Precision measurements on diatomic hydrogen molecules in search for extra dimensions

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PSAS 2016, Hebrew University of Jerusalem

Pillars of Physics

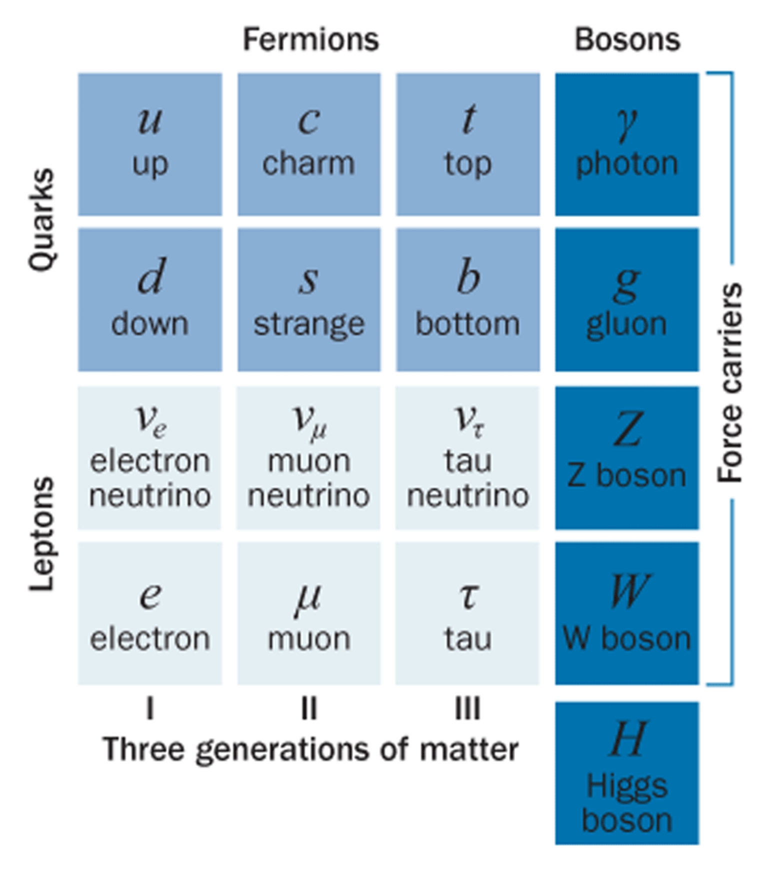
The Standard Model:

+ **Electromagnetic (QED)**

+ Weak

+ Strong

  → *Higgs boson*



General relativity:

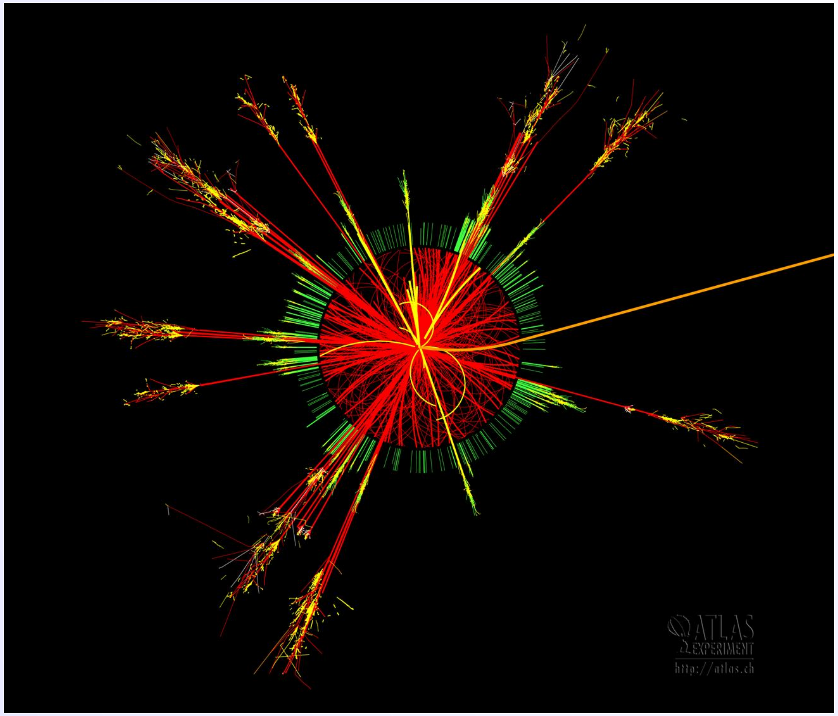
+ Gravity

  → *gravitational waves*

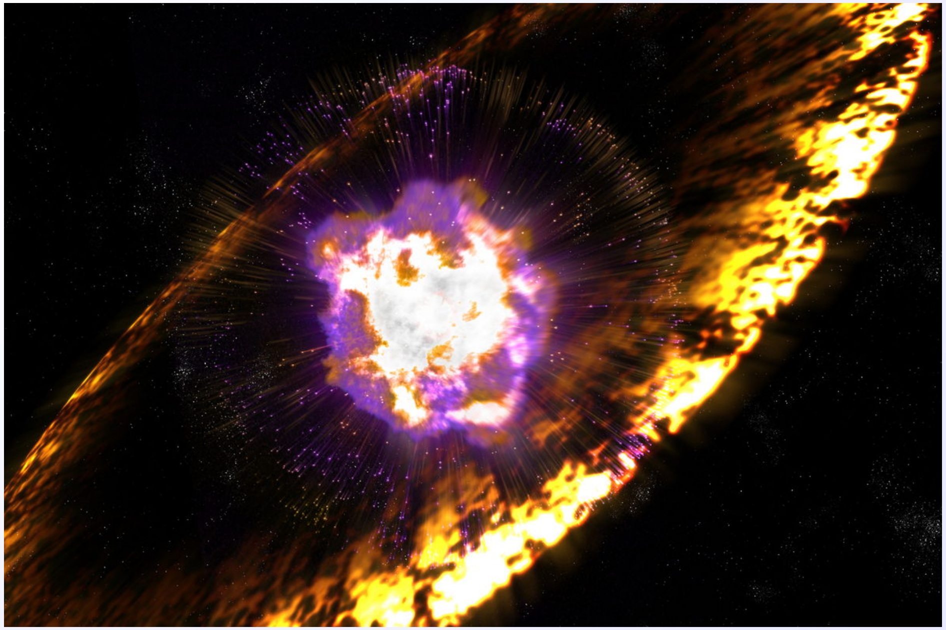
Searches on high-energy energy scale

Particle physics searches for new particles

Stellar cooling from production of new particles

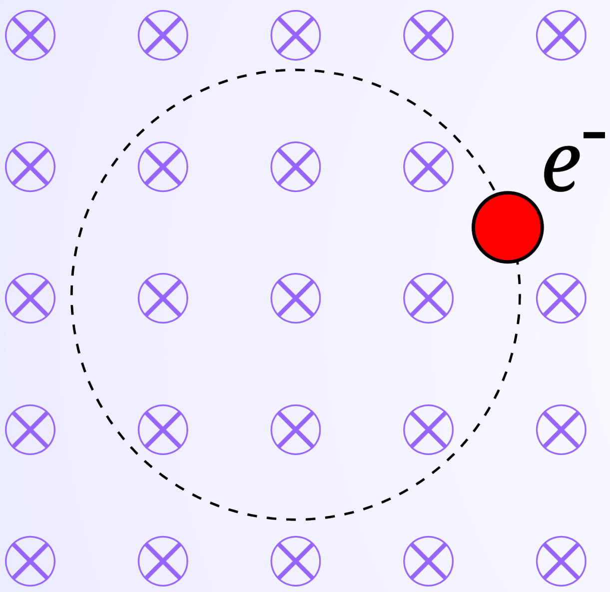


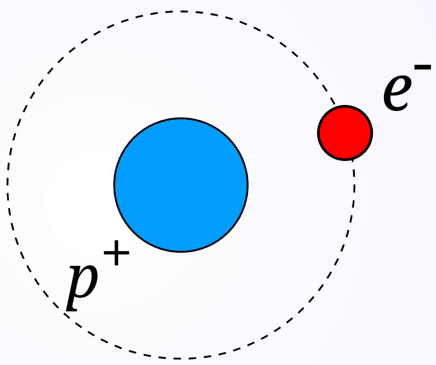
CERN

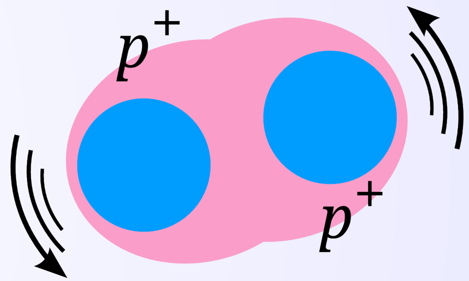


Supernova

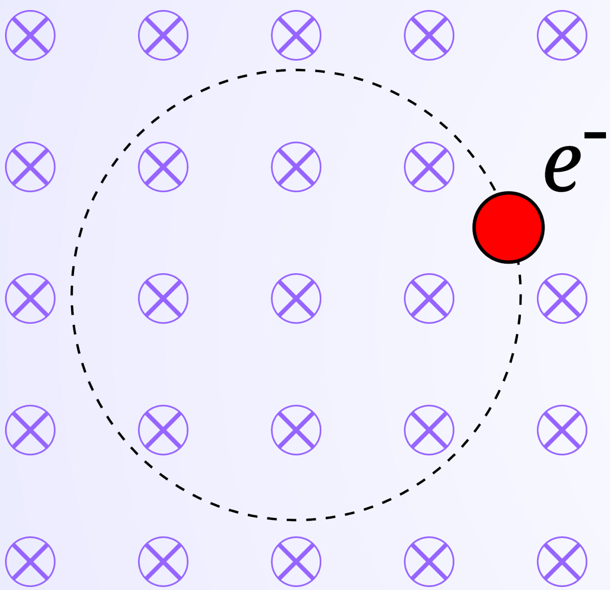
QED on simple systems



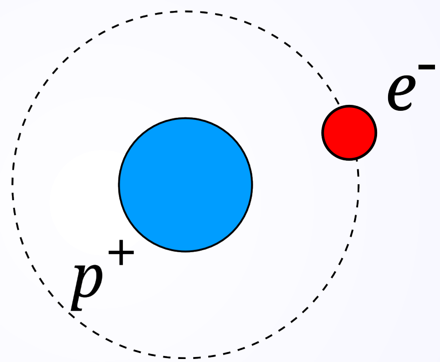




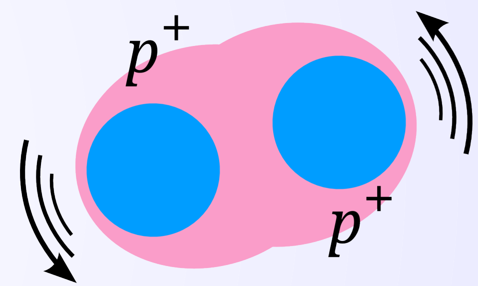
QED on simple systems



$g_e, (\alpha)$



$Ry, (r_p)$

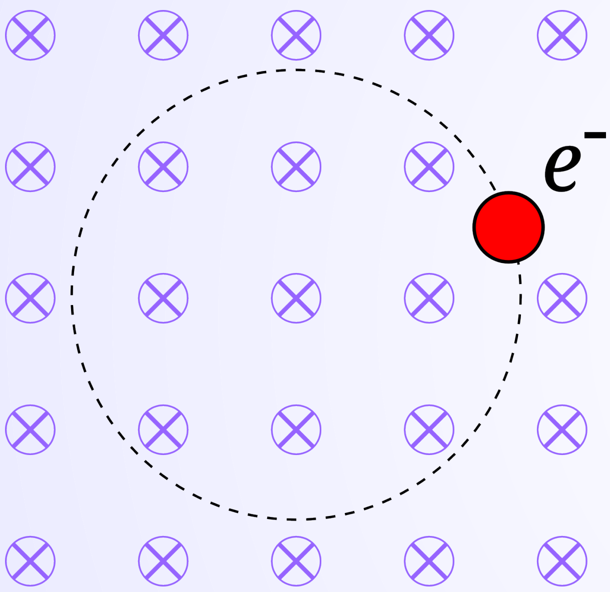


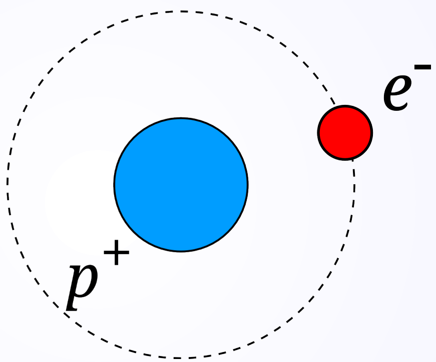
$\mu = m_p/m_e$

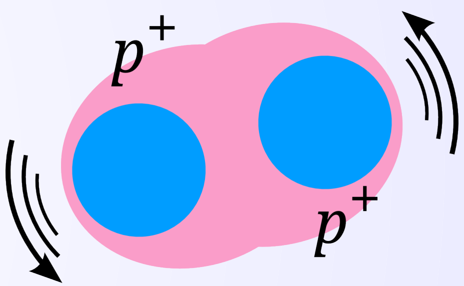
Excellent agreement between experiment and theory:

→ enables determination of fundamental constants

QED on simple systems



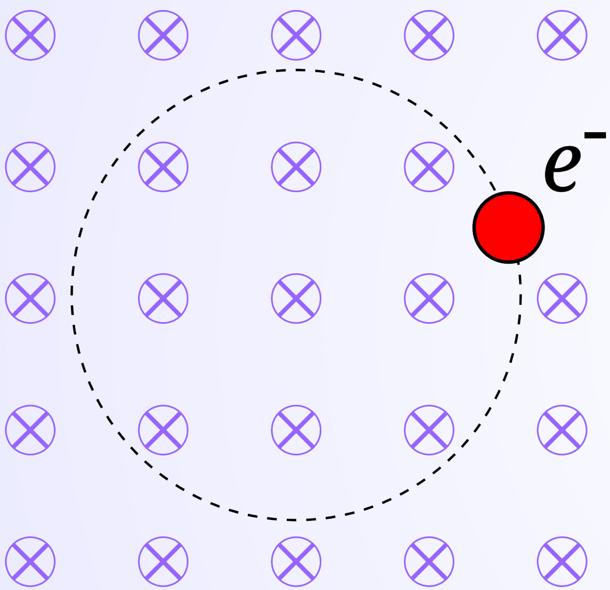


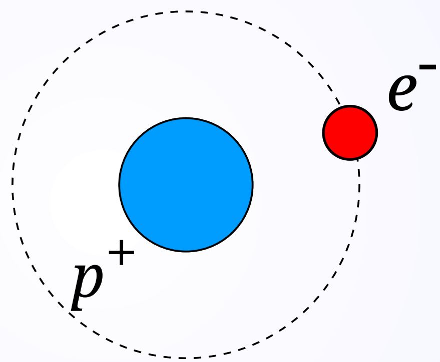


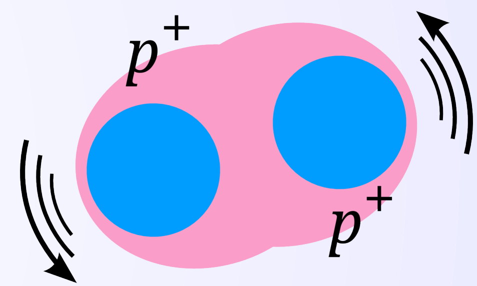
-proton can be replaced with deuteron,triton, alpha, helion

