Spectroscopy of hydrogen molecular ions

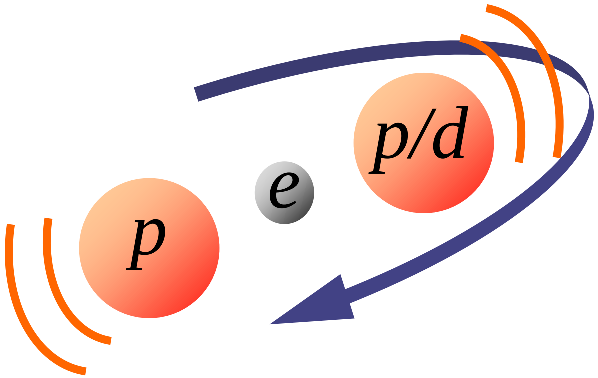
Jean-Philippe Karr[1,2]

[1] *Laboratoire Kastler Brossel (SU, CNRS, ENS, Collège de France)*

[2] *Université d'Evry – Val d'Essonne*

Muonic Atoms at PSI2022
Satellite Workshop "Proton structure in and out of muonic hydrogen — the ground-state hyperfine splitting"
15 October 2022

Hydrogen molecular ions (HMI)



H_2^+/HD^+

- Simple (one-electron, three-body) quantum systems
  Energy levels and other properties calculable with high accuracy.

- Many ultra-narrow ro-vibrational transitions
  natural lifetimes from tens of ms (HD^+) to weeks (H_2^+)

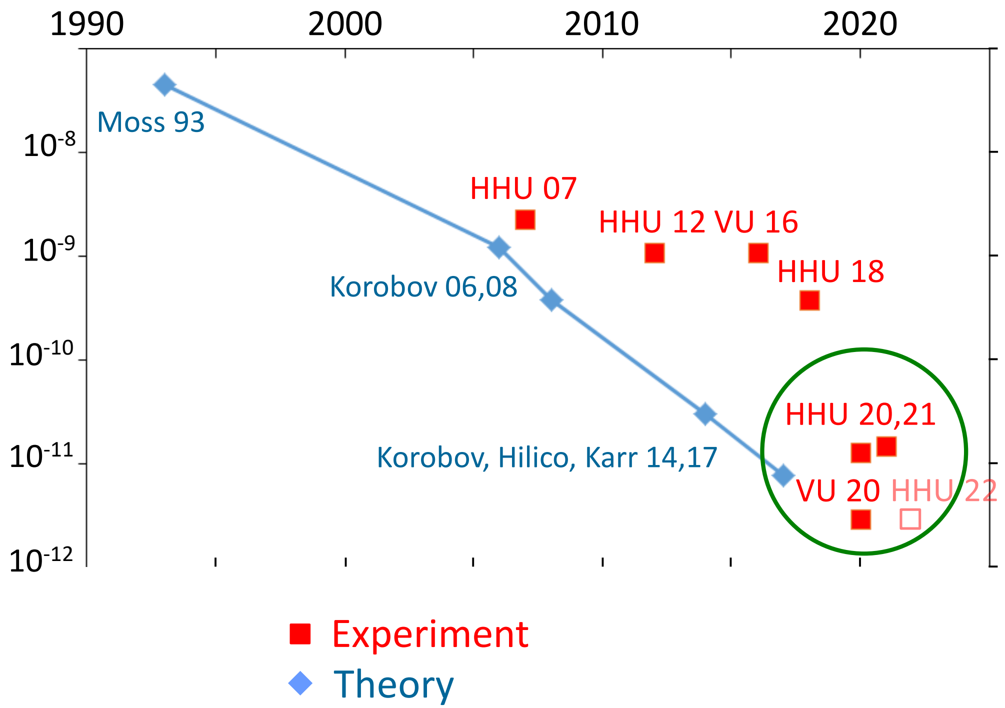
- High-accuracy techniques as in optical ion clocks:
  ion traps, laser cooling, Hz-linewidth laser, femtosecond comb…

