Hydrogen
absorption by
denser clouds
"forest"
Sharp "metal" absorption
lines from denser clouds
4500
5000
5500
6000
6500

Various
systems
observed



Analysis method: “comprehensive fitting”

Produce molecular fingerprint

λ_i – set of accurate wavelengths

f_i – set of line oscillator strengths (from ab initio theory)

Γ_i – set of damping coefficients (from ab initio theory)

Astrophysical conditions

b – Doppler width parameter

z – red shift

N_J – column densities

Fit equation onto spectrum
“Treat” HI and metal lines
Multiple velocity components (?)

$$\frac{\lambda_i^z}{\lambda_i^0} \equiv 1 + z_i = (1 + z_{abs})\left(1 + K_i \frac{\Delta\mu}{\mu}\right)$$

K_i – set of sensitivity coefficients

→ Fit entire spectrum → $\frac{\Delta\mu}{\mu}$

H_2 high redshift absorption systems

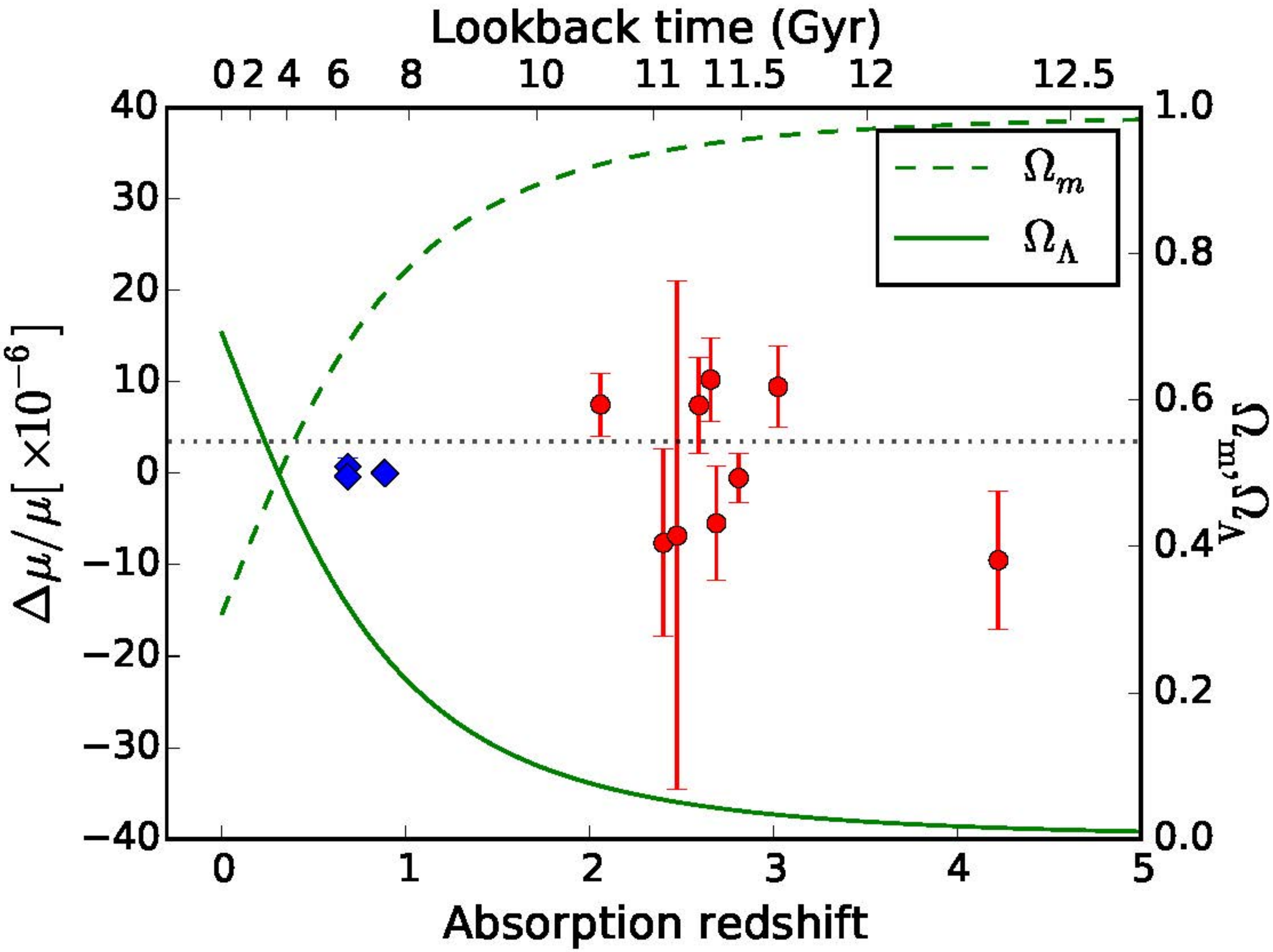
10 H_2 proper absorption systems towards quasars analyzed:

Quasar	z_{abs}	z_{em}	RA(J2000)	Decl.(J2000)	$N(H_2)$	N(HD)	N(CO)	N(H I)	R_{mag}
HE0027−1836	2.42	2.55	00:30:23.62	−18:19:56.0	17.3			21.7	17.37
Q0347−383	3.02	3.21	03:49:43.64	−38:10:30.6	14.5			20.6	17.48
Q0405−443	2.59	3.00	04:07:18.08	−44:10:13.9	18.2			20.9	17.34
Q0528−250	2.81	2.81	05:30:07.95	−25:03:29.7	18.2	13.3		21.1	17.37
B0642−5038	2.66	3.09	06:43:26.99	−50:41:12.7	18.4			21.0	18.06
Q1232+082	2.34	2.57	12:34:37.58	+07:58:43.6	19.7	15.5		20.9	18.40
J1237+064	2.69	2.78	12:37:14.60	+06:47:59.5	19.2	14.5	14.2	20.0	18.21
J1443+2724	4.22	4.42	14:43:31.18	+27:24:36.4	18.3			21.0	18.81
J2123−0050	2.06	2.26	21:23:29.46	−00:50:52.9	17.6	13.8		19.2	15.83
Q2348−011	2.42	3.02	23:50:57.87	−00:52:09.9	18.4			20.5	18.31

+ 23 additional H_2 absorption systems towards quasars known
+ some 20 tentative detections [Balashev et al (2014)]

Status/Review

$|\Delta\mu/\mu| = (3.1 \pm 1.6) \times 10^{-6}$



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)

Take Home

$|\Delta\mu/\mu| < 5 \times 10^{-6}$ at 3σ level for redshifts $z = 2\text{-}4$

Perspectives

Wavelength distortions ThAr relate to beam pointing.

Solutions for 'ESPRESSO'

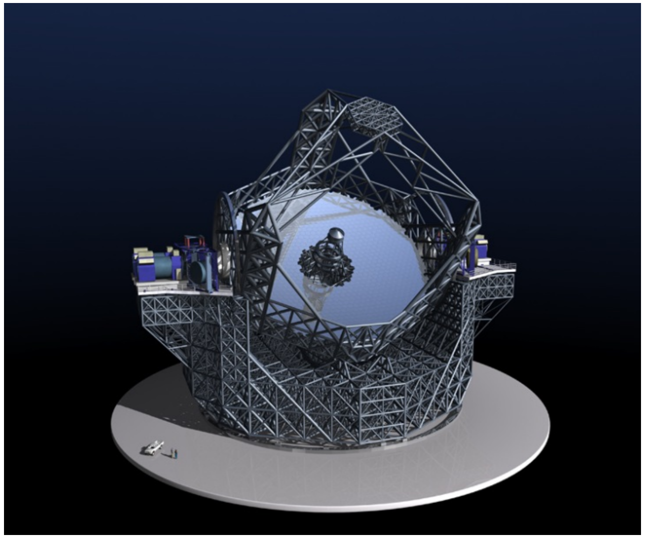
- Frequency comb calibration
- Fiber feeding
- Fibers designed for $\lambda > 3700$ Å

Problematic for H_2 studies, only $z > 3$

EELT

More light collection (39 m dish)