-other exotic (anti)particles substitution

QED on simple systems



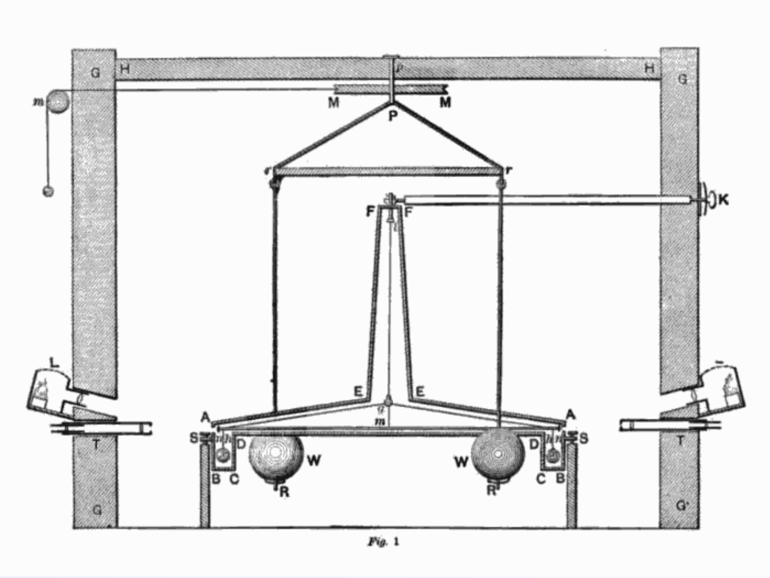




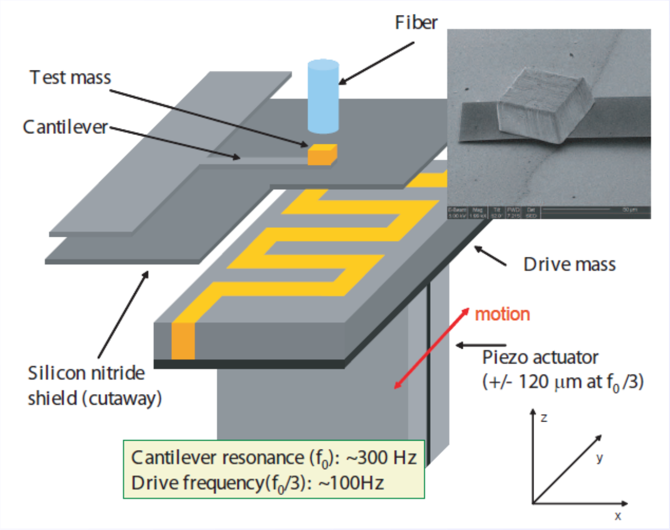
weak, strong, and gravitational forces negligible

Cavendish-type tests

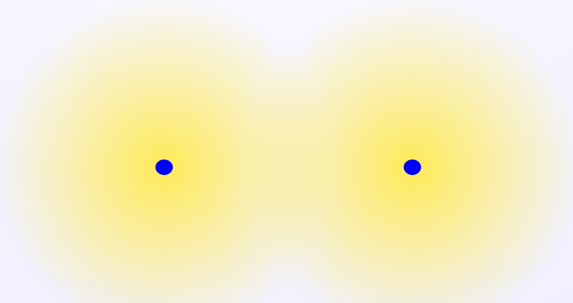
Tests on inverse square laws



Torsion balance: mm scale

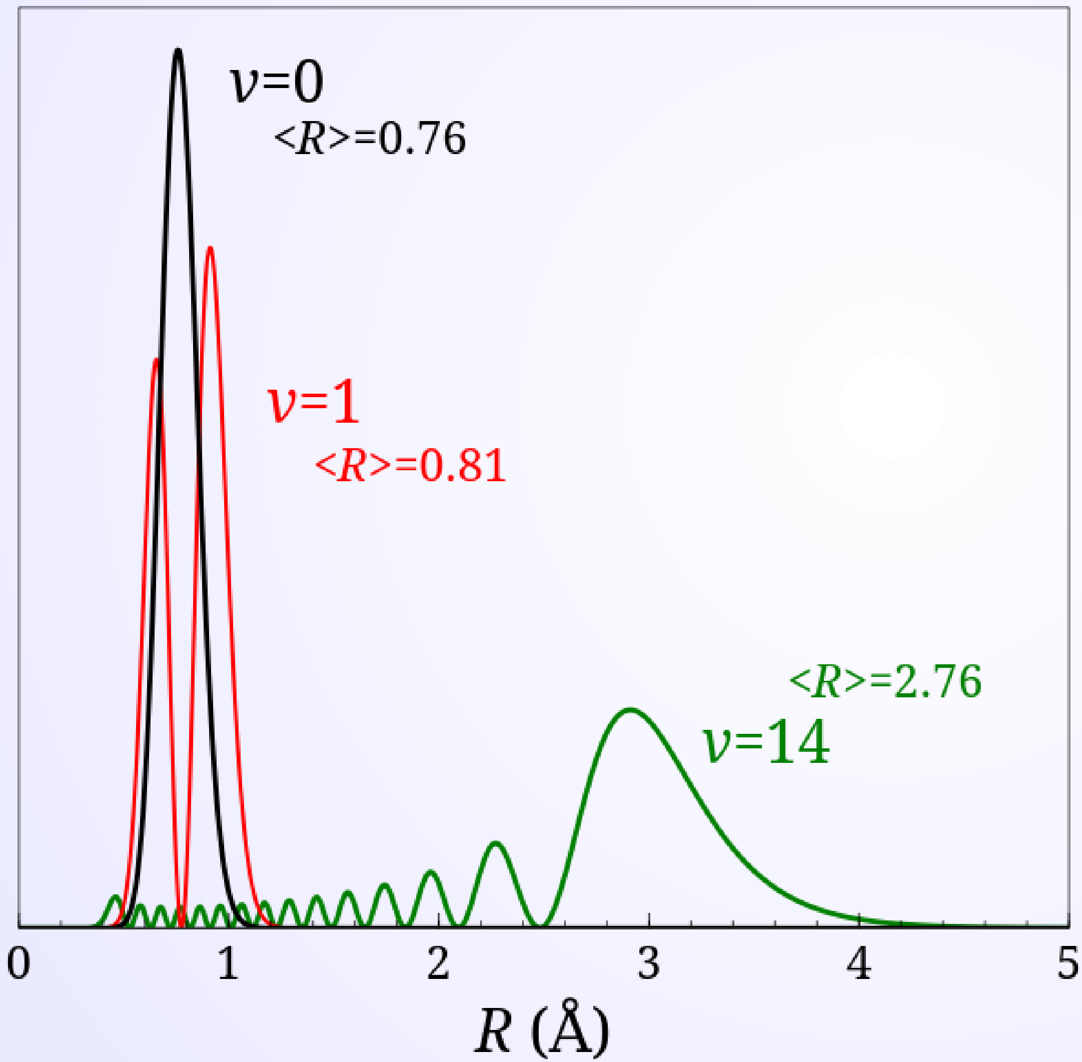


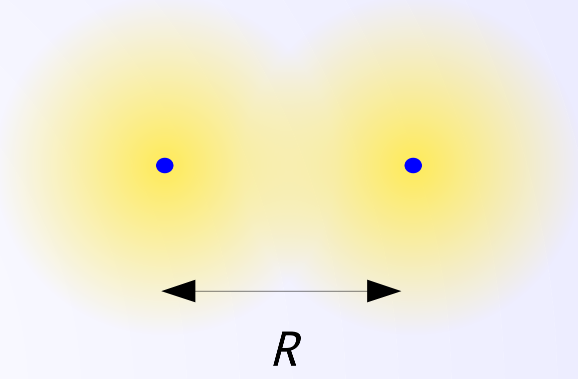
Cantilever: micron scale



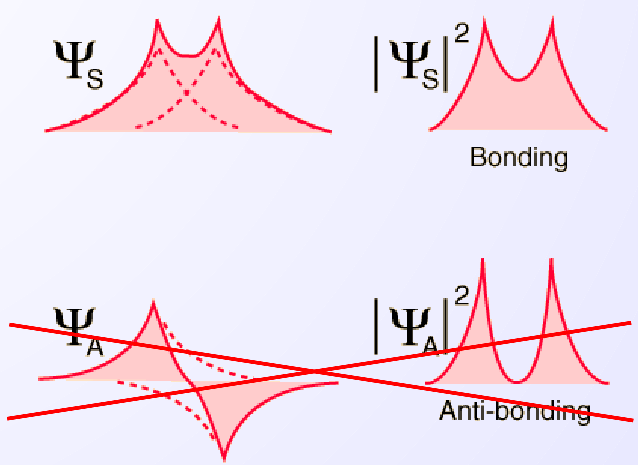
H_2: angstrom scale

Angstrom-scale Cavendish experiment





ground electronic state: 1s + 1s



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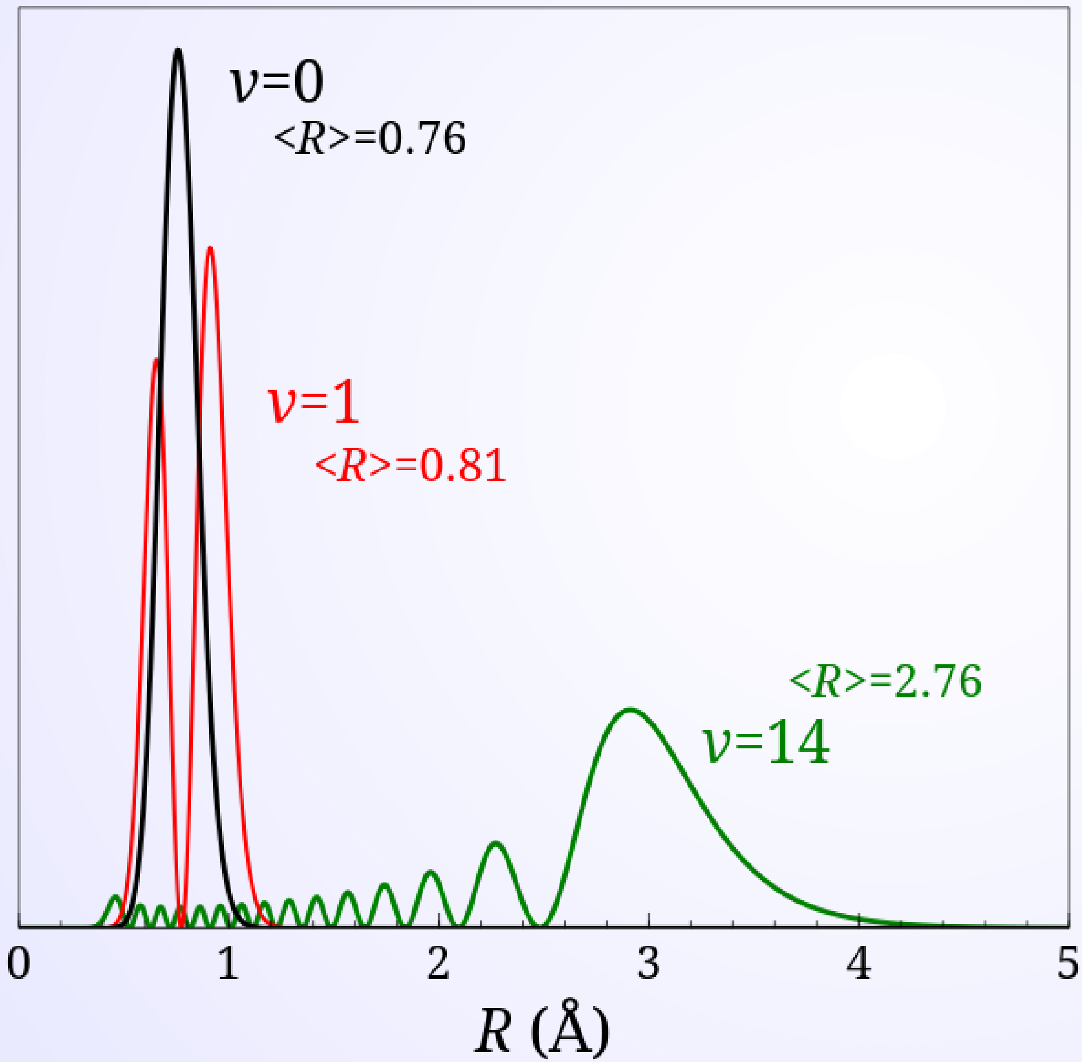
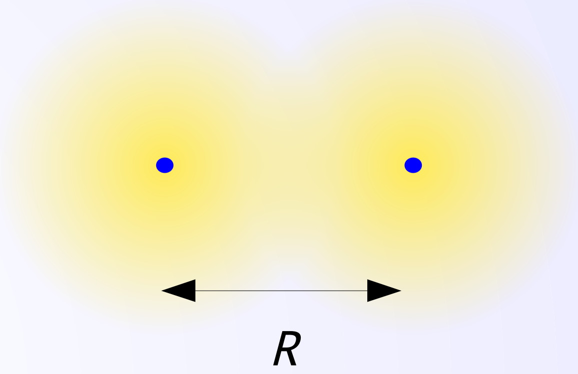