Outline

- Experiments : recent developments, ongoing projects
- Theory : hyperfine structure, energy levels
- Comparing theory with experiments
  - determination of fundamental constants
  - constraints on “new physics”

Progress in HD^+ spectroscopy

Precision of "Spin-averaged" rovibrational transition frequencies

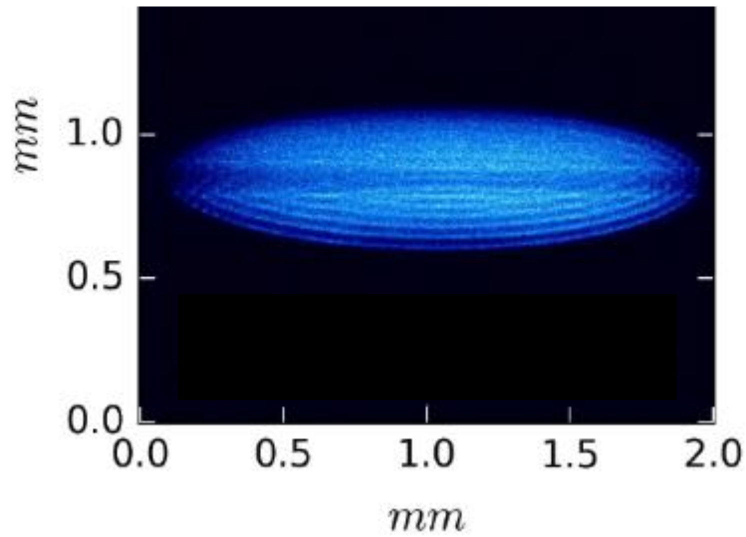


spectroscopy in the Lamb-Dicke regime

Experimental methods

- Ensembles of $\sim 50-100$ HD^+ ions sympathetically cooled by laser-cooled Be^+

Be^+/H_2^+ @LKB



$T \sim 10$ mK

- **HD^+ ion creation** by electron-impact ionization

  relax to $v = 0$, but distributed in many rotational/hyperfine sates

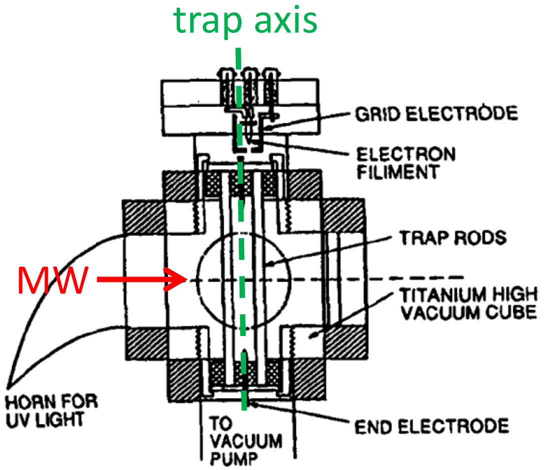
  - rotational cooling (T. Schneider et al., Nature Phys. 2010)
  - rf fields to transfer population between hyperfine levels

- **Detection** by selective photodissociation of excited state (REMPD)

  signal = ion loss, measured from Be^+ fluorescence change after secular excitation of HD^+

Trapped ion spectroscopy in the Lamb-Dicke regime

- Lamb-Dicke regime : $\delta x < \lambda/2\pi$
- Easy in the microwave domain (even at 300 K)
  Ex: Hg^+ ion clock ($\nu = 40.5$ GHz, $\lambda = 7.4$ mm) @JPL
- More challenging in the optical domain
  (requires tightly confining trap)