Improved signal to noise ratio



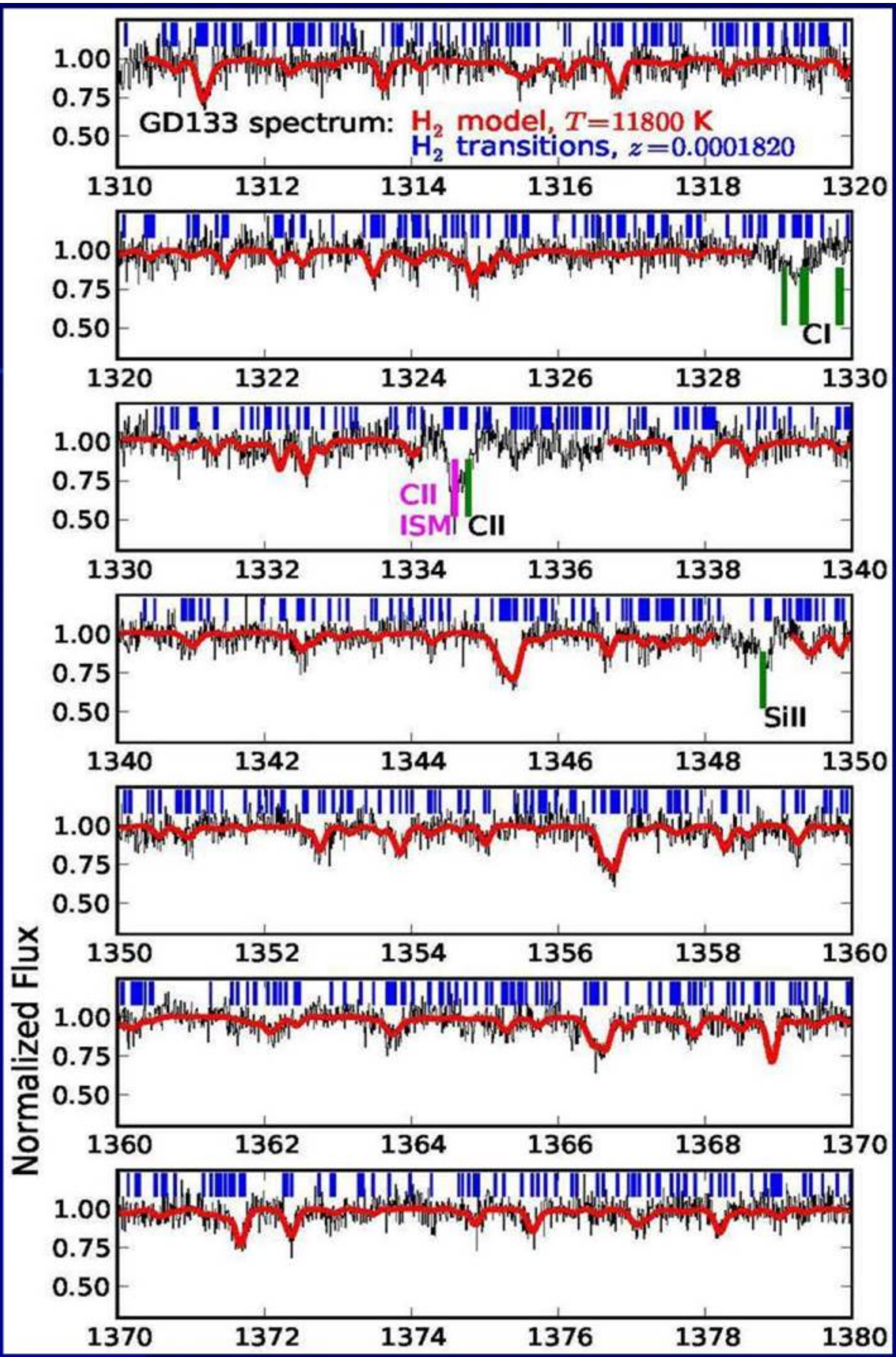
"Chameleon" Scenario

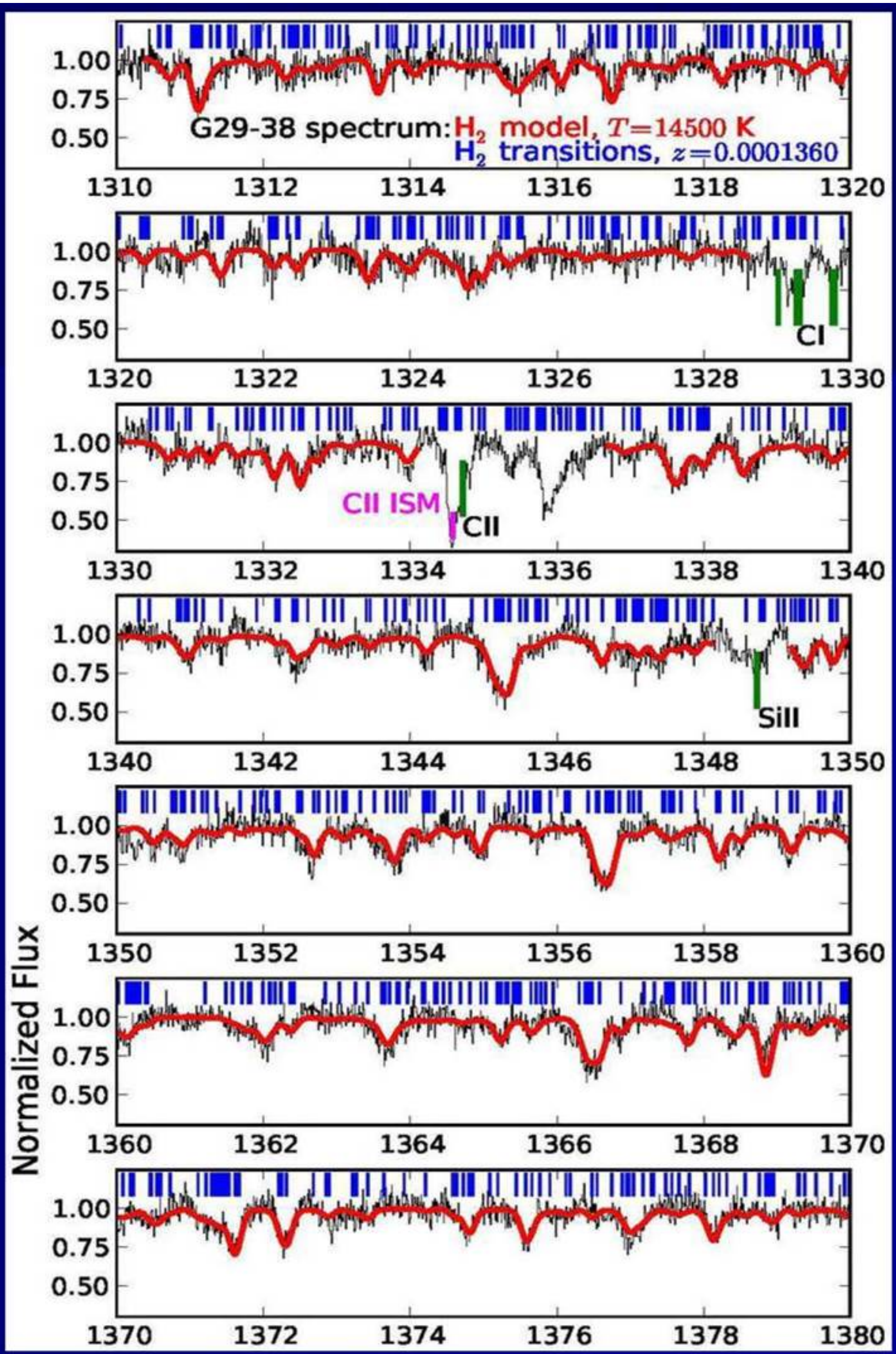
Dependence of μ
on gravitational field ?

$$\phi_{WD} = \frac{GM}{Rc^2} \sim 10^4 \times \phi_{Earth}$$

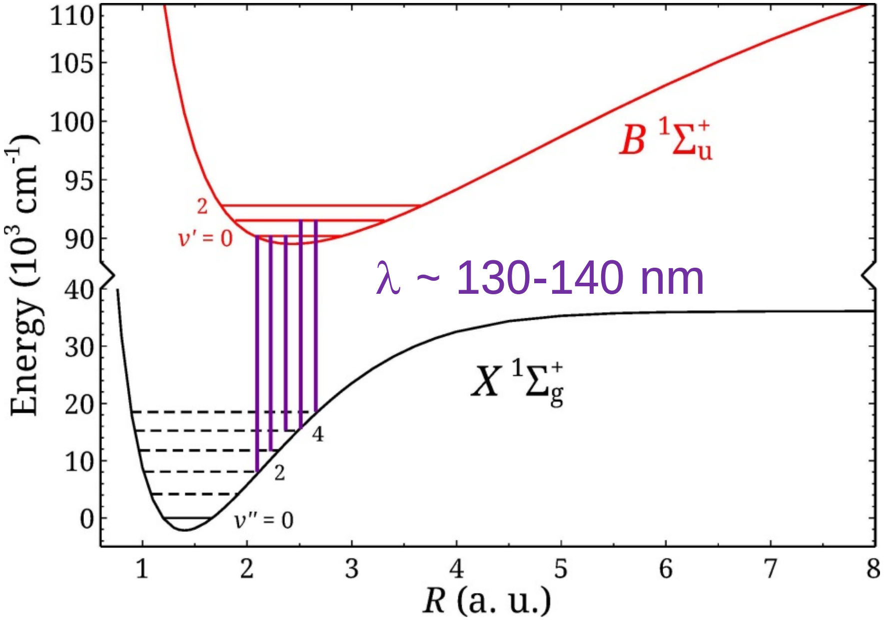
Spectrum of GD-133 and GD29-38
Photosphere of White Dwarf stars

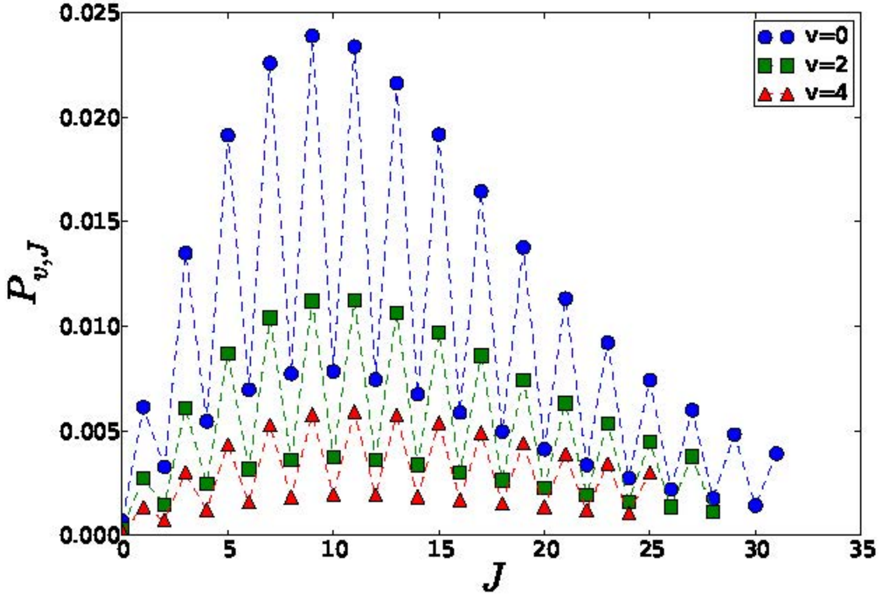
In the Galaxy !


GD133 spectrum: H_2 model, T=11800 K
H_2 transitions, z=0.0001820
CI
CII
ISM
CII
SiII
Normalized Flux


G29-38 spectrum: H_2 model, T=14500 K
H_2 transitions, z=0.0001360
CI
CII ISM
CII
SiII
Normalized Flux

Contributions of many lines in the B-X Lyman system





High temperatures
High v populated
Franck-Condon factors

Dependence of Δμ/μ on gravitational field

Invoke partition function:

$$P_{vJ}(T) = \frac{g_I(J)(2J+1)\exp\left(\frac{-E_{vJ}}{kT}\right)}{\sum_{v=0}^{v_{\max}} \sum_{J=0}^{J_{\max}(v)} g_I(J)(2J+1)\exp\left(\frac{-E_{vJ}}{kT}\right)}$$

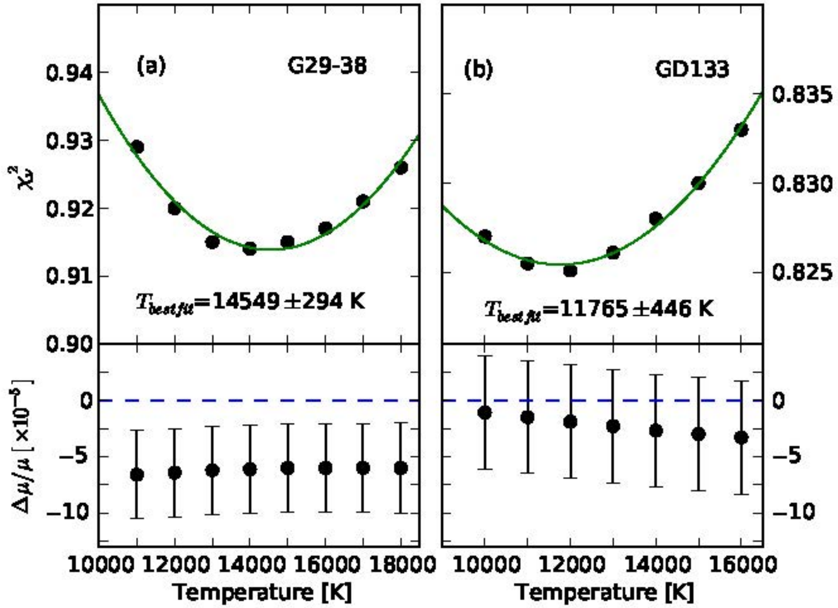
Invoke intensities (1500 lines):

$$I_i = N_{col} f_{v'v''J'J''} P_{v''J''}(T)$$

Lines

$$\frac{\lambda_i^z}{\lambda_i^0} \equiv 1 + z_i = (1 + z_{abs})\left(1 + K_i \frac{\Delta\mu}{\mu}\right)$$

Fit T and Δμ/μ



GD133: Δμ/μ = (-2.7 +/- 4.7) x 10^{-5}

GD29-38: Δμ/μ = (-5.9 +/-3.8) x 10^{-5}

Bagdonaite et al., Phys. Rev. Lett. 113, 123002 (2014)

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)

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

Theory is needed – only for “calculable” systems

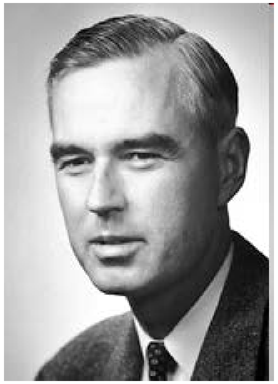
H_2 – Krzystof Pachucki & team ;