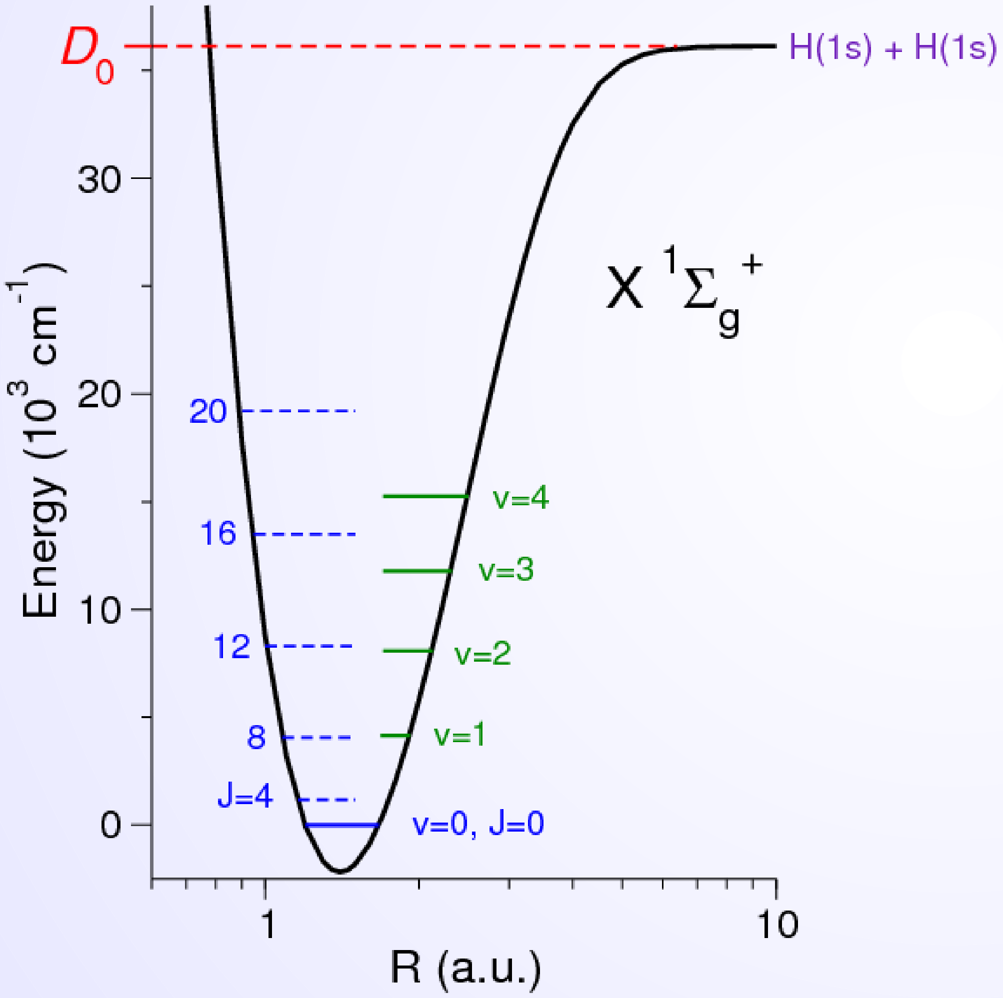
$$\Delta E \equiv E_{\mathrm{exp}} - E_{\mathrm{calc}}$$

$$\delta E \equiv \sqrt{(\delta E_{\mathrm{exp}})^2 + (\delta E_{\mathrm{calc}})^2}$$

agreement if:

$$\Delta E \leq \delta E$$

H_2 ground electronic state: Theory



Ab initio energy:

$$E = E_{BO} + E_{ad} + E_{nad} + E_{rel} + E_{QED}$$

Perturbative expansion:

$$E = E_0 + \alpha^2 E_2 + \alpha^3 E_3 + \alpha^4 E_4 + \ldots$$

K. Pachucki, J. Komasa, et al.

e.g. J. Komasa *et al. JCTC* **7**, 3105 (2011)

$1\ \text{cm}^{-1} = 1.24 \times 10^{-4}\ \text{eV} = 30\ \text{GHz}$

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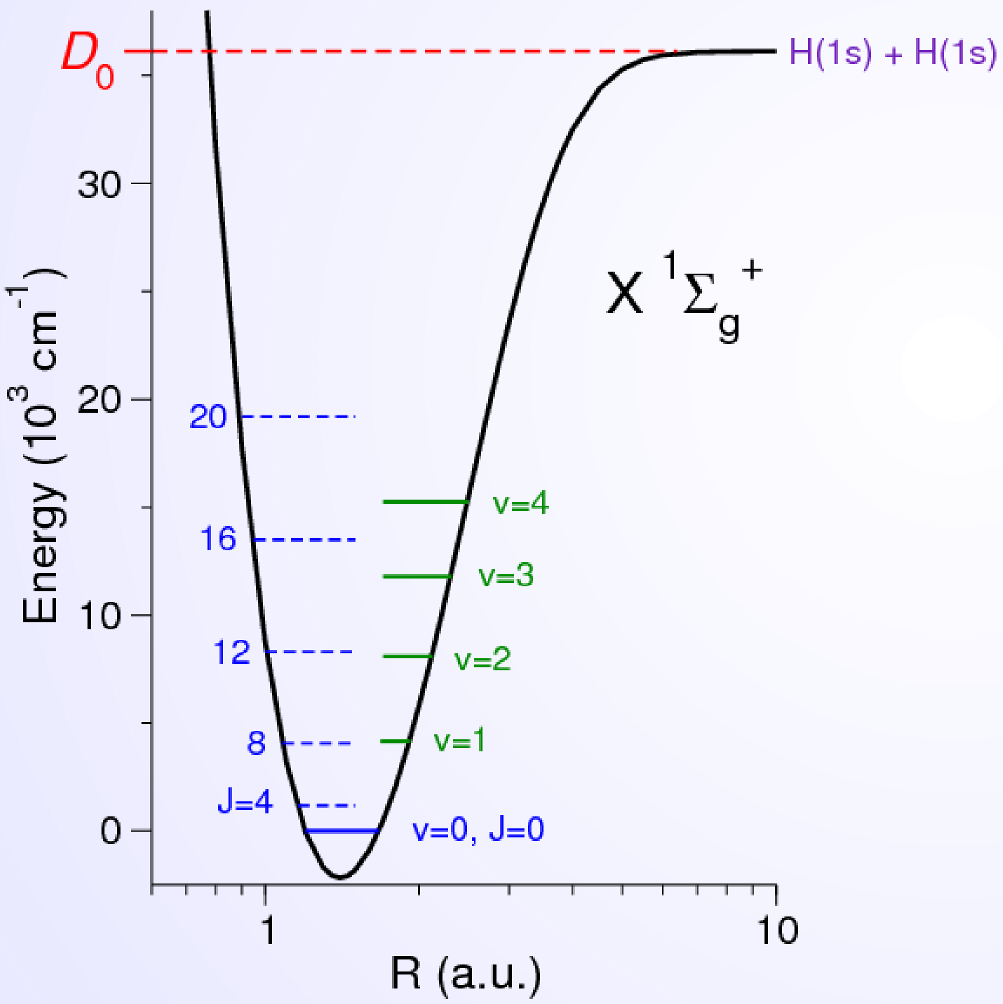

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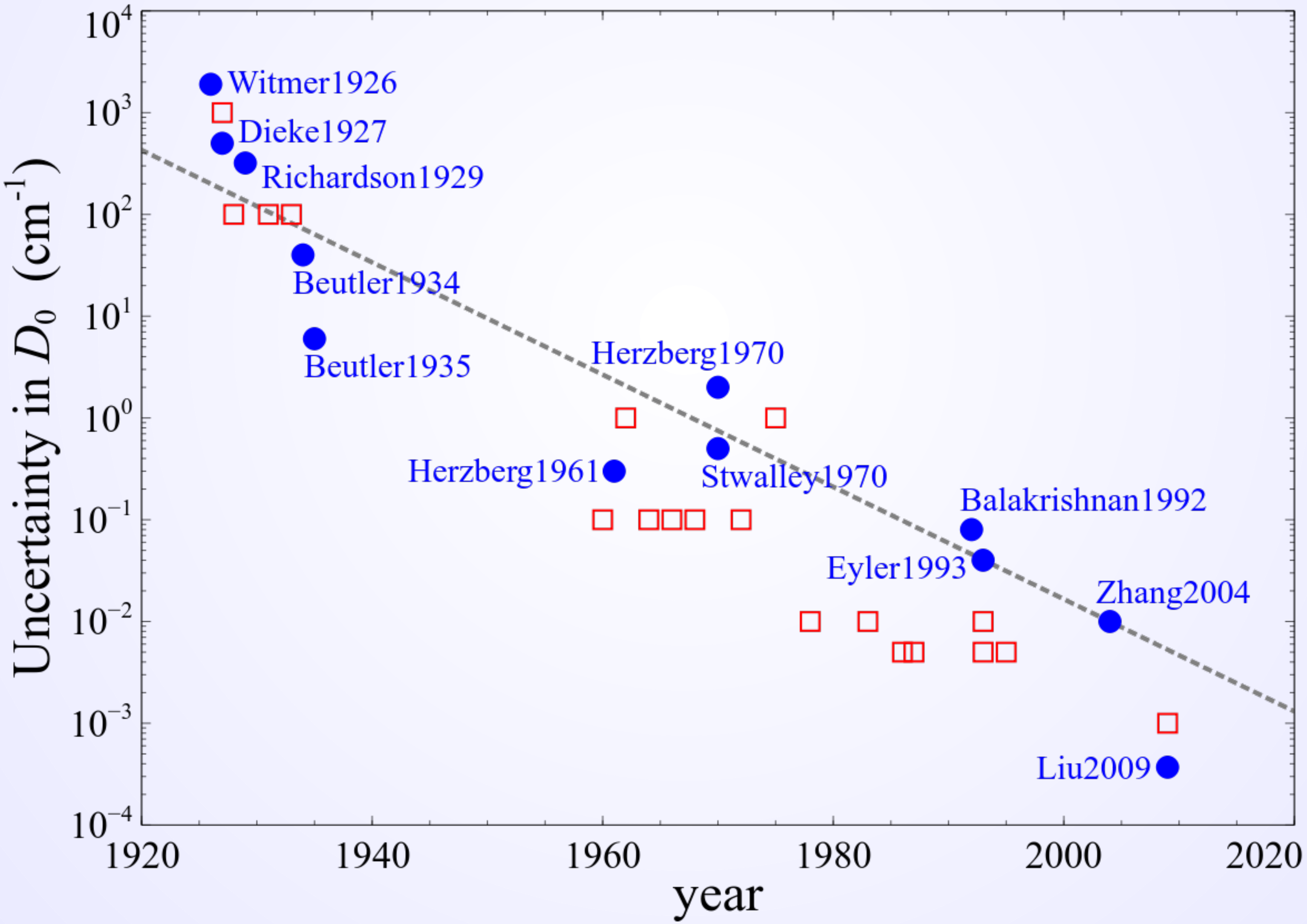
V. I. Korobov et al.

Molecular ions H_2^+, HD^+

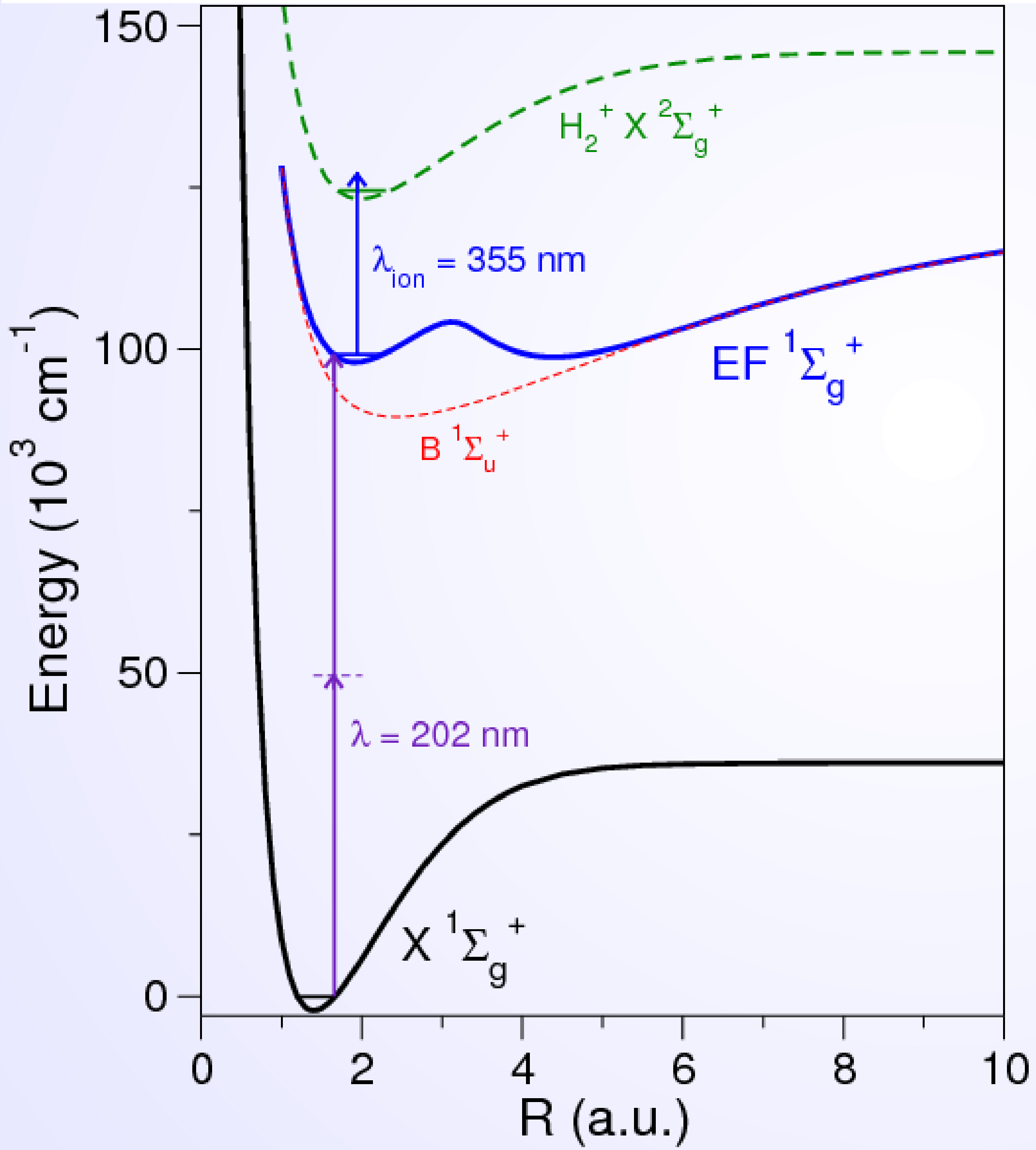
e.g. V. I. Korobov *et al.*, *PRA* **89**, 032511 (2014)