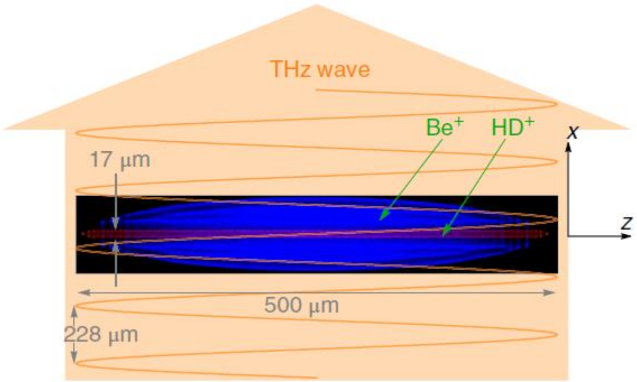


J.D. Prestage et al., IEEE 1990

- Easier for rotational/vibrational transitions in molecular ions (MIR/THz domain)

Sympathetic cooling ($T \sim 10$ mK), weakly confining trap:
$\delta x \sim 1 - 10$ µm

HD^+ rotational transition $(v = 0, L = 0) \rightarrow (v' = 0, L' = 1)$:
$\lambda = 228$ µm

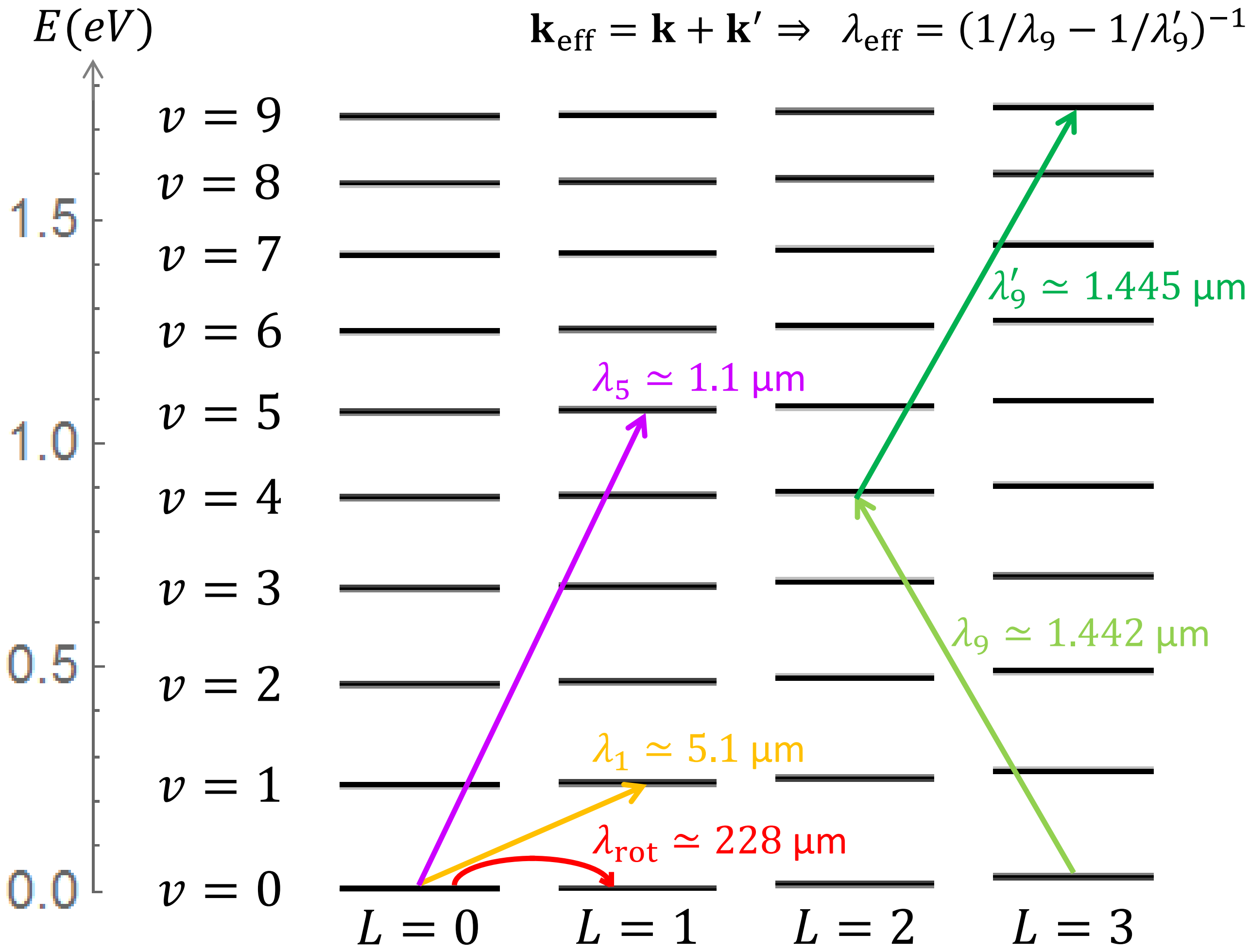


S. Alighanbari et al., Nature Phys. 2018

HD^+ high-precision measurements ($\sim 10^{-11} - 10^{-12}$)

counterpropagating photons (V. Q. Tran et al., PRA 2013)

$\mathbf{k}_{\rm eff} = \mathbf{k} + \mathbf{k}' \Rightarrow \lambda_{\rm eff} = (1/\lambda_9 - 1/\lambda'_9)^{-1} \simeq 700\ \mu\text{m}$

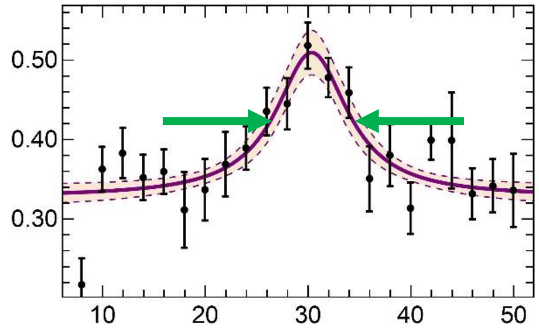


S. Alighanbari et al., Nature 2020
I. Kortunov et al., Nature Phys. 2021

S. Patra et al., Science 2020

Results, ongoing projects

$v = 0 \rightarrow 9$ transition (one hyperfine component)



Linewidth < 10 kHz

$\nu_{\mathrm{exp}} = 415\,264\,862\,249.2(0.4)_{\mathrm{syst}}(0.5)_{\mathrm{stat}}$ kHz

S. Patra et al., Science 2020

- 2 hyperfine components measured
- Theoretical hyperfine structure required to extract spin-averaged transition frequency

Outlook

- H_2^+ two-photon spectroscopy (LKB) $\rightarrow$ see next slides