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

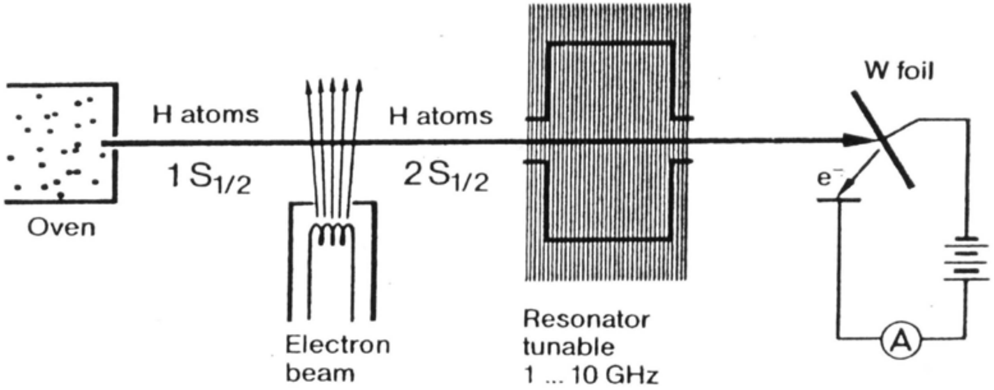
Discover new physics $\langle \Delta V_{new} \rangle > \delta E$

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

Historical Inspiration



Willis E Lamb

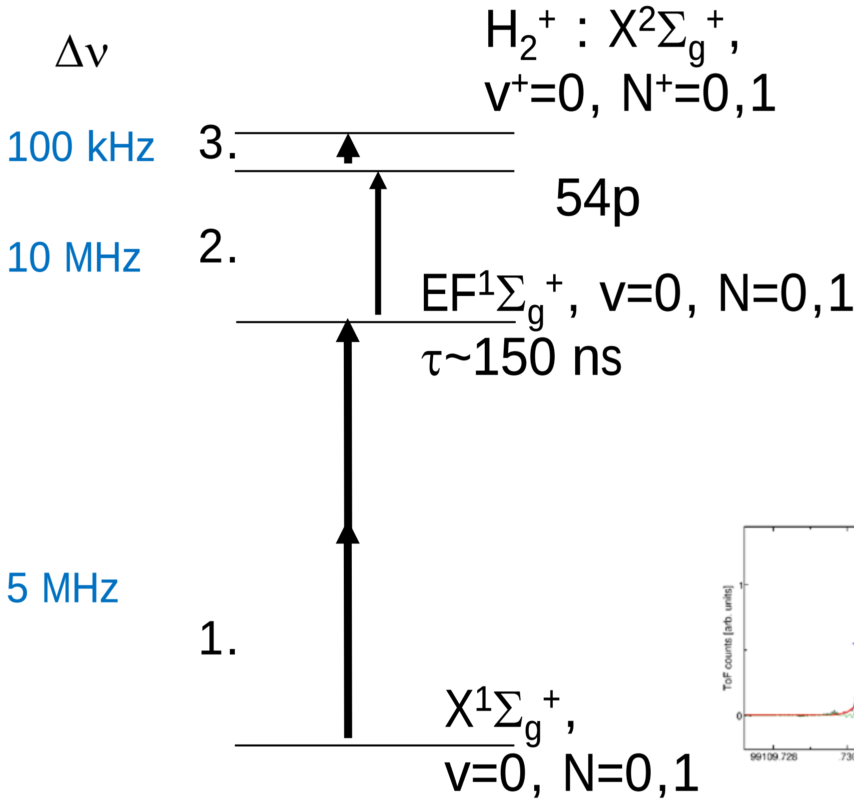


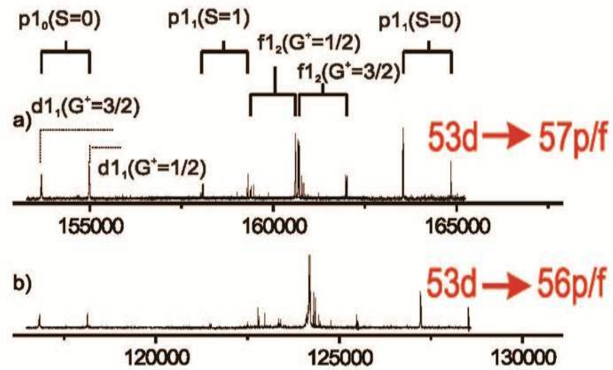
Measurement of the tiny $2S_{1/2} - 2P_{1/2}$ splitting

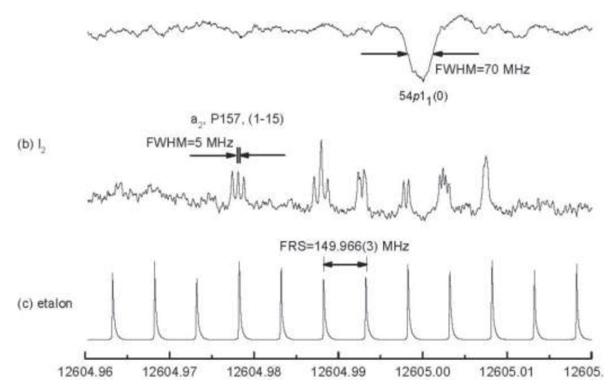
Breakdown of the Dirac theory of the electron
The advent of Quantum Electro Dynamics

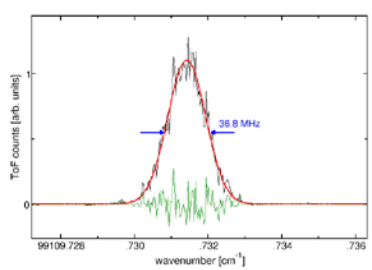
Measurement of IP in H_2

3 step approach (Zürich-Amsterdam collaboration)





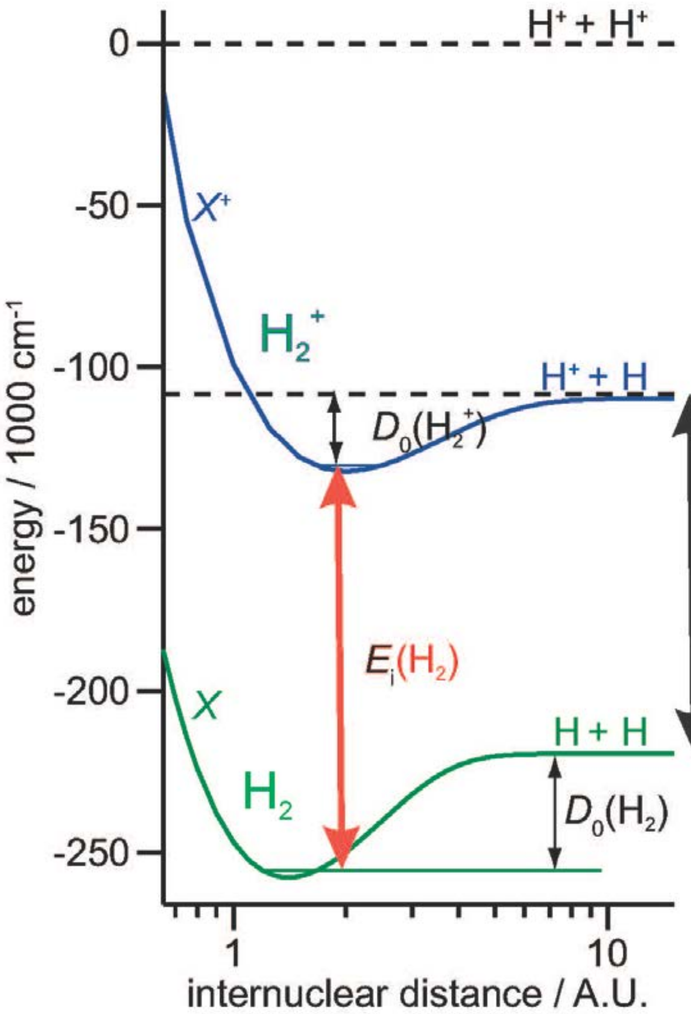




E_i (ortho) = 124 357.237 97 (36) cm^{-1}

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

Benchmark: Dissociation energy H_2



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

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

$$E_{IP}(H) = 109678.7717426(10)\ cm^{-1}$$

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

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}	QED
	α^3 all QED	– 0.1948(3) cm^{-1}	QED
	α^4 one-loop term	– 0.0016(8) cm^{-1}	QED
	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}	

Fundamental vibration in H_2

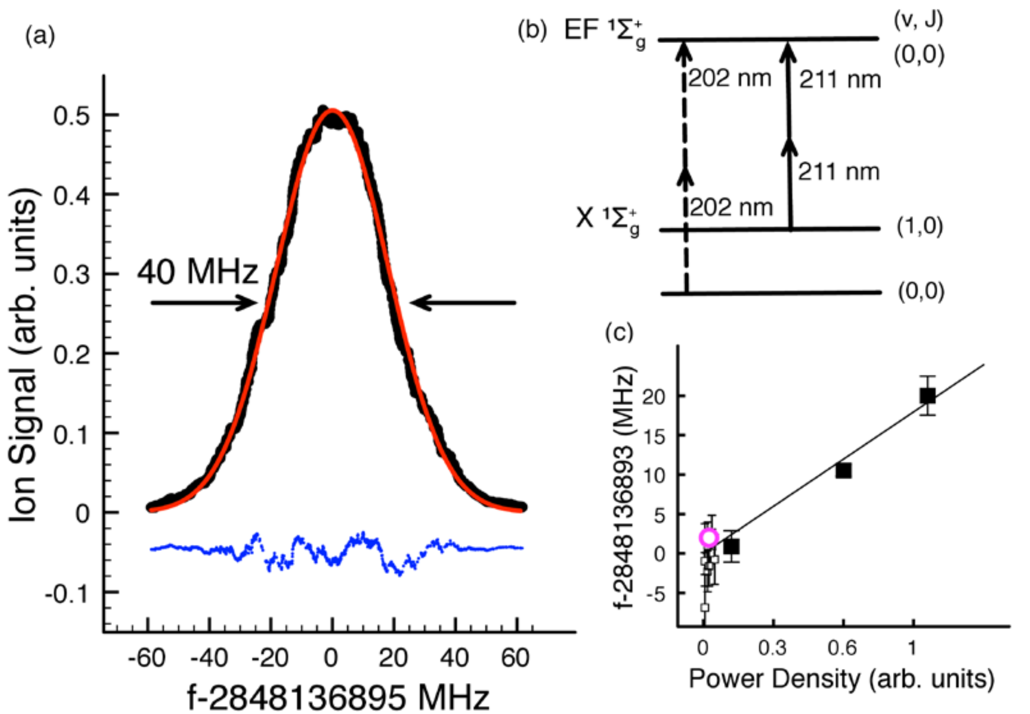
Collision-free measurement

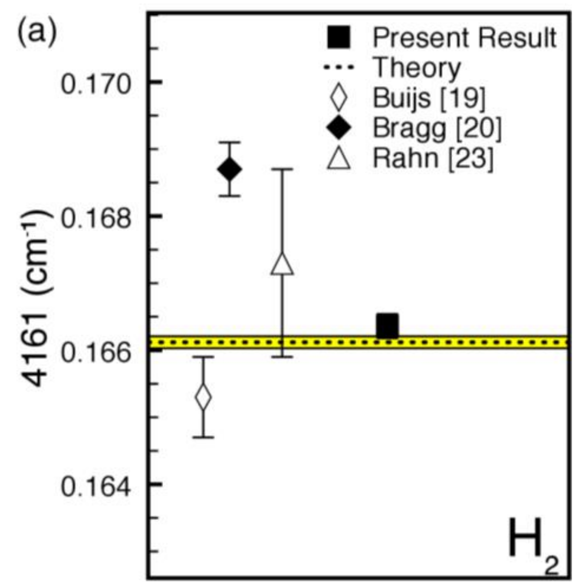
Features

Narrowband UV sources
Absolute frequency calibration
2-photon Doppler-free REMPI
Sagnac alignment
Delayed ionisation
ac-Stark extrapolation

$E = 4161.16632(18)\ cm^{-1}$

$\delta E_{exp} \sim 1.8 \times 10^{-4}\ cm^{-1}$





Dickenson, M. Niu, Salumbides, Komasa, Eikema, Pachucki, Ubachs, *PRL* **110**, 193601 (2013).