Benchmark binding energy: H_2 D_0

Theory and Experiment



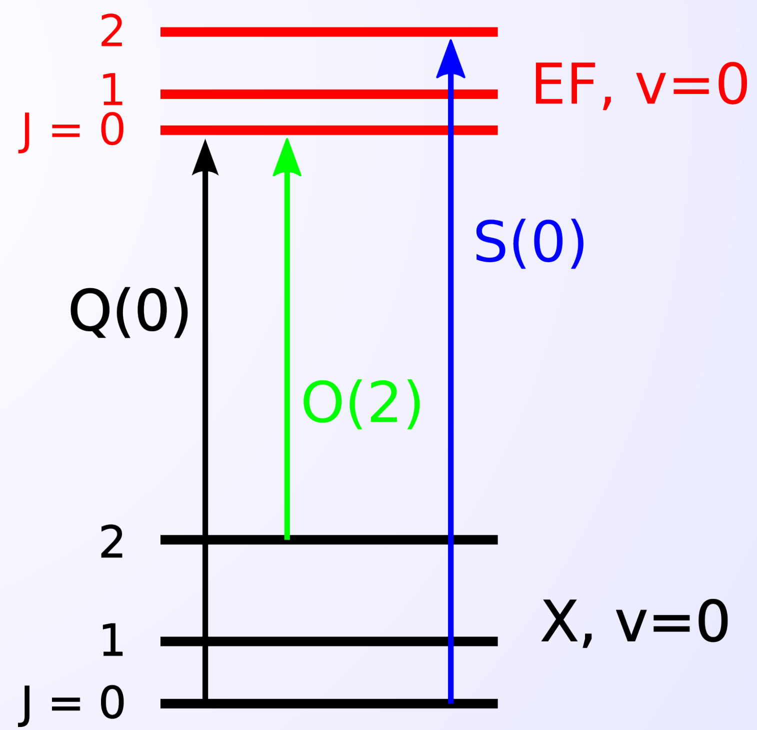
H_2 spectroscopic measurements



Direct excitation weak

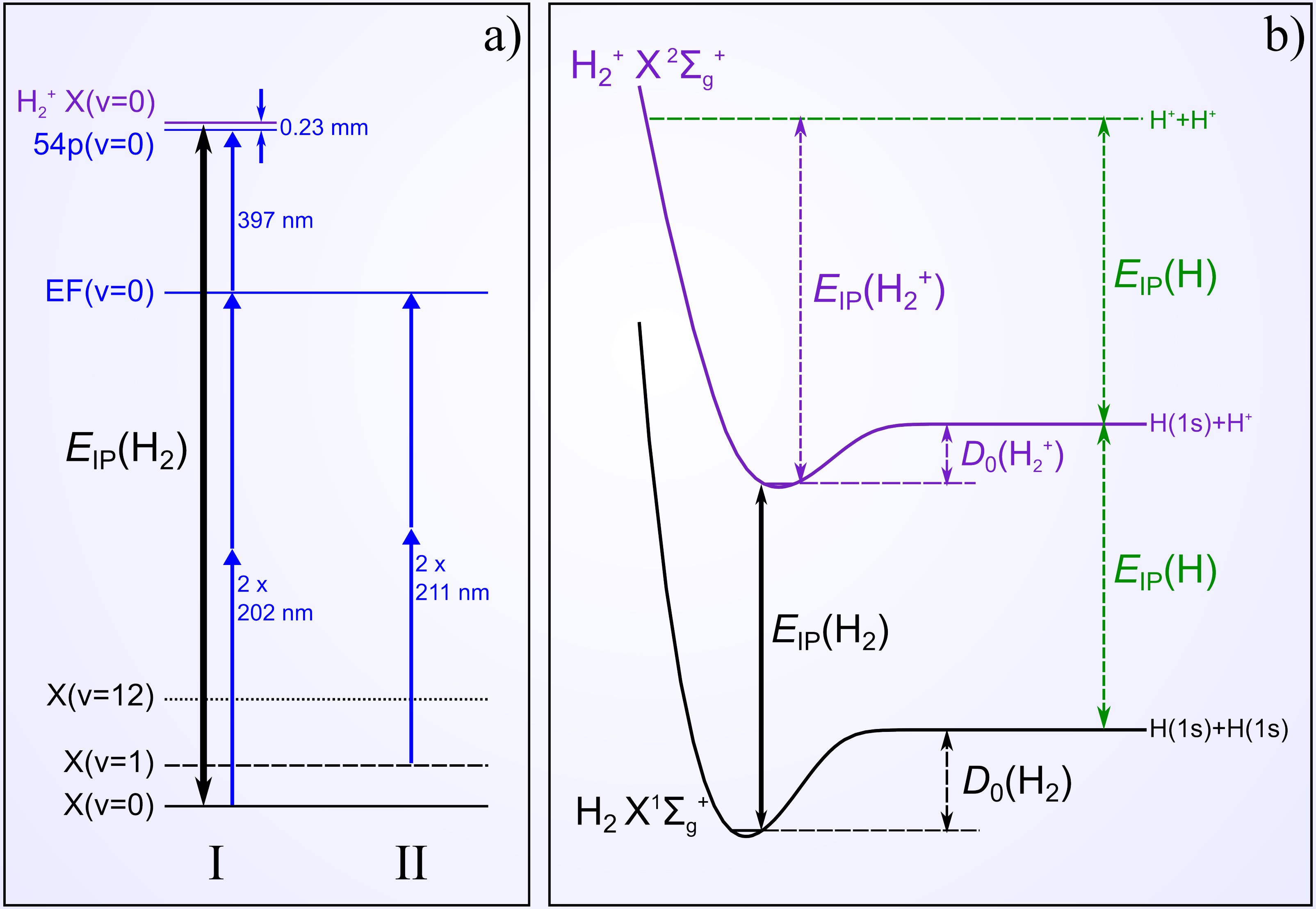
(no permanent dipole)

Combination differences



Q: ΔJ = 0; **O**: ΔJ = -2; **S**: ΔJ = 2

Expt. scheme: D_0 determination

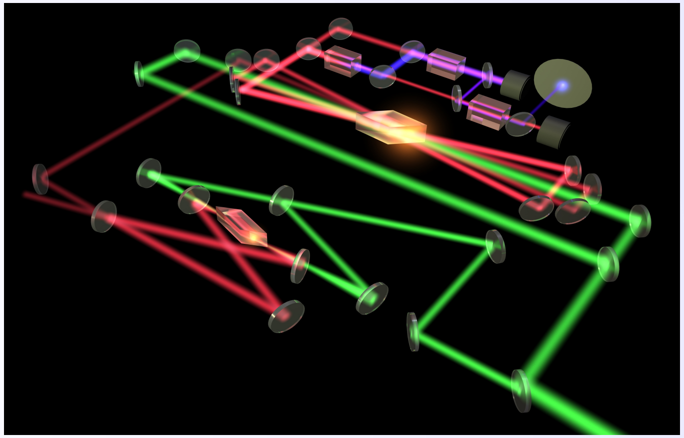


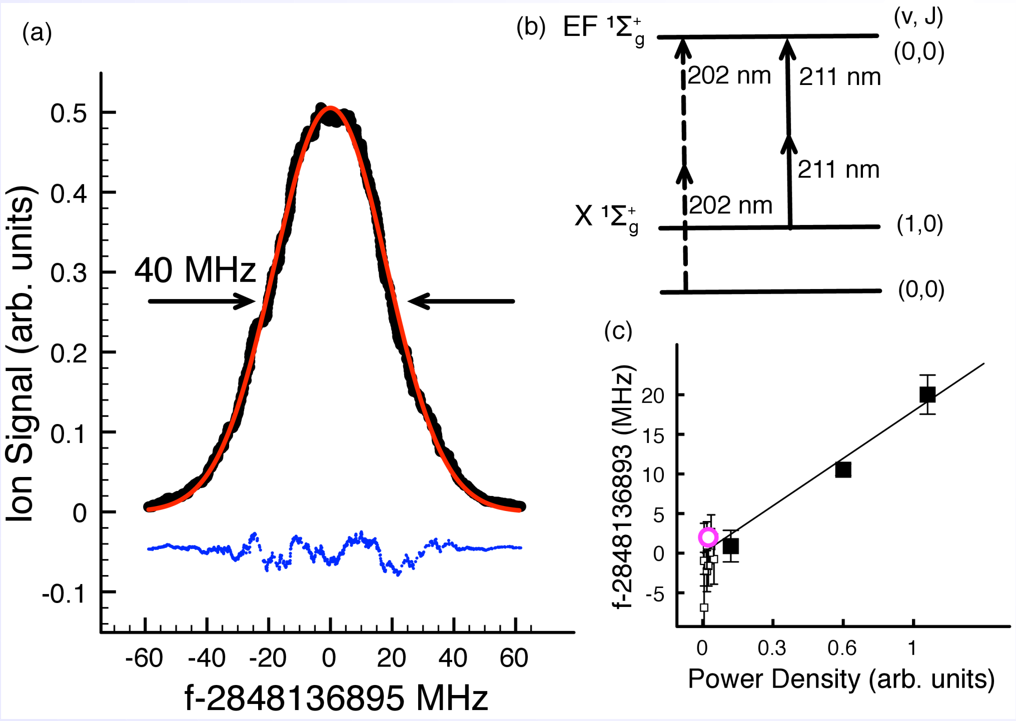
J. Liu, EJS, W. Ubachs, F. Merkt *et al.*, *J. Chem. Phys.* **130**, 174306 (2009)

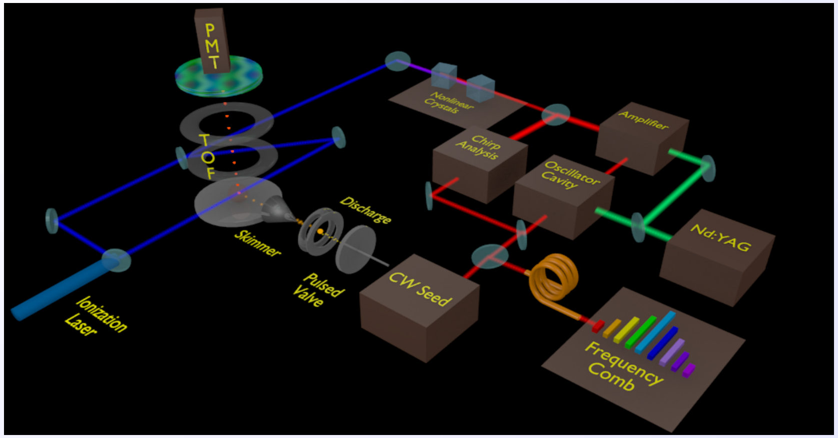
H_2 EF-X spectroscopy

Features

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







M. L. Niu *et al.*, J. Mol. Spectrosc. **300**, 44 (2014); G. Dickenson *et al.*, PRL **110**, 193601 (2013)

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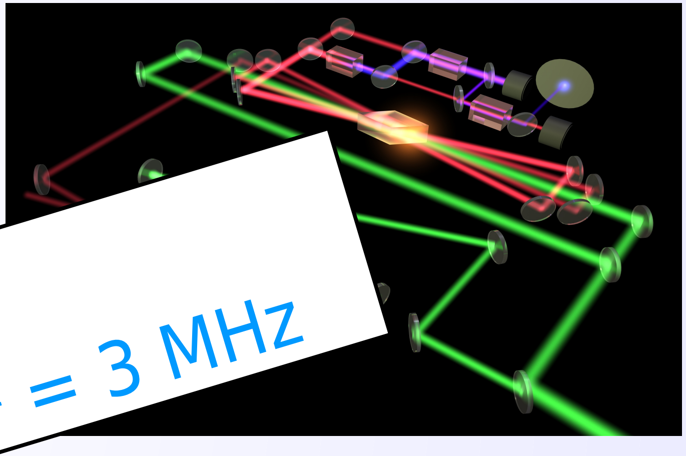
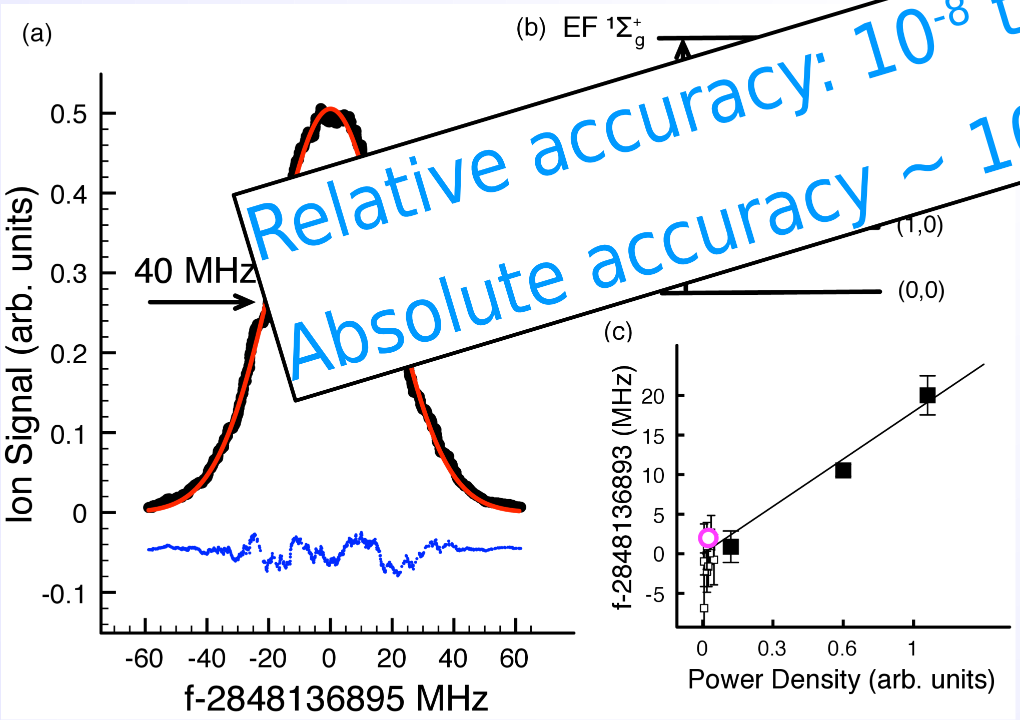
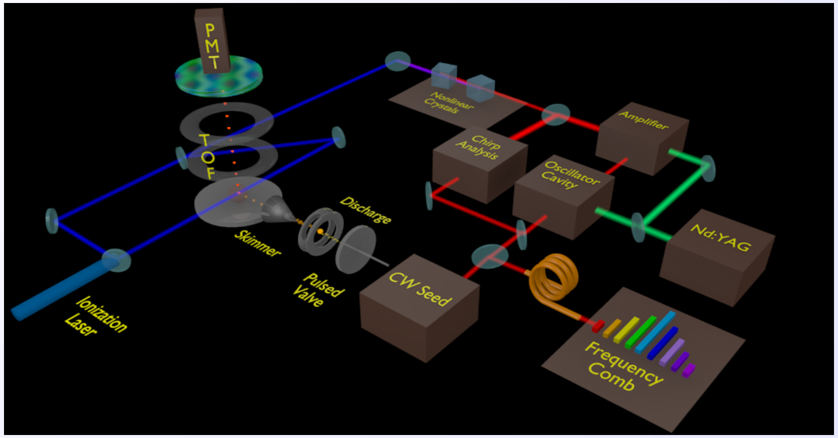


Relative accuracy: 10^{-8} to 10^{-10}

Absolute accuracy ~ 10^{-4} cm^{-1} = 3 MHz





M. L. Niu *et al.*, J. Mol. Spectrosc. **300**, 44 (2014); G. Dickenson *et al.*, PRL **110**, 193601 (2013)

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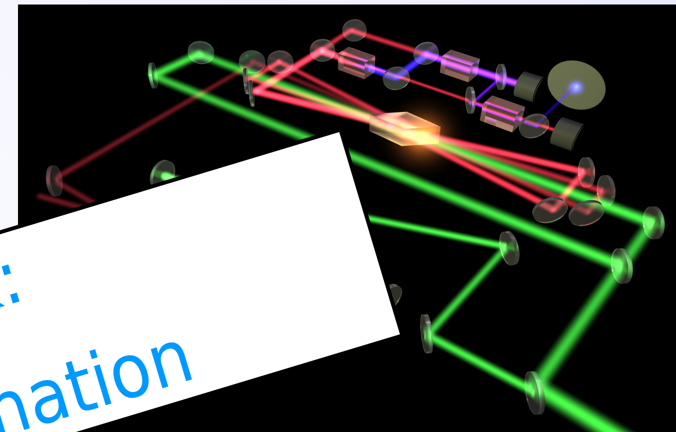
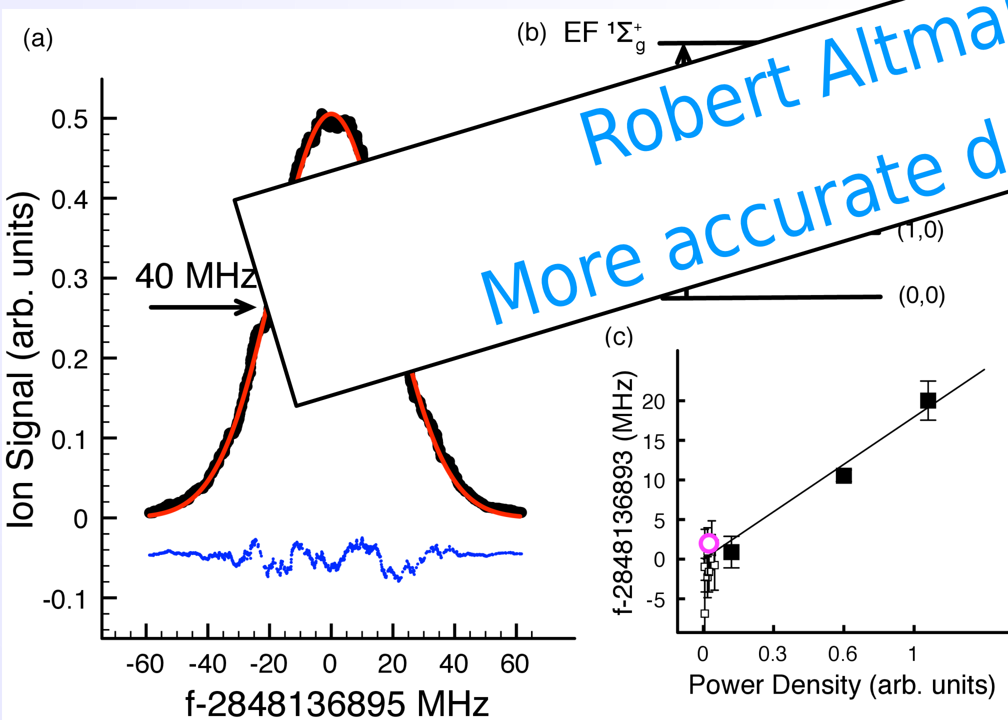
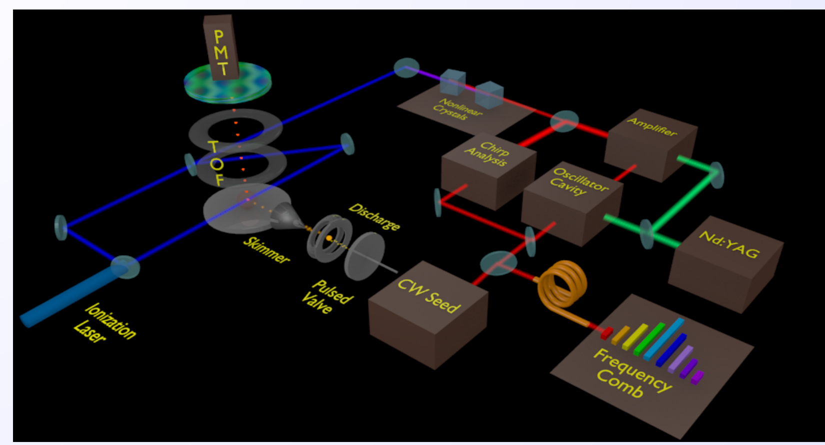


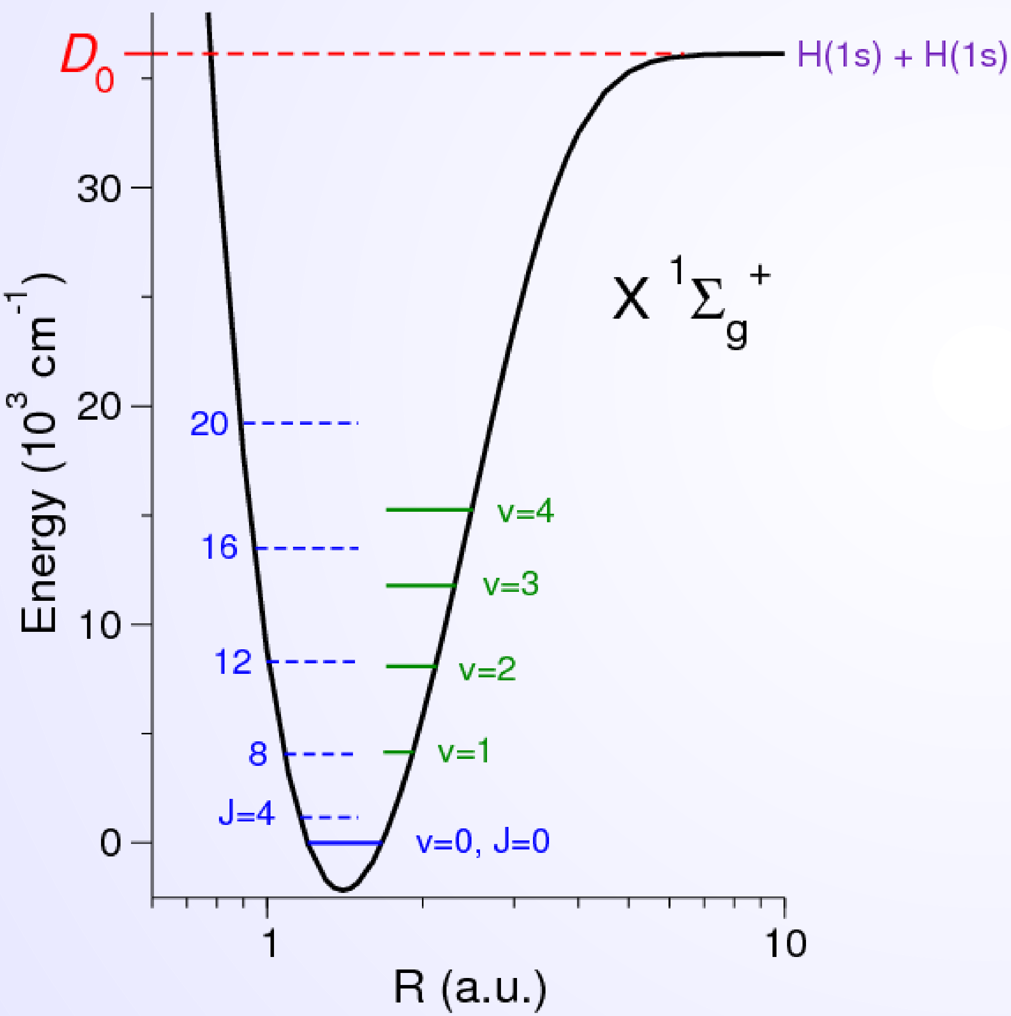


Robert Altmann talk:
More accurate determination



M. L. Niu *et al.*, J. Mol. Spectrosc. **300**, 44 (2014); G. Dickenson *et al.*, PRL **110**, 193601 (2013)

Precision measurements on the H_2 ground state



$1\ cm^{-1} = 1.24 \times 10^{-4}$ eV = 30 GHz

- Dissociation energy D_0

J. Liu *et al.*, *JCP* **130**, 174306 (2009)

- Rotational series *J*=0-16

EJS *et al. PRL* **107**, 043005 (2011)

- Fundamental vibration *v*(0,1)

G. D. Dickenson *et al.*, *PRL* **110**, 193601 (2013)

- Vibrationally excited *v*(10-12)

M. Niu *et al.*, *J. Chem. Phys.* **143**, 081102(2015)

Experiment – Calculation comparisons (in MHz)

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

W. Ubachs *et al.*, J. Mol. Spectrosc. **320**, 1 (2016).

Experiment – Calculation comparisons

Species	Splitting	δE_{exp}	Ref.	δE_{calc}	δE	ΔE
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	$v = 0 \to 3$	1.3	[58]	75	75	[illegible]
	$v = 0 \to 12$	105	[59]	[illegible]	[illegible]	150[b]
	D_0	12	[illegible]	[illegible]	3	36
HD	$v = 0 \to 1$	[illegible]	[illegible]	2.4	8	4
	D_0	[illegible]	[49]	30	27	32
D_2	[illegible]	4.5[a]	[54]	2.1	5	−0.6
	$v = 0 \to 2$	30	[60]	12	30	−12
	D_0	21	[48]	27	30	12
H_2^+	$v = 0, J = 0 \to 2$	2.3	[61]	0.003	2.3	−1.0
HD^+	$v = 0 \to 1$	0.064	[62]	0.002	0.064	−0.156
	$v = 0 \to 4$	0.50	[63]	0.008	0.50	−0.35
	$v = 0 \to 8$	0.41	[64]	0.015	0.41	0.22

Good agreement so far... No anomalies...

W. Ubachs, et al. *J. Mol. Spectrosc.* **320**, 1 (2016).

Constraning effects of new physics

Generic parameterization: *fifth-forces*

-Power law corrections to 1/*r* -potential

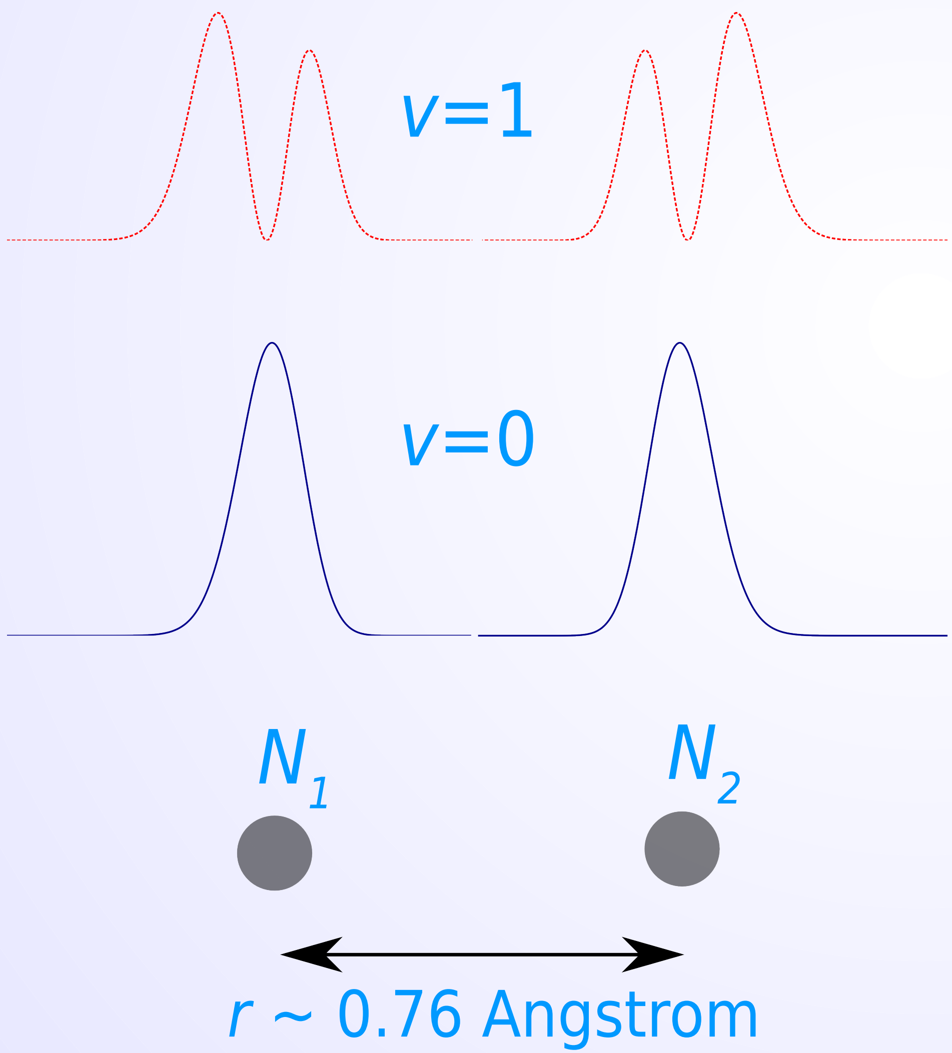
-**Yukawa potential**

Specific proposal: *large extra dimensions*

-**ADD theory**

-RS theory

Perturbative effect of V_{new}



Level shifts:

$$\langle \Psi_1 | V_{\text{new}} | \Psi_1 \rangle ; \langle \Psi_0 | V_{\text{new}} | \Psi_0 \rangle$$

Transition shift:

$$\langle \Psi_1 | V_{\text{new}} | \Psi_1 \rangle - \langle \Psi_0 | V_{\text{new}} | \Psi_0 \rangle$$

Differential effect

Greater with very **different** Ψ's

Fifth-force potential

New *hadron-hadron* interaction?

(in atoms: *hadron-lepton* interaction)

Hideki Yukawa

Yukawa potential (Phenomenological)

$$V_5(r) = N_1 N_2 \left\{ \alpha_5 \frac{\exp(-r/\lambda_5)}{r} \right\} \hbar c$$

strength: α_5

range: $\lambda_5 = \hbar/(m_5 c)$

internuclear distance: r

Fifth-force potential

New *hadron-hadron* interaction
(in atoms: *hadron-lepton* interaction)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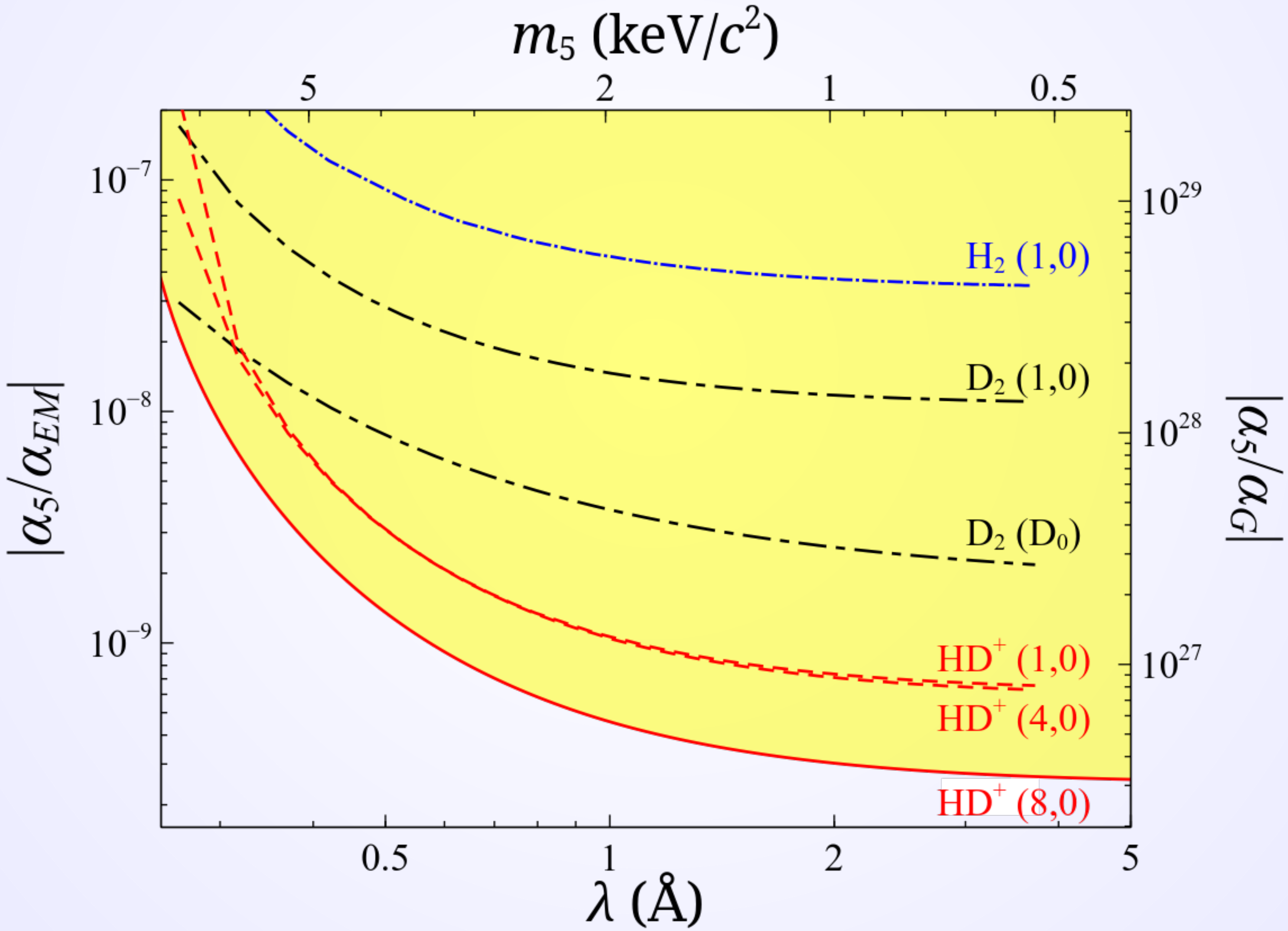
strength: α_5
range: $\lambda_5 = \hbar/(m_5 c)$