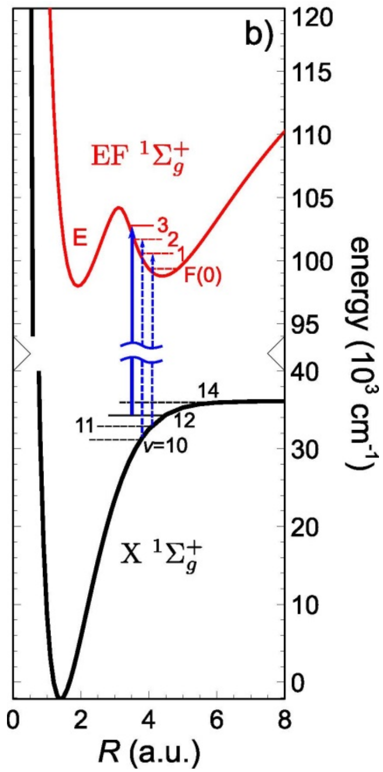
Precision study of H_2 $X^1\Sigma_g^+$ v=12, 11

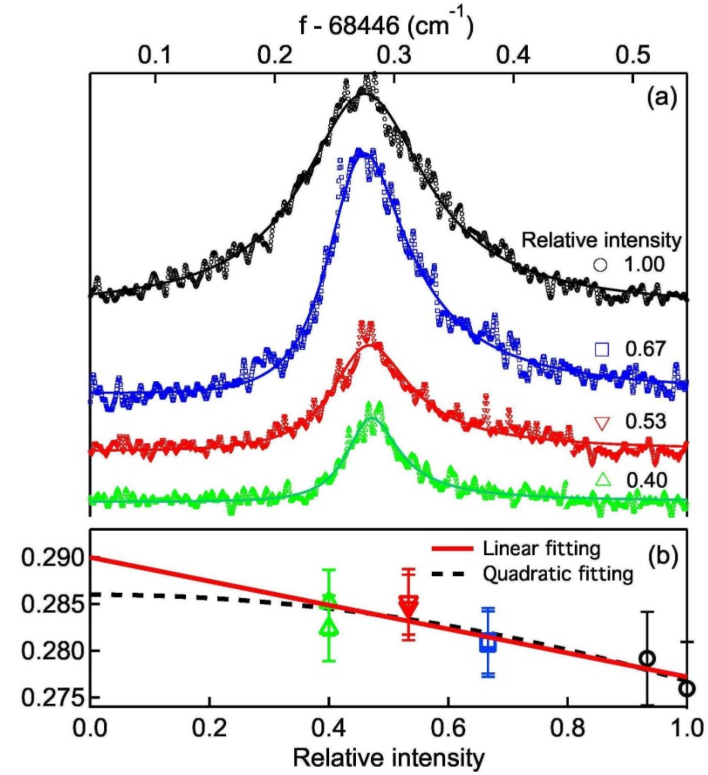
Production of H_2, v
Photolysis of H_2S
Steadman & Baer (1989)

Now:
Three independent lasers

V=12: Niu et al.
JCP Comm 142 (2015) 081102

V=11: New results
Trivikram et al.
Appl. Phys. B 122, 294 (2016)





J''	E_{exp}	E_{the}	$\Delta E_{exp-the}$
0	34 302.1823 (35)	34 302.1741 (47)	0.008 (6)
1	34 343.8531 (35)	34 343.8483 (46)	0.005 (6)
2	34 426.2216 (35)	34 426.2179 (46)	0.004 (6)
3	34 547.3362 (35)	34 547.3332 (45)	0.003 (6)

Progress in theory

PHYSICAL REVIEW A **82**, 032509 (2010)

Born-Oppenheimer potential for H_2

Krzysztof Pachucki*

In the whole range of internuclear distance, about 10^{-15} precision is achieved; as an example, at the equilibrium distance $r = 1.4011$ a.u., the Born-Oppenheimer potential amounts to $-1.174\,475\,931\,400\,216\,7(3)$.

THE JOURNAL OF CHEMICAL PHYSICS **141**, 224103 (2014)

Accurate adiabatic correction in the hydrogen molecule

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

(Received 8 October 2014; accepted 18 November 2014; published online 8 December 2014)

For the ground state of H_2 the estimated precision is $3 \times 10^{-7}\,\mathrm{cm}^{-1}$, which is almost three orders of magnitude higher than that of the best previous result.

THE JOURNAL OF CHEMICAL PHYSICS **143**, 034111 (2015)

Leading order nonadiabatic corrections to rovibrational levels of H_2, D_2, and T_2

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

(Received 22 May 2015; accepted 8 July 2015; published online 21 July 2015)

An estimated accuracy of the leading nonadiabatic correction to the rovibrational energy levels is of the order of $10^{-7}\,\mathrm{cm}^{-1}$.

Progress in theory

Complete $\alpha^6 m$ corrections to the ground state of H_2

Mariusz Puchalski and Jacek Komasa
Faculty of Chemistry, Adam Mickiewicz University, Umultowska 89b, 61-614 Poznań, Poland

Paweł Czachorowski and Krzysztof Pachucki
Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland

QED

(Dated: July 29, 2016)

Phys. Rev. Lett. 117, 263002 (2016)

REL

PHYSICAL REVIEW A **95**, 052506 (2017)

Relativistic corrections for the ground electronic state of molecular hydrogen

Mariusz Puchalski and Jacek Komasa
Faculty of Chemistry, Adam Mickiewicz University, Umultowska 89b, 61-614 Poznań, Poland

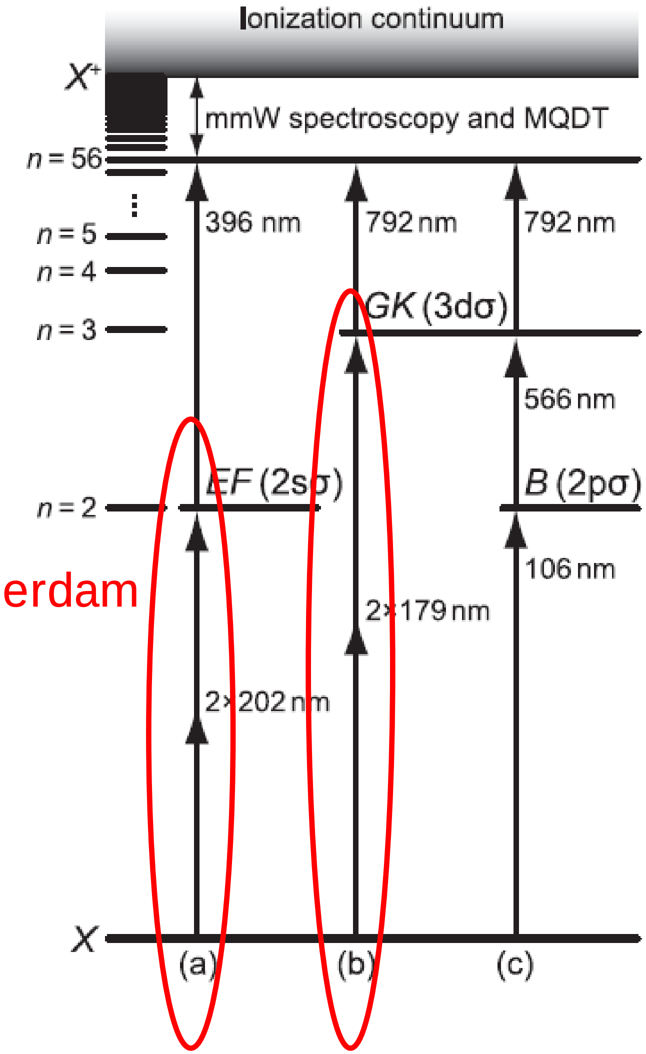
Krzysztof Pachucki
Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland

(Received 13 April 2017; published 25 May 2017)

More importantly, the updated theoretical energies became discrepant with the known experimental values and we conclude that the yet unknown relativistic recoil corrections might be larger than previously anticipated.

Important estimate: 10 kHz on rovibrational energies ~ proton radius at 1%

Strategies to improve the experimental side



Amsterdam

Three step approach to IP
has been probed via nanosecond excitation
Accuracy: 11 MHz

THE JOURNAL OF CHEMICAL PHYSICS **130**, 174306 (2009)

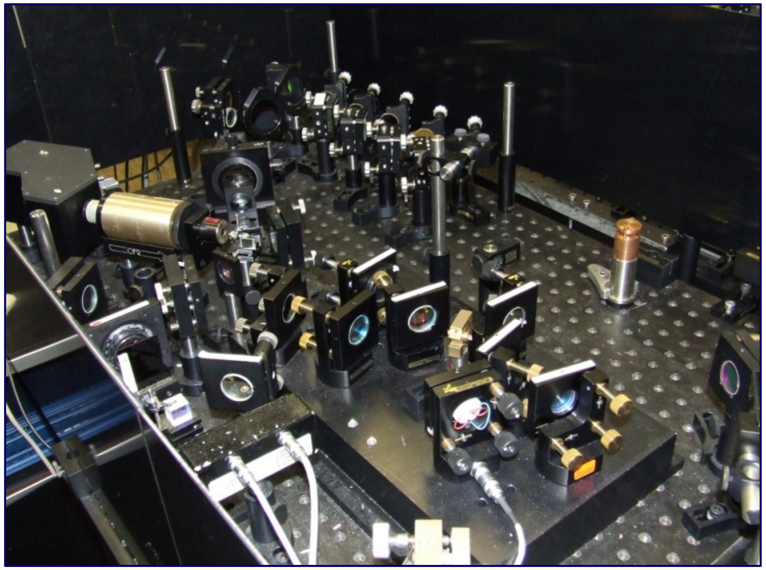
Determination of the ionization and dissociation energies of the hydrogen molecule

Jinjun Liu,[1] Edcel J. Salumbides,[2] Urs Hollenstein,[1] Jeroen C. J. Koelemeij,[2] Kjeld S. E. Eikema,[2] Wim Ubachs,[2] and Frédéric Merkt[1,a)]
[1]*Laboratorium für Physikalische Chemie, ETH-Zürich, 8093 Zürich, Switzerland*
[2]*Department of Physics and Astronomy, Laser Centre, Vrije Universiteit, De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands*

GK level splitting to IP is known to 1.2 MHz
Sprecher, Beyer, Merkt
Mol. Phys. 111, 2100 (2011)

Improvements ongoing (2017) GK and EF to IP
Max Beyer, Frederic Merkt

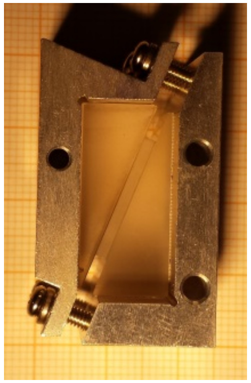
Measurement of the GK-X transition - ongoing