internuclear distance: r
hadron number: $N_1; N_2$

Coulomb potential:
$\alpha_5 \to \alpha; \lambda_5 \to \infty$

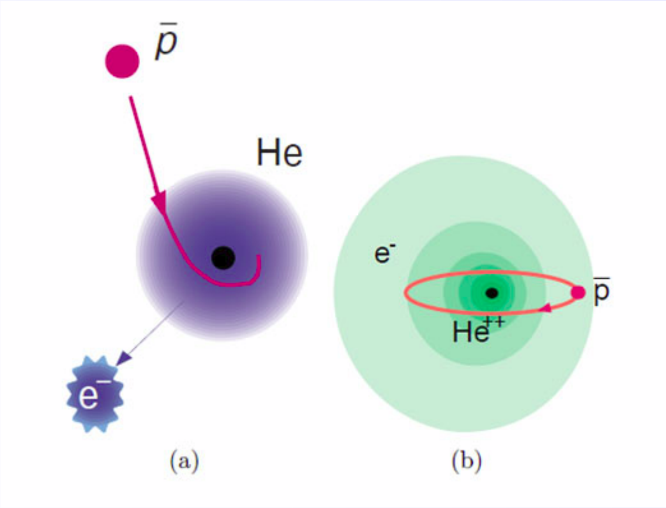
Fifth force constraints: $< V_5 > \leq \delta E$



EJS, K. Pachucki, W. Ubachs *et al.*, *Phys. Rev. D* **87**, 112008 (2013)

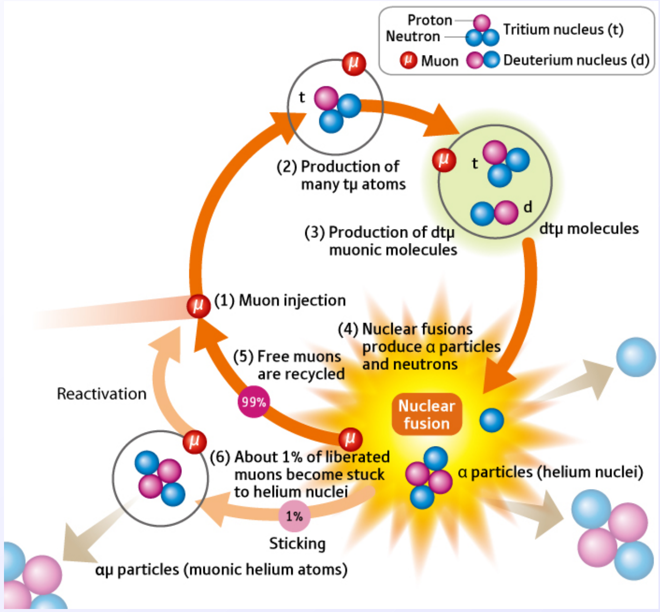
HD^+ (8,0): J. Biesheuvel,W. Ubachs, J. C. J. Koelemeij, et al., *Nat. Comm.* **7**, 10385 (2016).

Exotic atom and molecules



Antiprotonic helium

$\bar{p}$-He^+ distance ~ 0.5 a_0

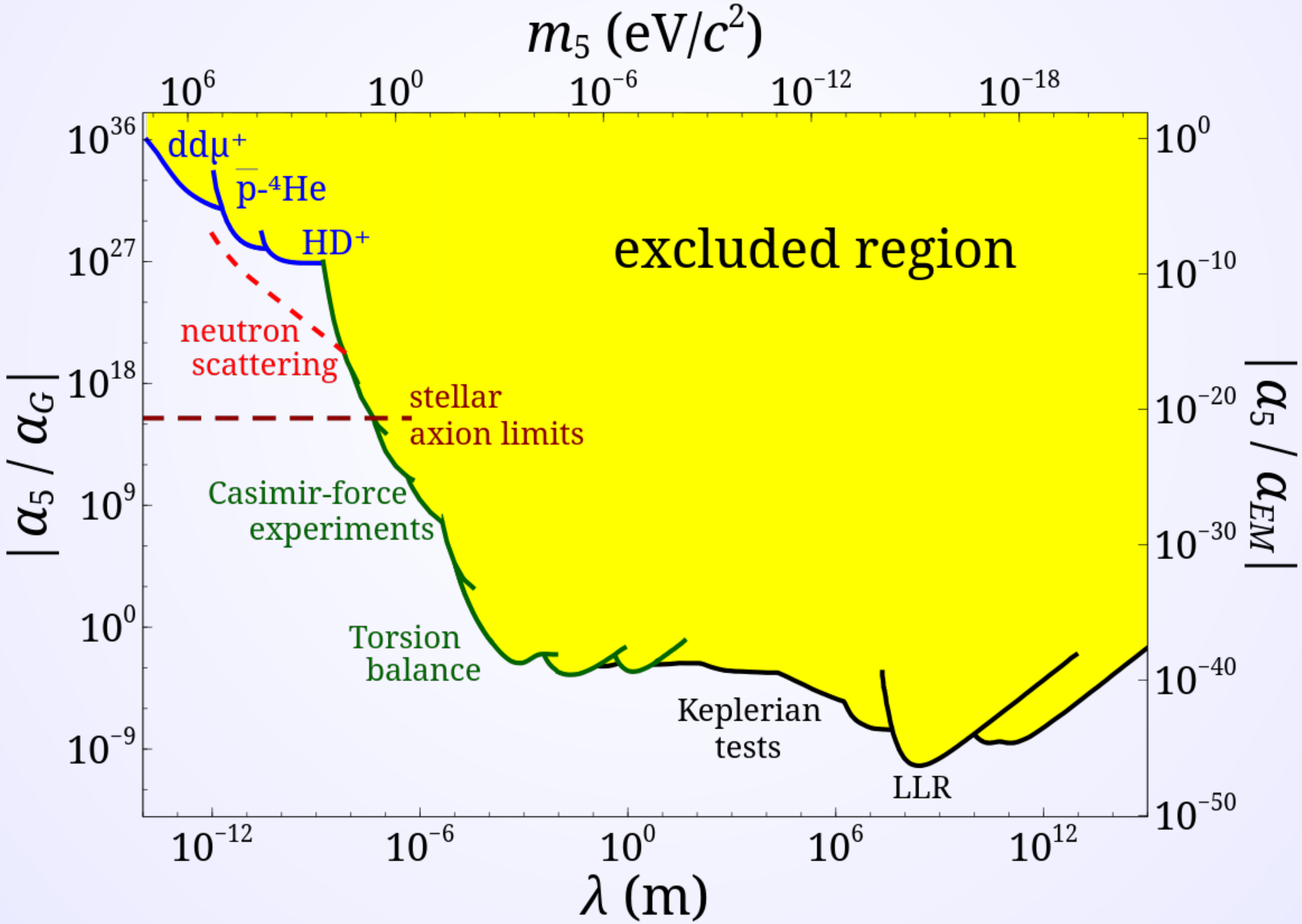


Muonic D_2^+:

$(dd\mu)^+$ distance ~ 0.01 a_0

M. Hori et al., *Nature* **475**, 484 (2011).
V.I. Korobov, *PRA* **77**, 1995 (2008).
D.V. Balin et al., *Phys. Part. & Nuclei* **42**, 185 (2011).
V.I. Korobov, *J. Phys. B* **37**, 2331 (2004).

Fifth-force constraints

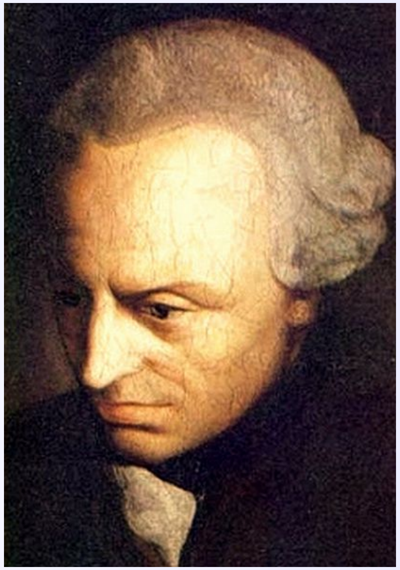


EJS, W. Ubachs, V.I. Korobov, J. Mol. Spectrosc. **300**, 65 (2014)

On extra dimensions

Immanuel Kant (1749)

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



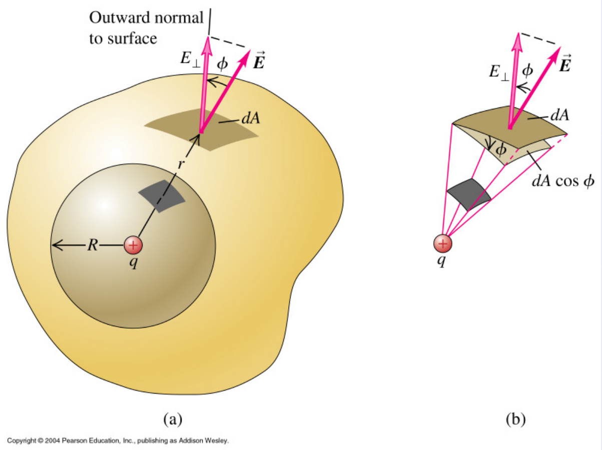
Immanuel Kant

Gauss flux law:

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

3-dim : $A_{\mathrm{V}} \propto r^2 \rightarrow F \propto \frac{1}{r^2}$

N-dim : $A_{\mathrm{V}} \propto r^{N-1} \rightarrow F \propto \frac{1}{r^{N-1}}$



ADD theory

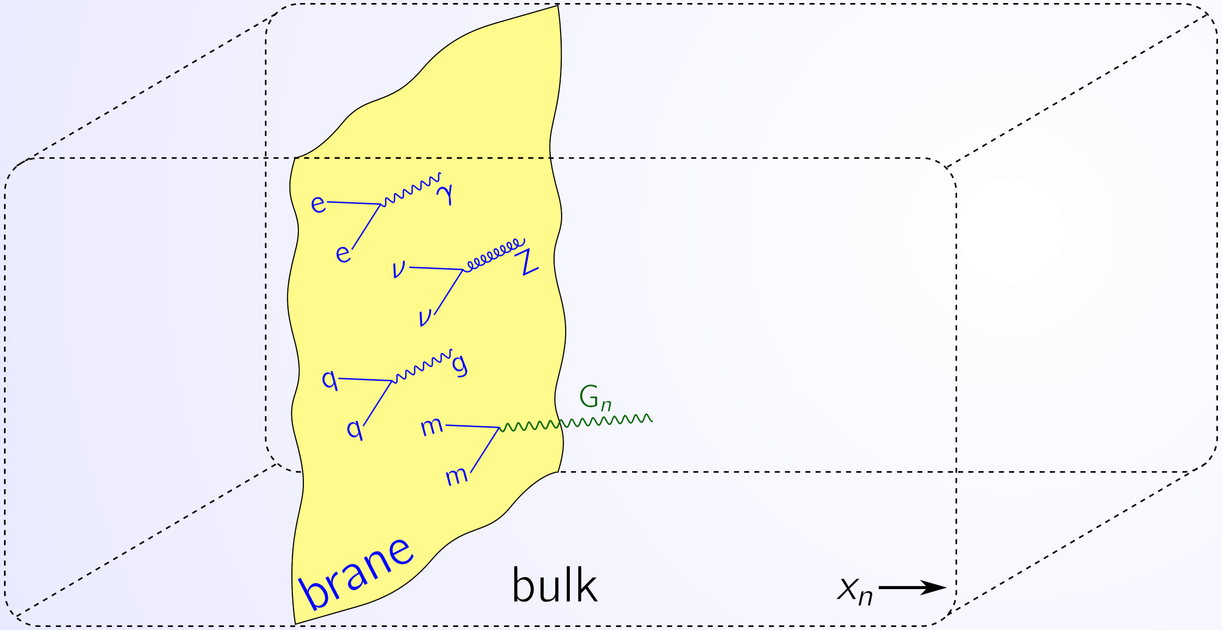
Arkani–Hamed, Dimopoulos, Dvali

Phys. Lett. B **429**, 263–272 (1998)

Hierarchy problem: Why is gravity so much weaker?

e.g. between two protons $\frac{V_G}{V_{em}} = 8 \times 10^{-37}$

ADD and "branes"



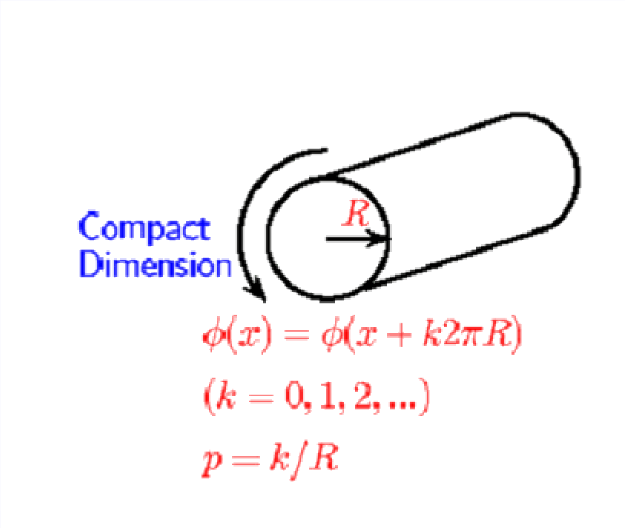
Electromagnetism, Weak and Strong forces confined in normal (3+1)-dim space

Gravity leaks out to *compactified* extra *n*-dim diluting its strength

At time of ADD proposal, possibility of large extra dimensions up to ~mm

ADD and Kaluza-Klein particles

Extra *n* dimensions assumed to be curled up



Boundary condition:

quantized modes associated with Kaluza-Klein (KK) particles

KK particles or gravitons fly off into extra dimensions:

missing energy signatures in particle accelerator experiments

ADD potential: modified gravity

ADD modified gravity with n_e extra dimensions:

$$V_{\mathrm{ADD}}(r) = -G_{(4+n)} \frac{m_1 m_2}{r^{1+n_e}}$$

$$G_{(4+n)} = (R_{\mathrm{c}})^{n_e} G$$

R_c : compactification length

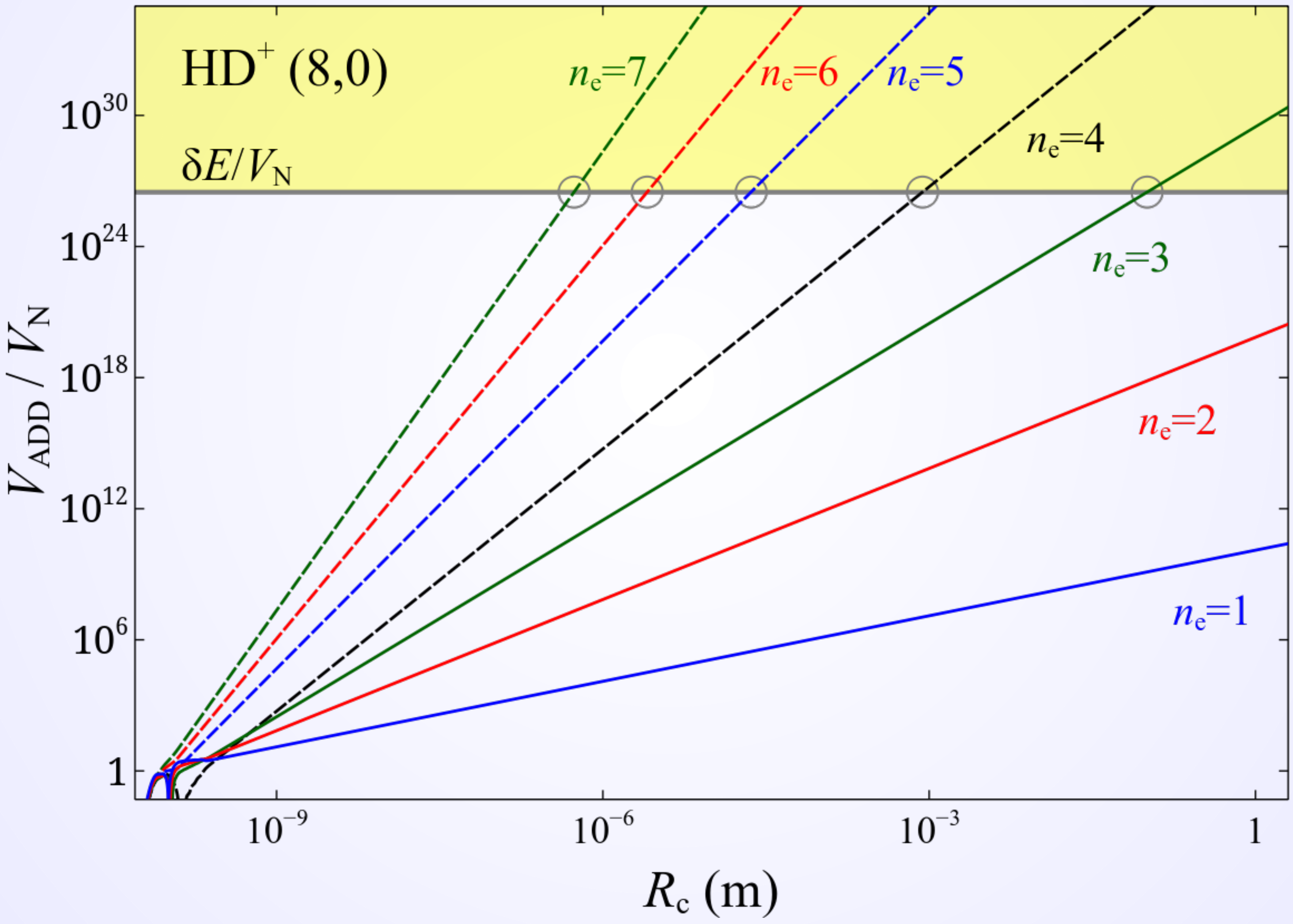
$$V_{\mathrm{ADD}}(r) = -G \frac{m_1 m_2}{r} \left(\frac{R_{\mathrm{c}}}{r}\right)^{n_e}$$

Newtonian: V_N

enhancement factor

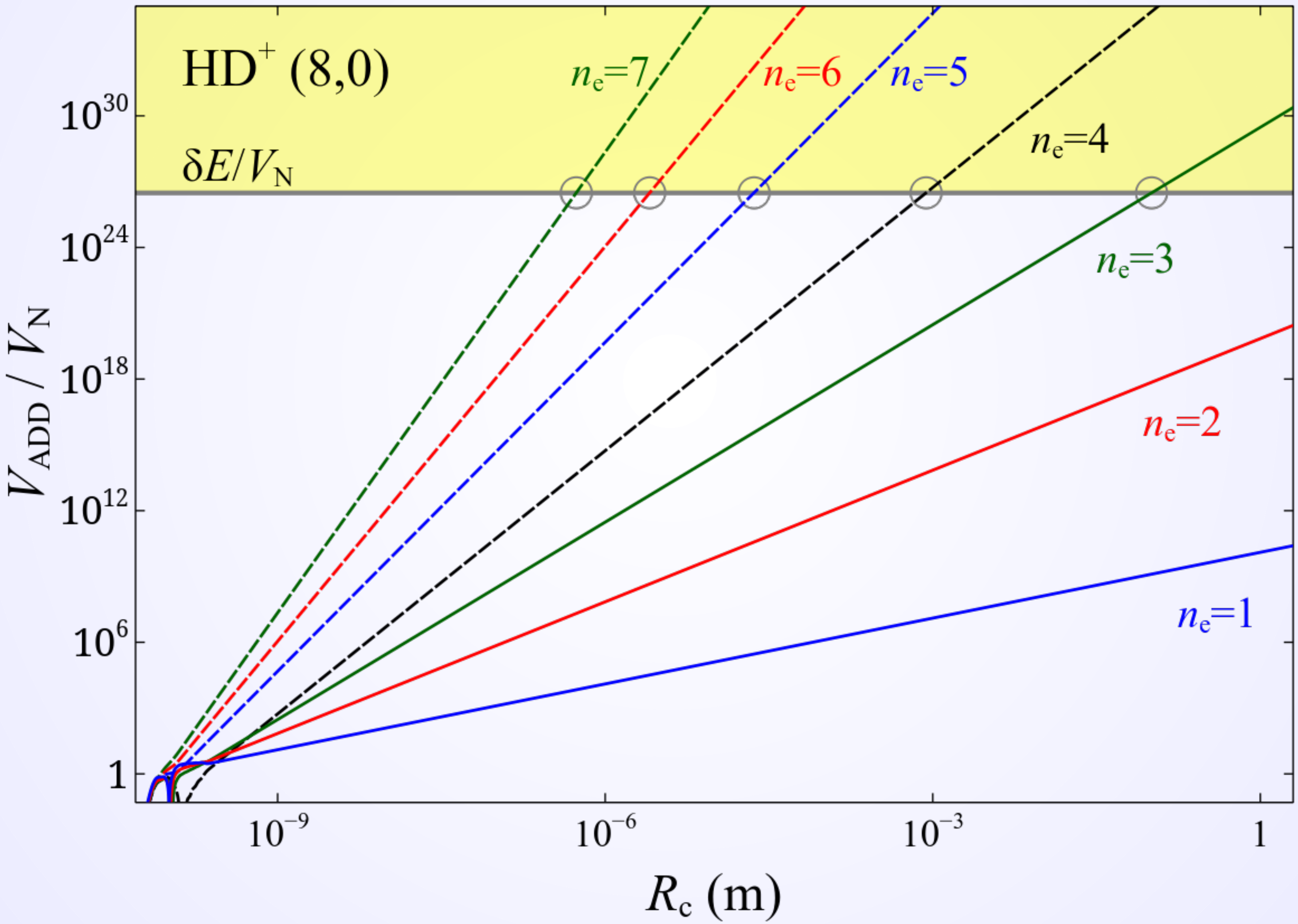
EJS, A. N. Schellekens, B. Gato-Rivera and W. Ubachs, *New J. Phys* **17**, 033015 (2015).

Constraints on extra dimensions $< V_{\mathrm{ADD}} > \leq \delta E$



EJS et al., *New J. Phys.* **17**, 033015 (2015); W. Ubachs, et al., *J. Mol. Spectrosc.* **320**, 1 (2016).

Constraints on extra dimensions $< V_{\mathrm{ADD}} > \leq \delta E$



For M-theory with n_e=7, R_c < 0.6 microns...

ADD constraints from other methods

Large Hadron Collider: $R_3 < 2 \times 10^{-9}$ m

Supernova cooling: $R_3 < 4 \times 10^{-7}$ m

Torsion balance: $R_2 < 5 \times 10^{-5}$ m

atomic H: $R_7 = 1.3 \times 10^{-10}$ m (r_p puzzle; hard core 1 fm)

QCD (nucleon masses): $R_7 < 3 \times 10^{-10}$ m

Different sets of assumption; different length scales

G. Aad *et al.* (Atlas Collaboration) *Phys. Rev. Lett.* **110**, 011802 (2013)

S. Cullen and M. Perelstein, *Phys. Rev. Lett.* **83**, 268 (1999).

W-H Tan *et al.*, *Phys. Rev. Lett.* **116**, 131101 (2016).

L-B Wang and W-T Ni, *Mod. Phys. Lett. A* **28**, 1350094 (2013).

S. Dürr *et al.*, 2008 *Science* **322**, 1224 (2008); EJS et al., *New J. Phys* **17**, 033015 (2015).

Prospects: Experiments

H_2 GK-X measurement for D_0 determination: ~10^{-5} cm^{-1}

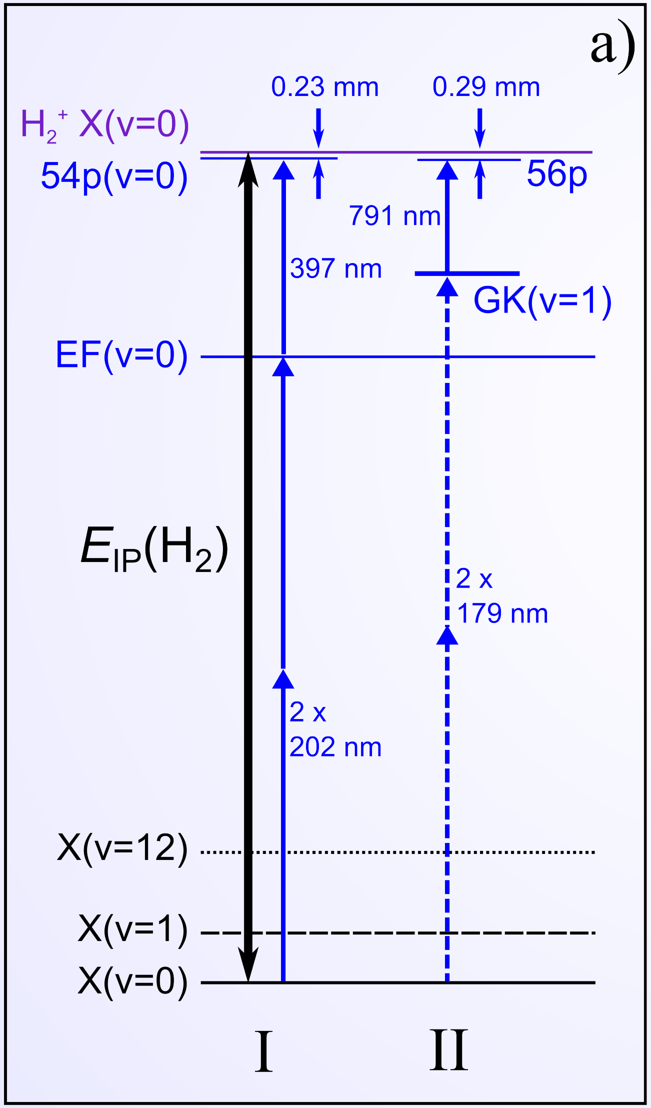
Level energy determination of H_2 X,v=10-14: ~10^{-3} cm^{-1}

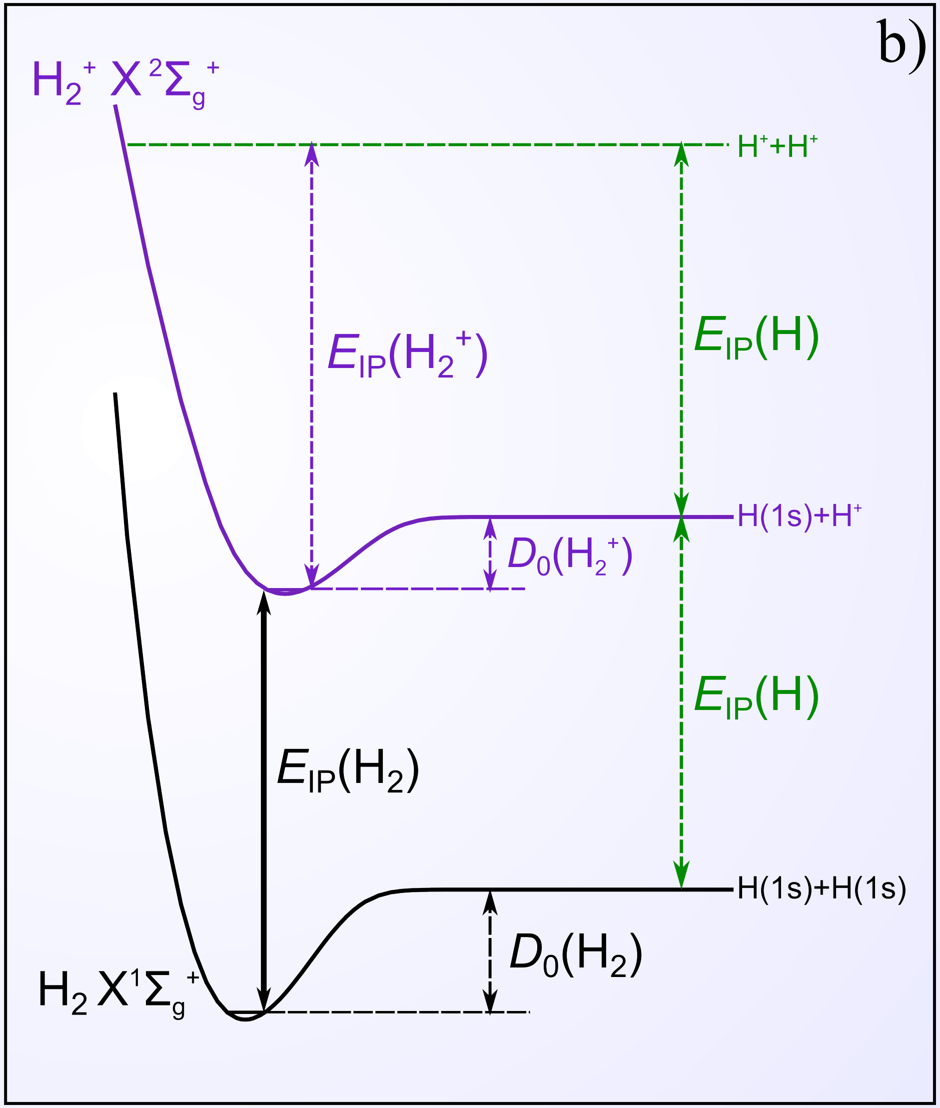
Direct (weak) dipoles in HD X,v=(0 → 2): ~10^{-5} → 10^{-7} cm^{-1}