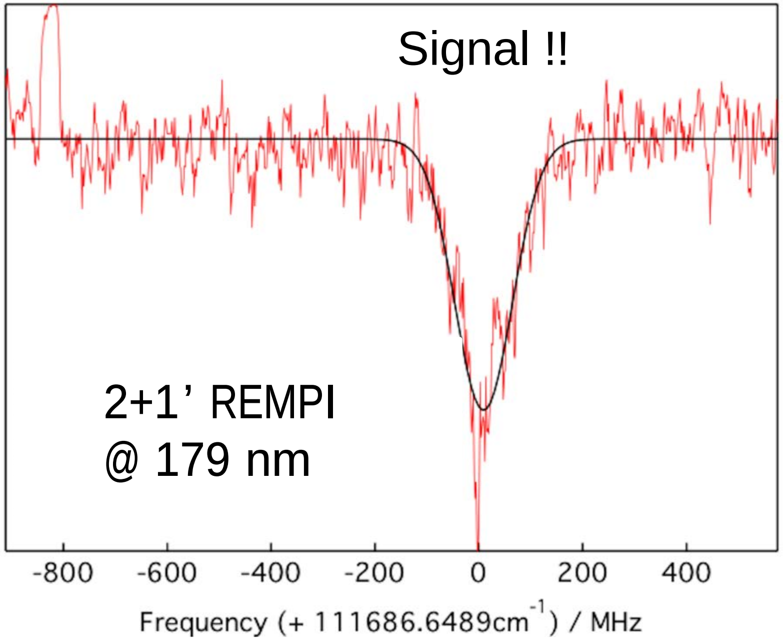


Home-built long-pulse narrowband Ti:Sa laser @ 716 nm

KBBF crystal for doubling to 179 nm

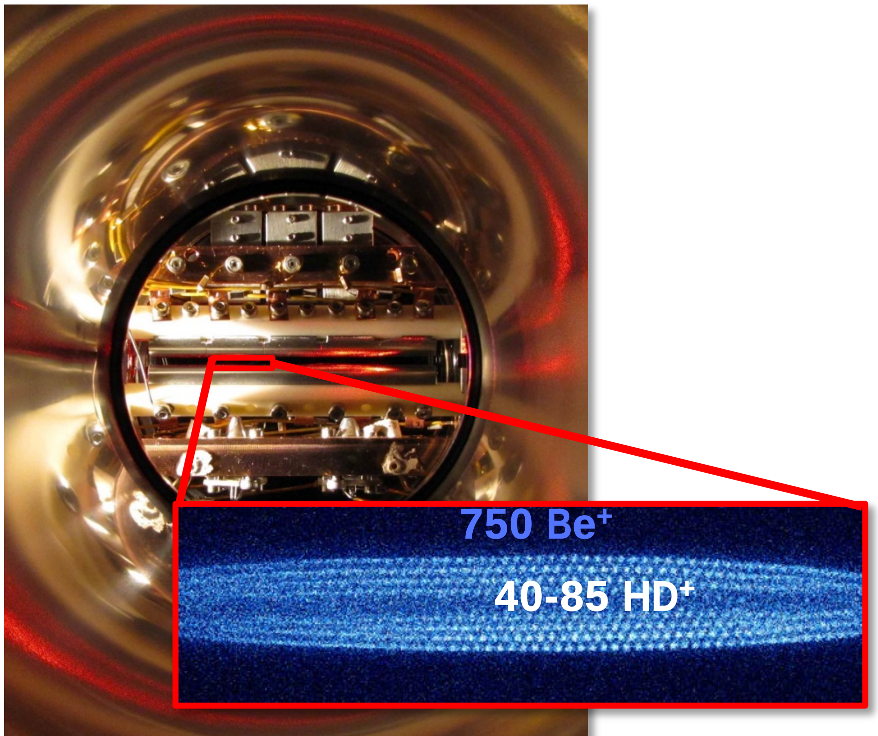
VUV mirror for retroreflect

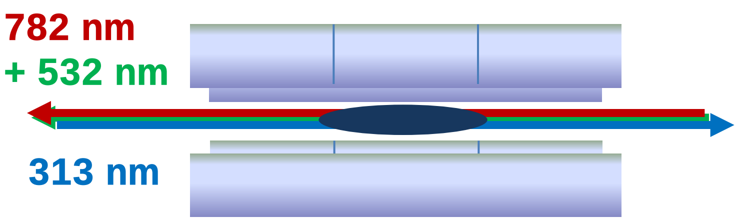


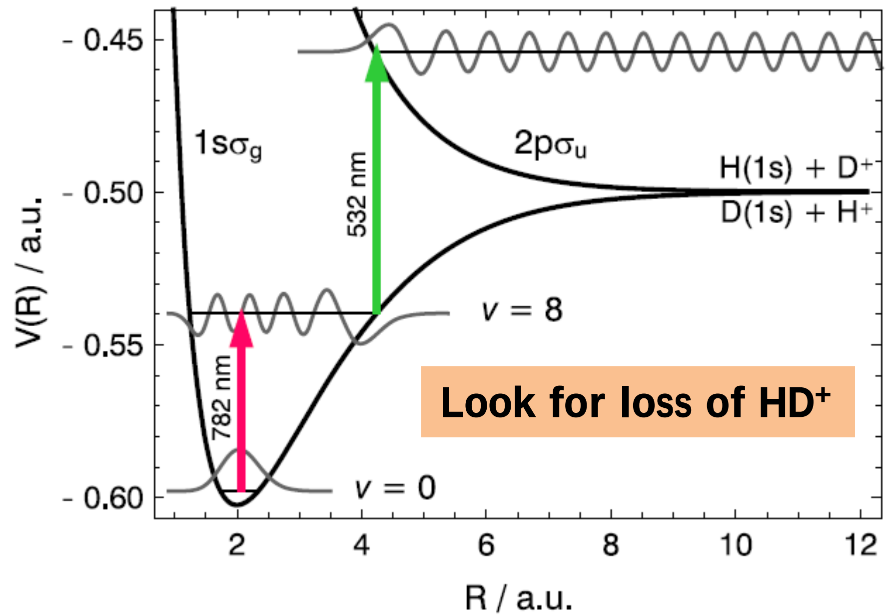


- Adjustable pulse duration (match τ=30 ns)
- Two-photon Doppler-free
- Study of auto-ionization
- Improved molecular beam source
- Chirp measurement
- AC Stark studies
- Seed-laser locked to Freq. comb

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

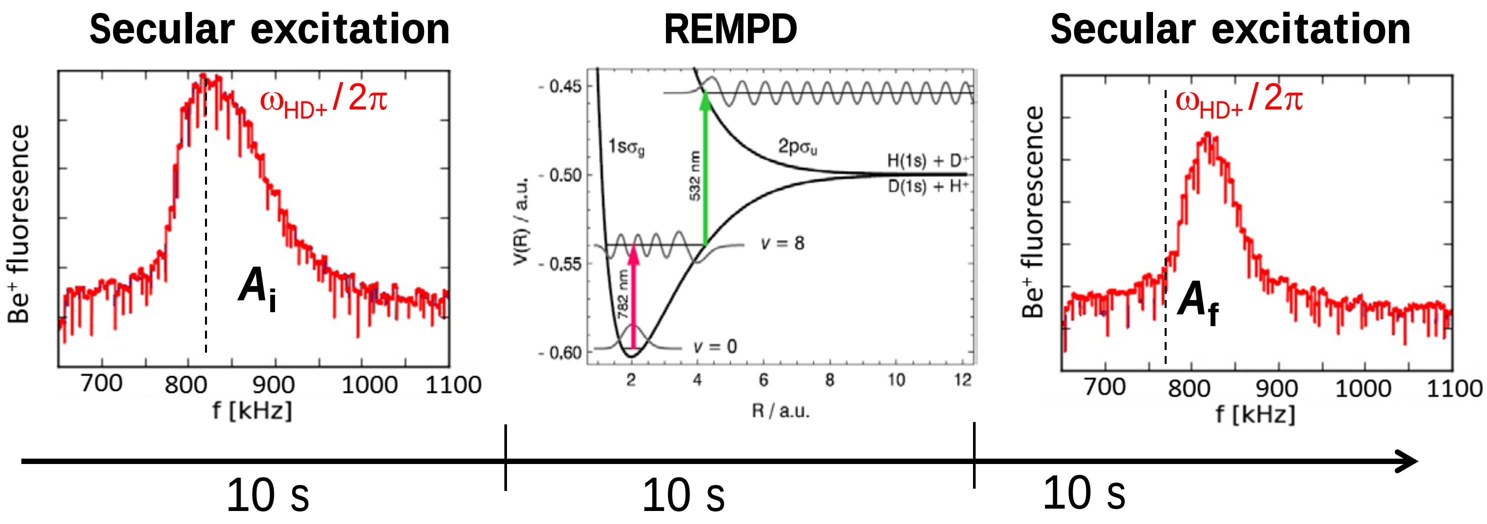






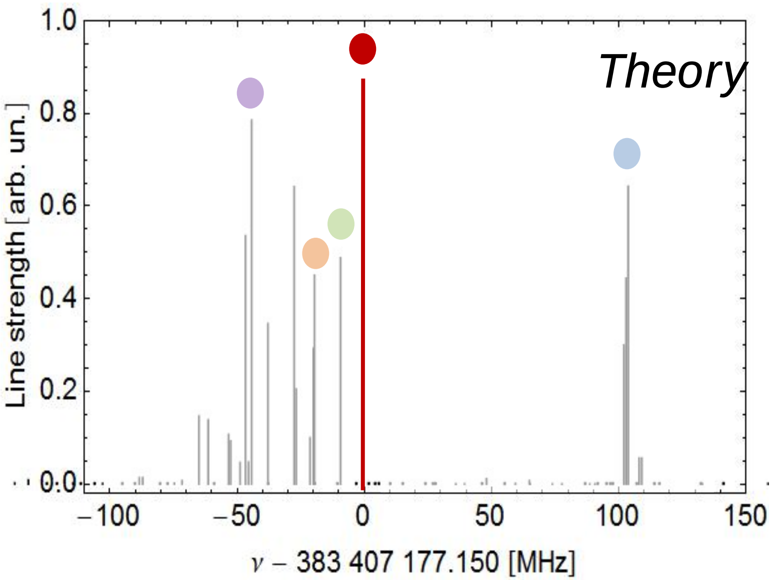
Signal detection by REMPD

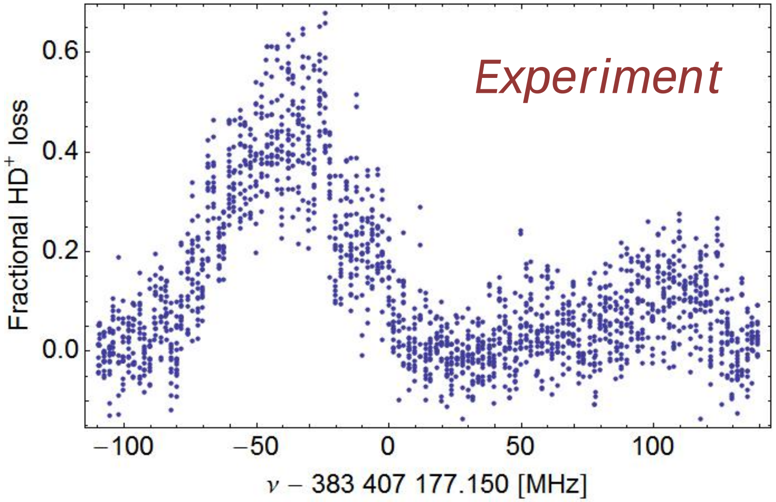
REMPD detection cycle:

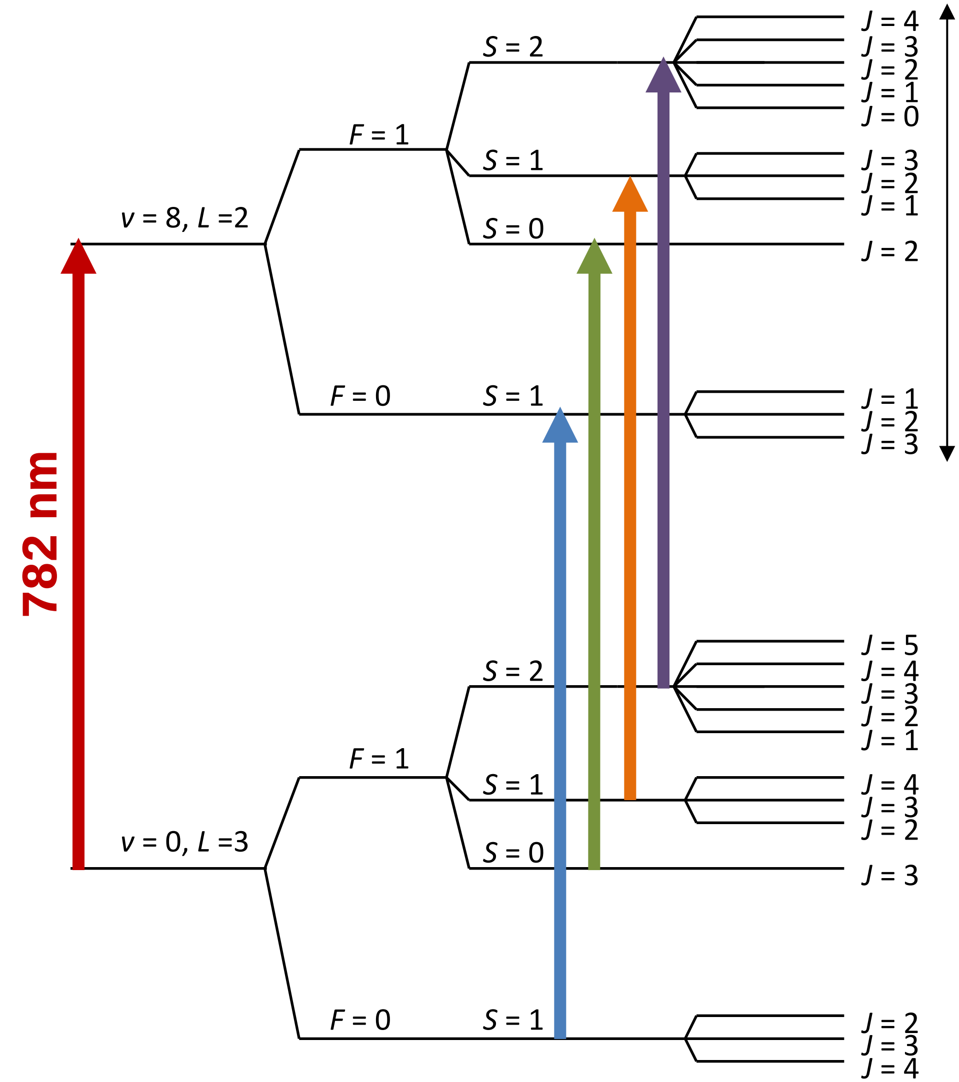


- **Signal = fractional loss of ions**
- **During secular excitation, T_{Be+} rises to T_{max}**
- **$A_i \propto T \propto N_{HD+}$ for $T_{max} <$ 400 mK**
- **BUT in practice $T_{max} \approx$ 4 K …**
- **Be^+ fluoresence modeled (non-linear)**

HD^+ spectrum







Experiment: **383,407,177.38(41) MHz**

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

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

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

Tests of QED in molecules

$$\Delta E < \delta E$$

Species	Splitting	δE_{exp}	Ref.	δE_{calc}	δE	ΔE
H_2	$v = 0, J = 6 - 12$	150[c]	[56]	12	150[c]	20
	$v = 0, J = 13 - 16$	300[c]	[56]	27	300[c]	90
	$v = 0 \rightarrow 1$	4.5[a]	[54]	2.7	5	7
	$v = 0 \rightarrow 2$	30	[57]	50	60	12
	$v = 0 \rightarrow 3$	1.3	[58]	75	75	10
	$v = 0 \rightarrow 12$	105	[59]	140	170	150[b]
	D_0	12	[44]	30	3	36
HD	$v = 0 \rightarrow 1$	7[a]	[54]	2.4	8	4
	D_0	11	[49]	30	27	32
D_2	$v = 0 \rightarrow 1$	4.5[a]	[54]	2.1	5	−0.6
	$v = 0 \rightarrow 2$	30	[60]	12	30	−12
	D_0	21	[48]	27	30	12
H_2^+	$v = 0, J = 0 \rightarrow 2$	2.3	[61]	0.003	2.3	−1.0
HD^+	$v = 0 \rightarrow 1$	0.064	[62]	0.002	0.064	−0.156
	$v = 0 \rightarrow 4$	0.50	[63]	0.008	0.50	−0.35
	$v = 0 \rightarrow 8$	0.41	[64]	0.015	0.41	0.22

Fifth-force searches

Assume: Extra *hadron-hadron* interaction
Parametrize (quantum field theory) as:

Yukawa potential

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

Hideki Yukawa

Strength: α_5

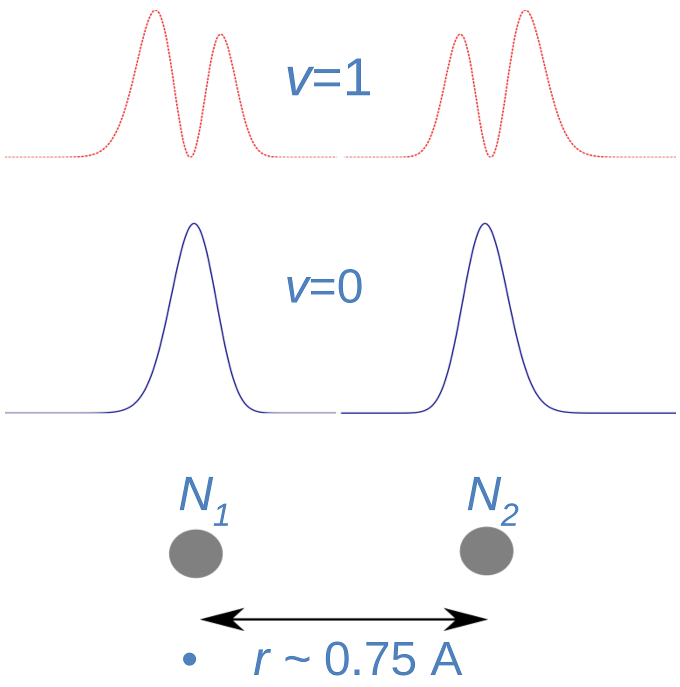
Range: $\lambda = \hbar / m_5 c$

Mass of force carrying particle: m_5

Hadron numbers: N_1, N_2

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

Calculate the expectation value of the energy operator



Level shifts:

$$\langle \Psi_1 | V_5 | \Psi_1 \rangle ; \langle \Psi_0 | V_5 | \Psi_0 \rangle$$

Transition shift:

$$\langle \Psi_1 | V_5 | \Psi_1 \rangle - \langle \Psi_0 | V_5 | \Psi_0 \rangle$$

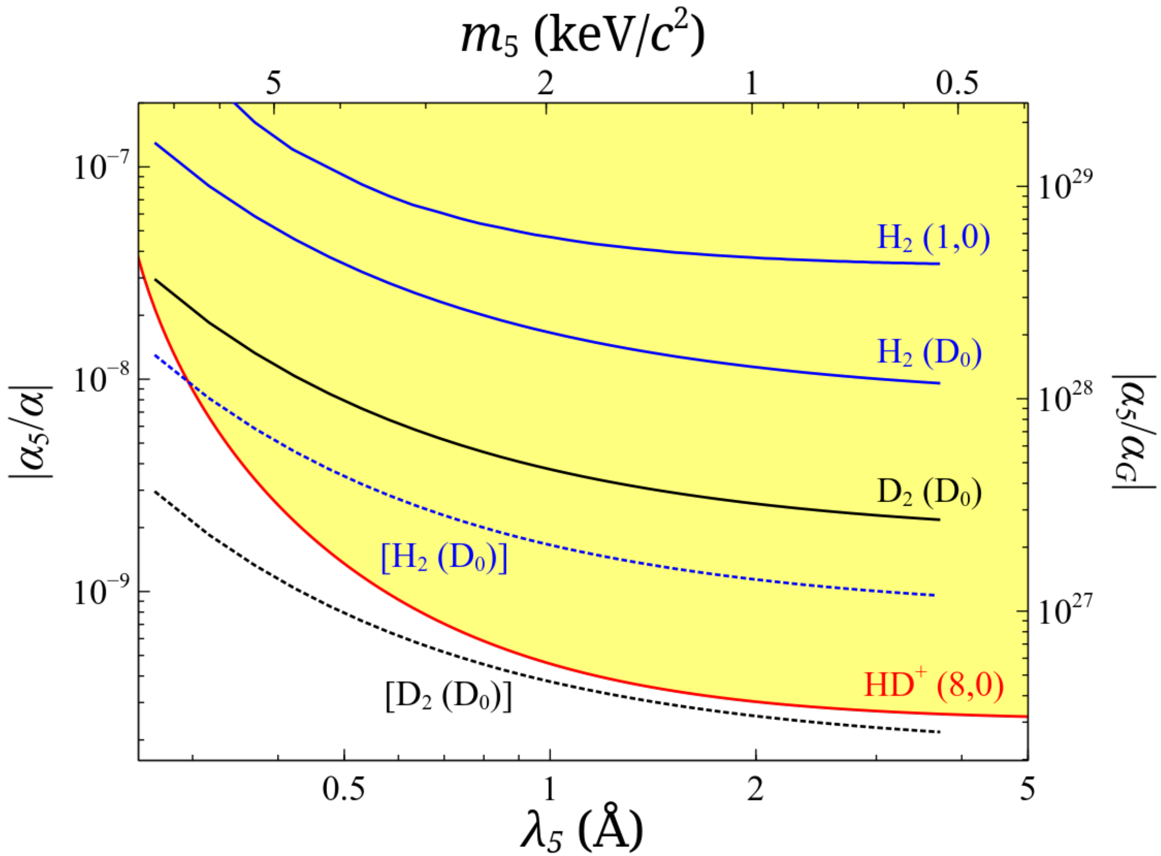
Differential effect larger for very high v's (D_0 limit)

$$\langle \Delta V_{5,\lambda} \rangle = \alpha_5 N_1 N_2 \hbar c \left\{ \left\langle \Psi_{v'J'}(r) \left| \frac{\exp(-r/\lambda)}{r} \right| \Psi_{v'J'}(r) \right\rangle - \left\langle \Psi_{v''J''}(r) \left| \frac{\exp(-r/\lambda)}{r} \right| \Psi_{v''J''}(r) \right\rangle \right\}$$

Parameters α_5 and λ

Impose constraints on 5th force from spectroscopy HD^+/H_2

$$\langle \Delta V_5 \rangle < \delta E \qquad \text{hence} \qquad \alpha_5 < \frac{\delta E}{N_1 N_2 \hbar c \langle \Delta\Psi \rangle}(\lambda)$$



E.J. Salumbides, J.C.J. Koelemeij, J. Komasa, K. Pachucki, K.S.E. Eikema, W. Ubachs, Phys. Rev. D87 (2013) 112008