Tritium containing isotopes: T_2, HT, DT

Collaboration: Tritium Laboratory Karlsruhe, KATRIN

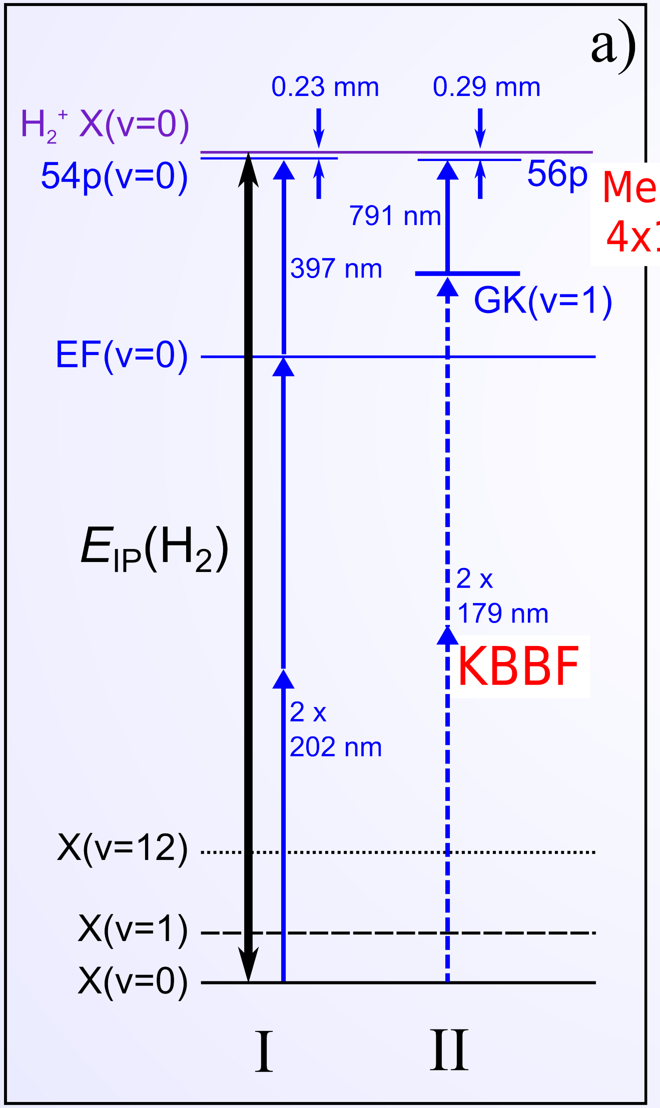
Prospects: H_2 GK-X

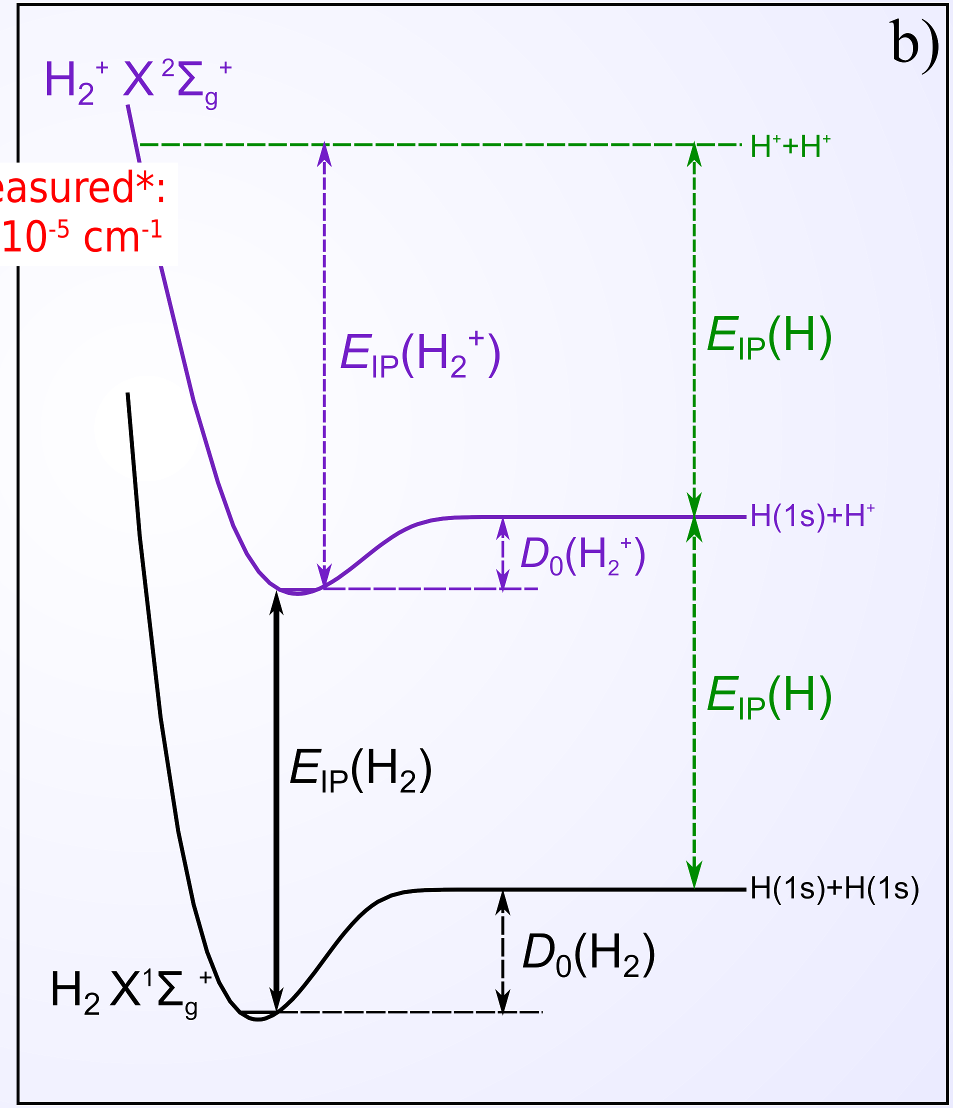




*D. Sprecher, M. Beyer, F. Merkt , Mol. Phys. 111, 2100 (2013)

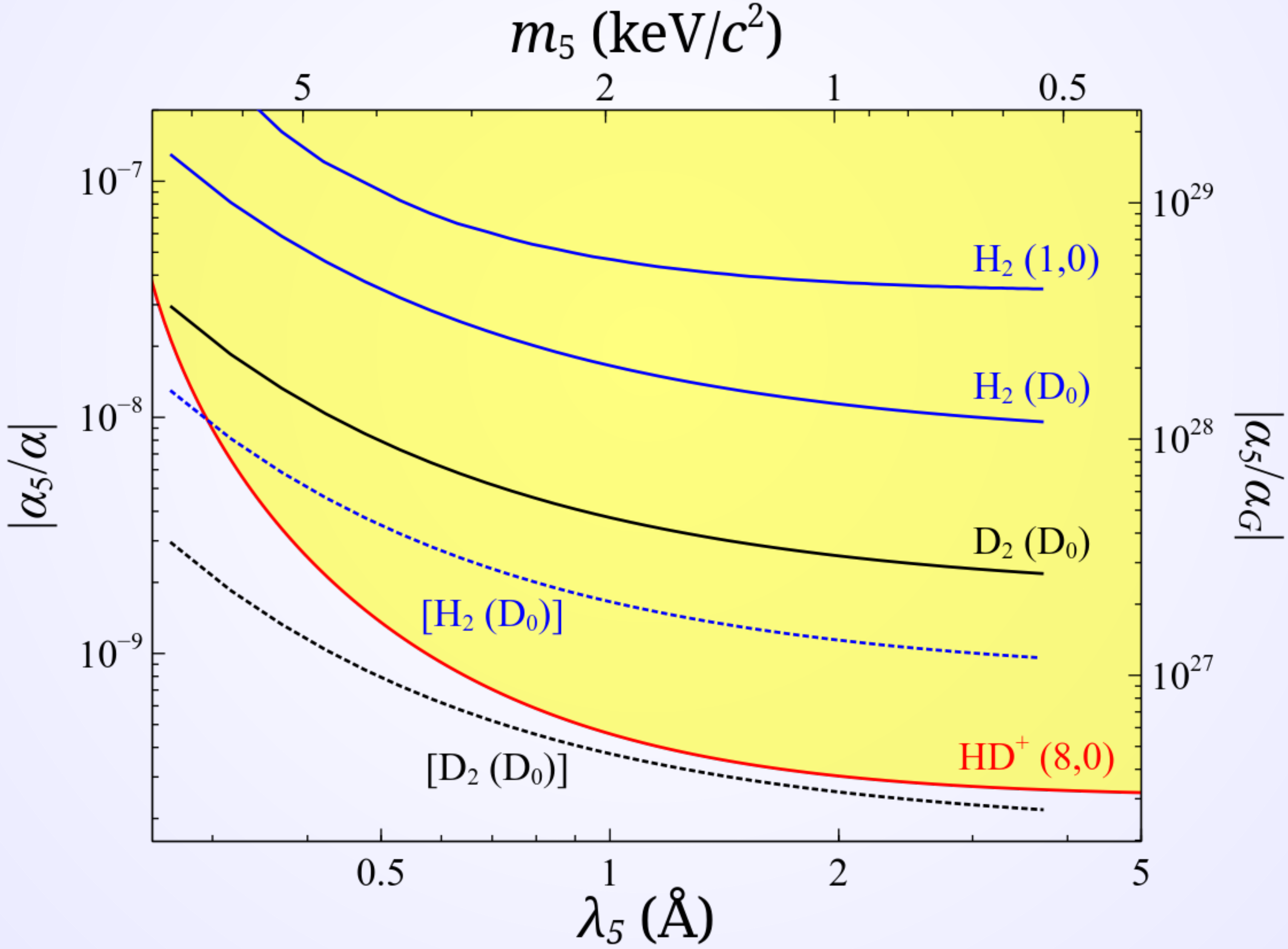
Prospects: H_2 GK-X



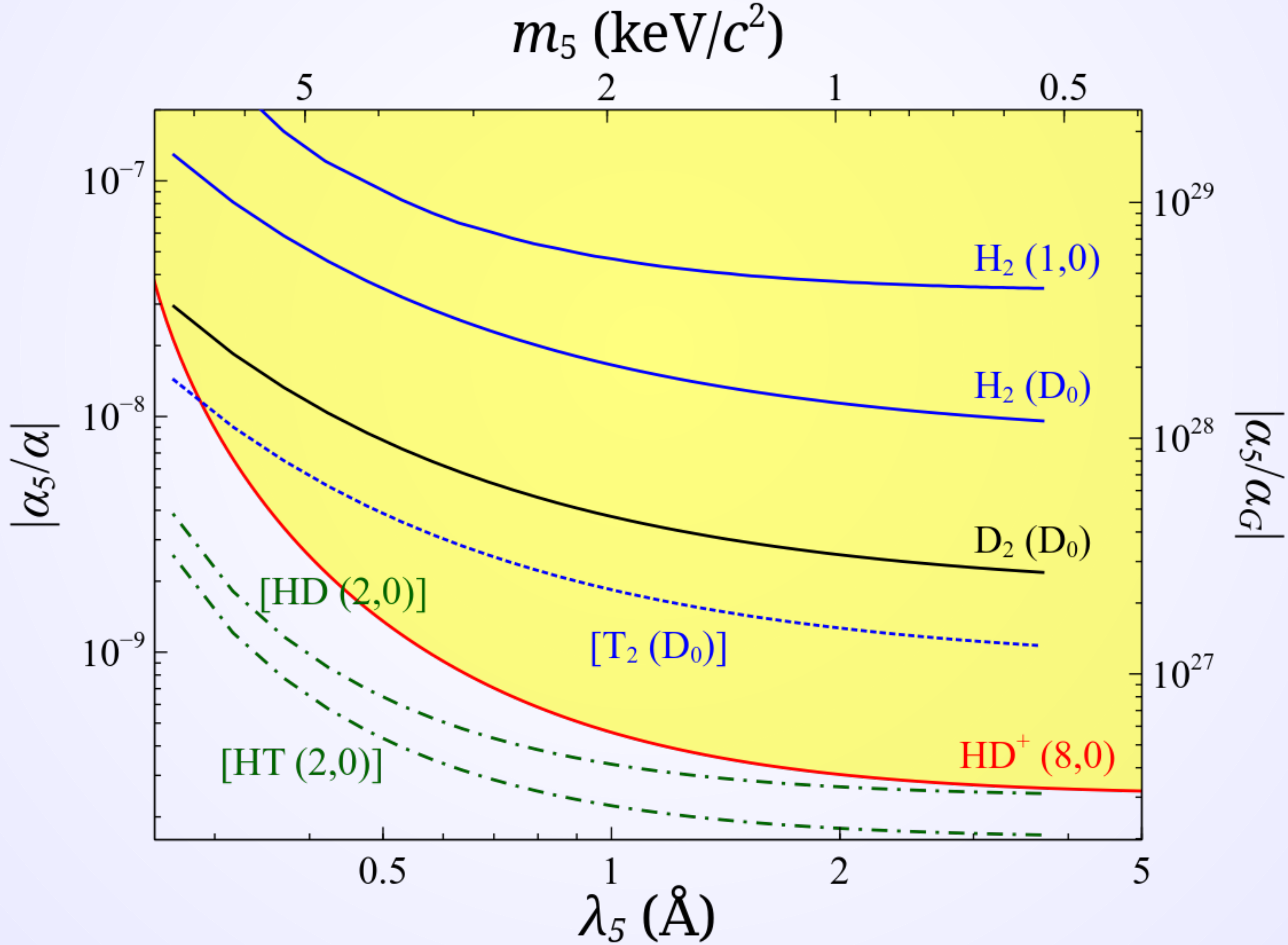


*D. Sprecher, M. Beyer, F. Merkt , Mol. Phys. 111, 2100 (2013)

Prospects: factor 10 improvement



Prospects: Tritium-containing



Conclusions

High-precision molecular spectroscopic results and accurate *ab initio* theory are used to constrain new physics

Comparisons set constraints for strength and range of fifth forces

Comparisons set constraints for number and size (volume) of extra spatial dimensions

Extracted constraints in low energy scale and Angstrom length scales

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Wim Ubachs

Krzysztof Pachucki

Jacek Komasa

Vladimir Korobov

Bert Schellekens

Beatriz Gato-Rivera