Physics of extra spatial dimensions

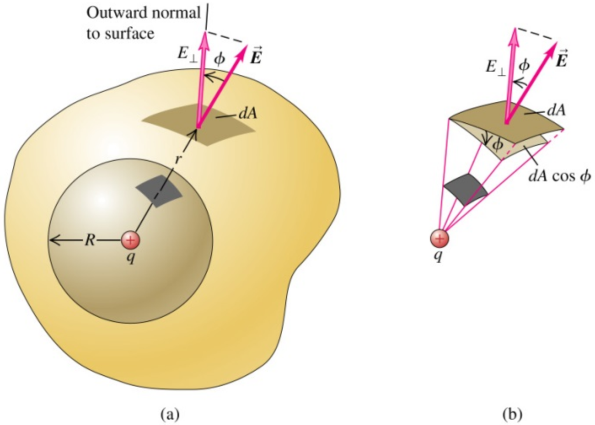
Immanuel Kant

Number of dimensions consequence
of Newton's Universal law of gravitation

$$\oint_V \vec{F} \cdot d\vec{A} = kQ_{encl}$$

3-dim: $A_V \propto r^2 \Rightarrow F \propto \frac{1}{r^2}$

N-dim: $A_V \propto r^{N-1} \Rightarrow F \propto \frac{1}{r^{N-1}}$



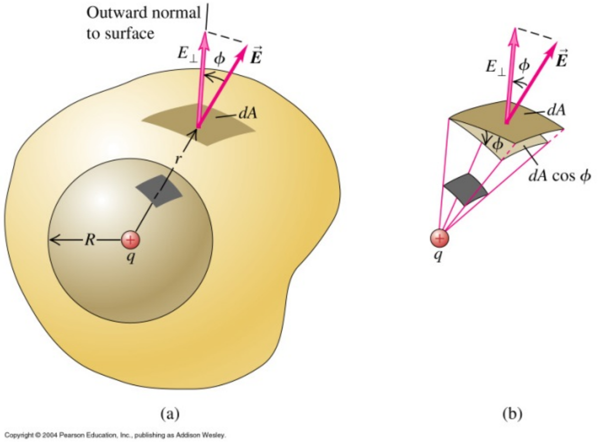
Physics of extra spatial dimensions

Immanuel Kant

Number of dimensions consequence
of Newton's Universal law of gravitation

$$\oint_V \frac{\vec{F}}{m}\cdot d\vec{A}_n = -\hat{A}_n G_n M$$

n-dim: $$A_n = \hat{A}_n r^{n-1} = \left[\frac{n\pi^{n/2}}{\Gamma\left(\frac{n}{2}+1\right)}\right] r^{n-1} \Rightarrow F \propto \frac{1}{r^{n-1}}$$



Gravitational attraction
depends on dimensionality

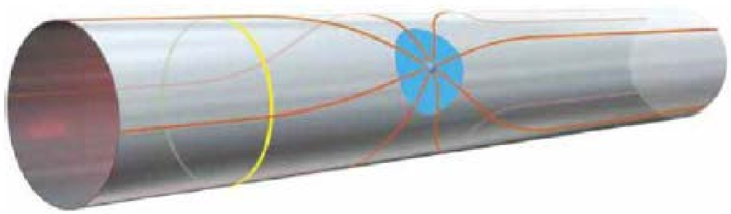
W. Ubachs, J. Mol. Spectr. 320 (2016) 1-12

“Compactification”

Theory of consistent EM + Gravity in 5 dimensions (Kaluza)

Oscar Klein

Extra dimensions are not observed in the macroscopic world
They may be compactified: rolled up (Klein 1926)



String theory: “M-Theory” (Witten) is consistent in 11 dimensions

ADD-theory and Large Extra Dimensions

Arkani–Hamed, Dimopoulos, Dvali

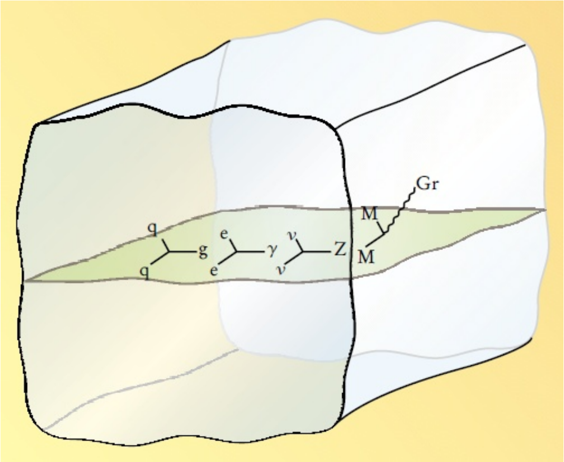
Phys. Lett. B **429**, 263–272 (1998)

Hierarchy Problem:
Why is gravity so much weaker ?
For protons

$$\frac{V_G}{V_{em}} = 8 \times 10^{-37}$$

Why is the Planck mass so much bigger
then SM masses ?

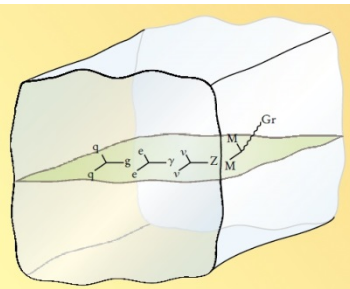
$$\frac{M_{\rm Pl}}{M_Z} \sim 10^{17}$$



Solution :
Gravity "escapes" into higher dimensions

3-brane (SM) and "Bulk" (gravity)

Large Extra Dimensions (compactified *n* extra)



$$V_{ADD}(r) = -G_{(3+n)} \frac{m_1 m_2}{R_{comp}^n} \frac{1}{r} \quad \text{for} \quad r > R_n$$

Gravity outside Klein radius

$$V_{Newton}(r) = -G_3 m_1 m_2 \frac{1}{r}$$

$$V_{ADD}(r) = -G_{(3+n)} m_1 m_2 \frac{1}{r^{n+1}} \quad \text{for} \quad r < R_n$$

Gravity inside Klein radius

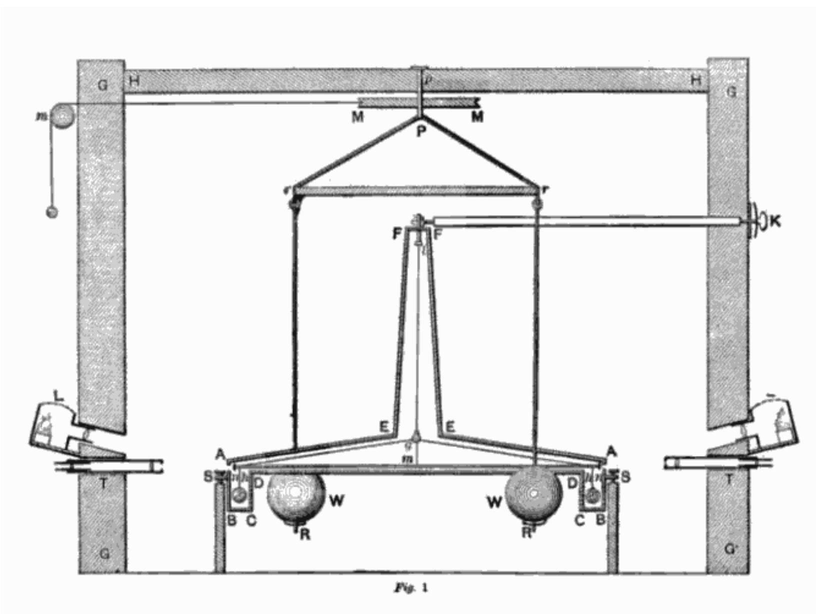
---

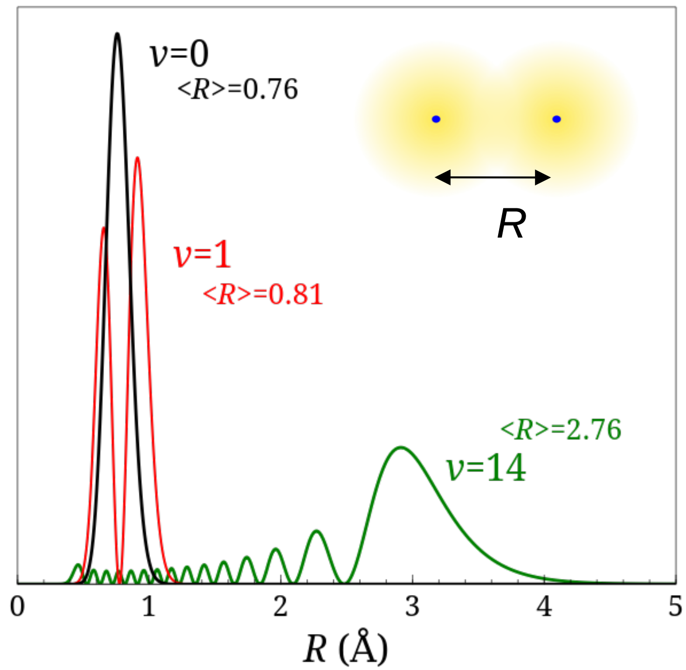
derive $G_{(3+n)} = \left(R_{comp}\right)^n G_3$

$$V_{ADD}(r) = -G_3 \frac{m_1 m_2}{r} \boxed{\left(\frac{R_{comp}}{r}\right)^n}$$

Enhancement factor for gravity in *n* extra dimensions

A Cavendish torsion balance at 1 Å distance





Two protons act as
Cavendish gravitating balls

ADD in Molecules

Expectation value for the ADD-compactification in a molecule:

$$\left\langle V_{ADD}(r) \right\rangle_{\text{state}} = \alpha_G N_1 N_2 \left[R_n^n \int_0^{R_n} \Psi^*(r) \frac{1}{r^{n+1}} \Psi(r) r^2 dr + \int_{R_n}^{\infty} \Psi^*(r) \frac{1}{r} \Psi(r) r^2 dr \right]$$

Difference between two quantum states:

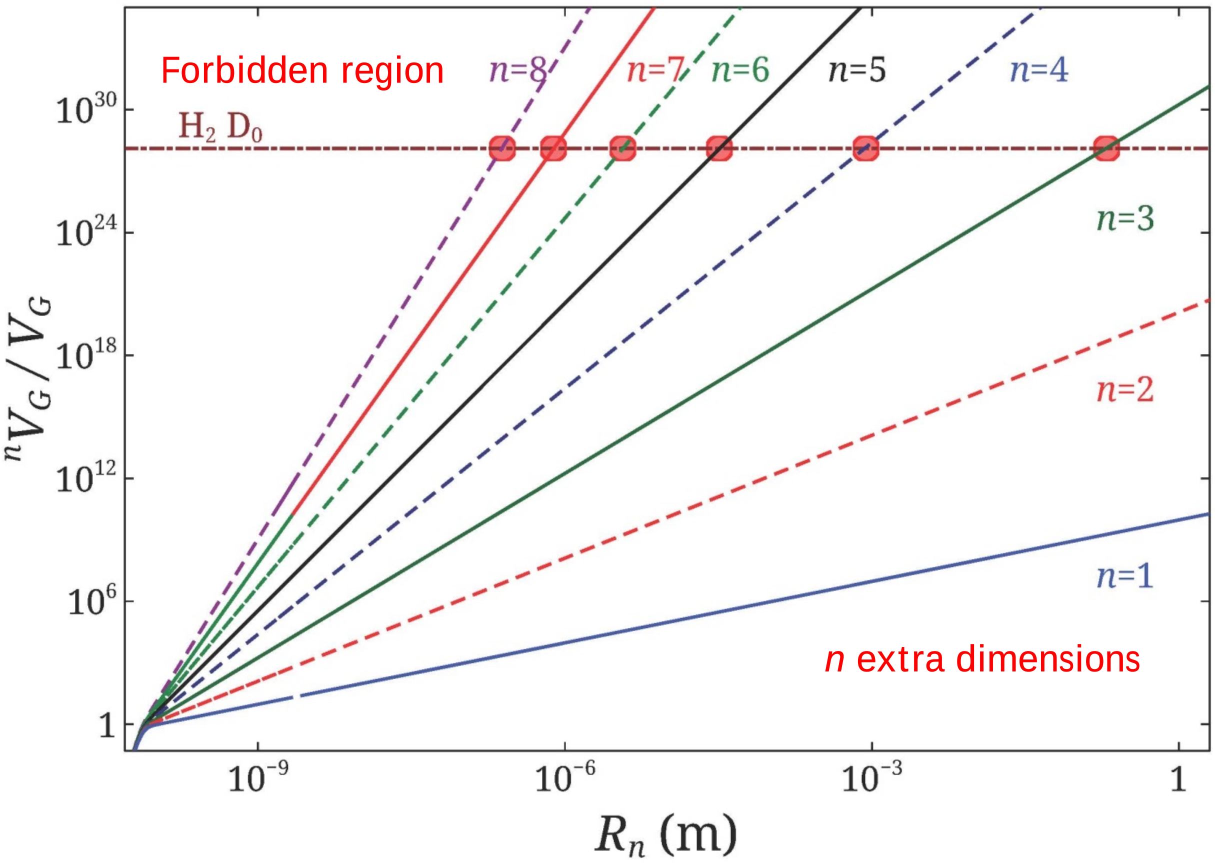
$$\left\langle \Delta V_{ADD}(r) \right\rangle_{\text{transition}} = \alpha_G N_1 N_2 \left[\left\langle \frac{1}{r^{n+1}} \right\rangle_{\Psi_1} - \left\langle \frac{1}{r^{n+1}} \right\rangle_{\Psi_0} \right]$$

Test for:

$$\left\langle \Delta V_{ADD} \right\rangle_{transition} < \delta E$$

Constraints from H_2 D_0

$$\left(R_{comp}\right)^n < \frac{\delta E}{\alpha_G \hbar c N_1 N_2 \Delta \left\langle r^{-(n+1)} \right\rangle}$$



	H_2 D_0
n	R_n (m)
2	2.2×10^{4}
3	1.9×10^{-1}
4	8.5×10^{-4}
5	3.2×10^{-5}
6	3.7×10^{-6}

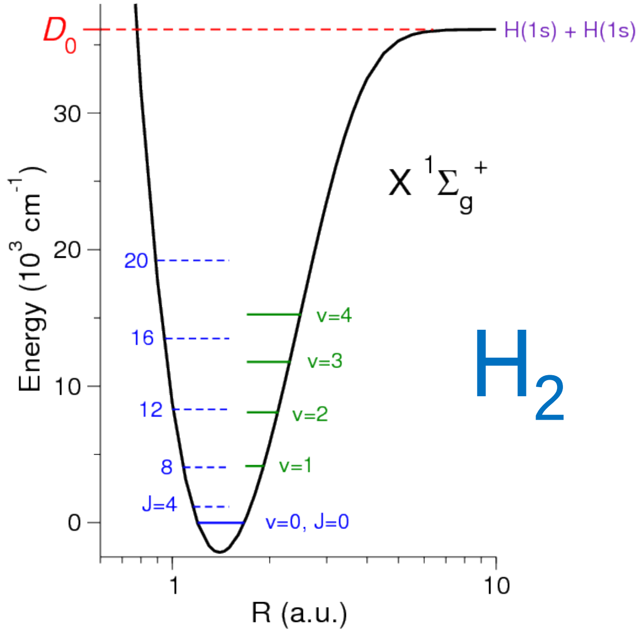
M-theory (10 dim): Compactification on μm scale !!

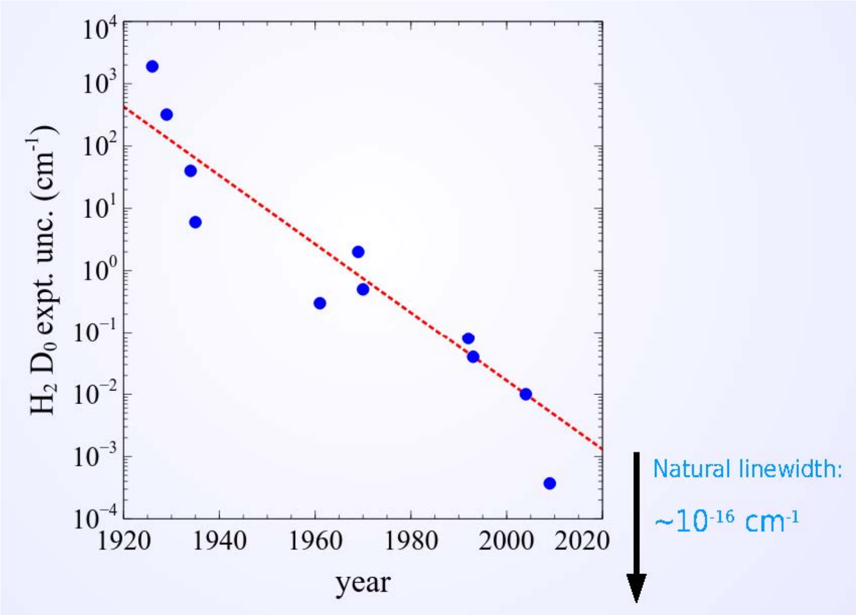
$R_c < 0.6$ μm

E. J. Salumbides, A. N. Schellekens, B. Gato-Rivera, W. Ubachs, New J. Phys. 17 (2015) 033015

OUTLOOK:

A future molecular test system for physics





Lifetimes 10^6 seconds (!)

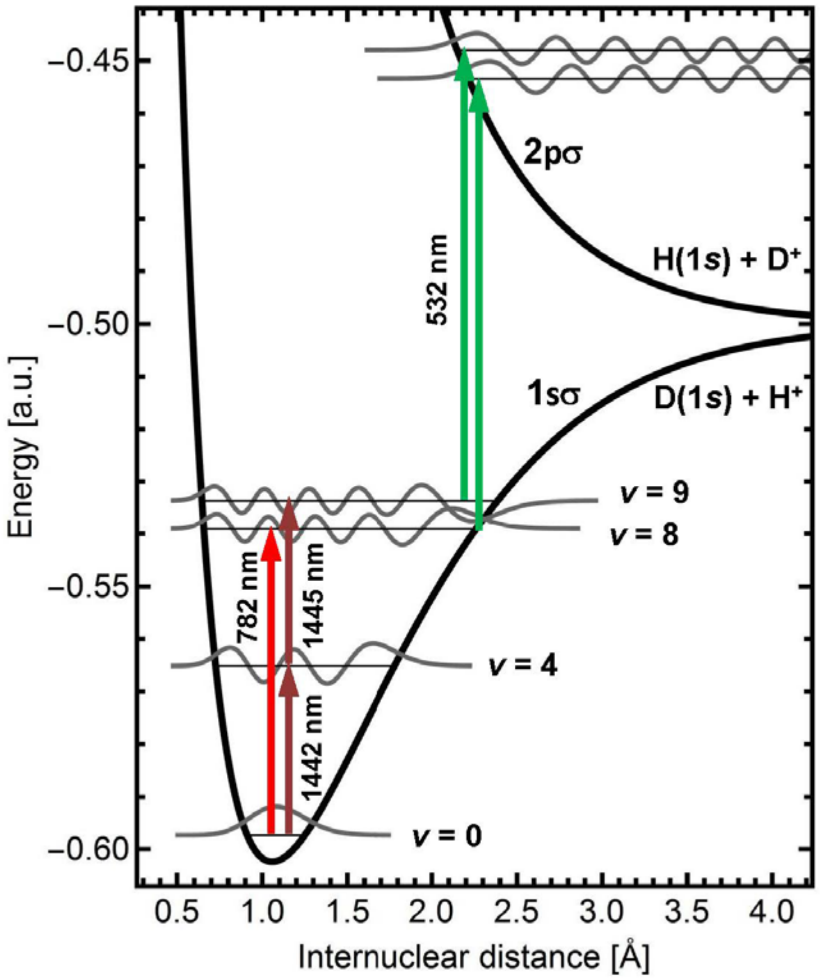
Quadrupole transitions ~ 10^{14} Hz

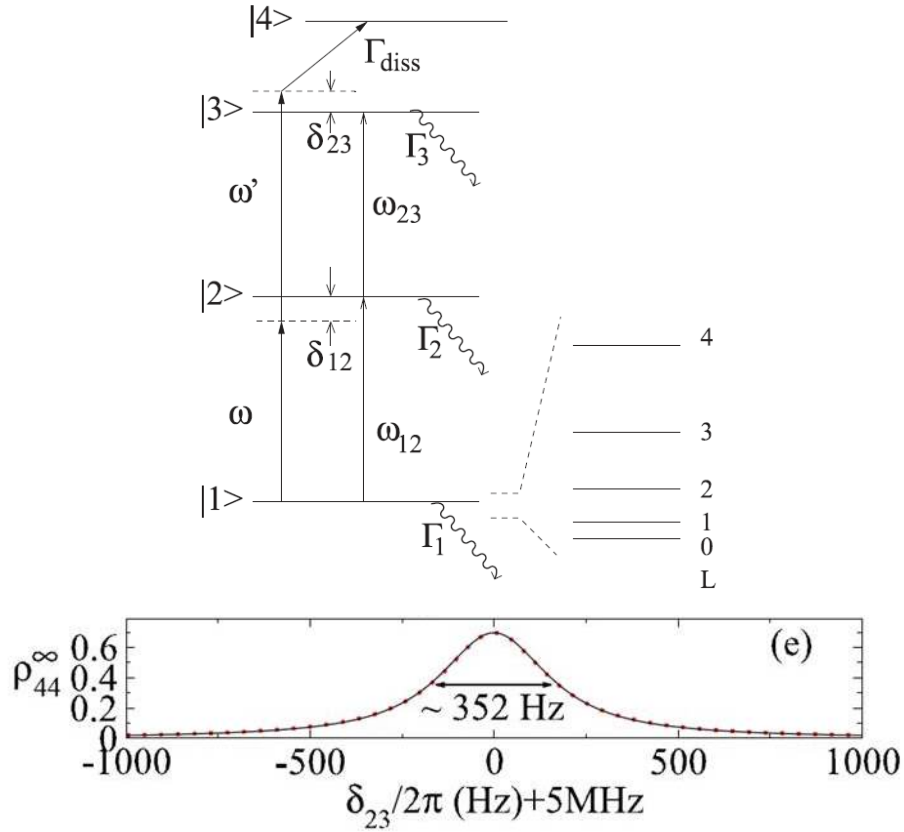
Possible precision 20-digit

There is room at the bottom guys

OUTLOOK

HD$^+$: Doppler-free spectroscopy in Lamb-Dicke regime





V.Q. Tran *et al.*, Phys. Rev. A **88**, 033421 (2013)

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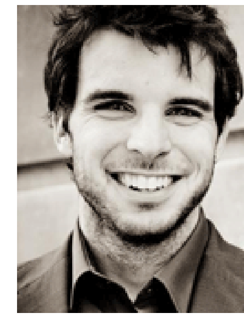

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Michael Murphy

Krzysztof Pachucki

Magnus Schloesser

Jeroen Koelemeij

Kjeld Eikema