- Quantum-logic spectroscopy

  Be^+/HD^+ Ch. Wellers et al., Mol. Phys. 2021

  Be^+/H_2^+ D. Kienzler, ETH Zürich

- Spectroscopy of a single molecular ion in a Penning trap

  Proposal for H_2^+/anti-H_2^+ E.G. Myers, PRA 2018 ; J.-Ph. Karr, PRA 2018 and 2021

  Ongoing experiment: HD^+ (hfs) S. Sturm, MPIK Heidelberg

H_2^+ two-photon spectroscopy (LKB)

Abdessamad Mbardi, Bérangère Argence, Laurent Hilico

Complications with respect to HD^+

Ro-vibrational transitions are not dipole-allowed, thus…

- Worse population problem
  - long-lived excited vibrational states (~ 1 week)
  - Our solution : state-selective production of H_2^+ by multiphoton (3+1) ionization (REMPI) from a pulsed H_2 molecular beam J. Schmidt et al., PR Appl. 2020
- Weaker transitions
  - Doppler-free two-photon transition : $(v = 0, L = 2) \rightarrow (v' = 1, L' = 2), \lambda = 9.17$ µm
  - No enhancement from quasi-resonant intermediate states
  - In-vacuum enhancement cavity required

✓ Trapped, sympathetically cooled, state-selected H_2^+

✓ Selective photodissociation (213 nm) + ion counting for REMPD spectroscopy

✓ Ultrastable laser source @ 9.17 µm : QCL phase-locked to single-mode CO_2 laser, injected in-vacuum cavity

- Lastly: absolute frequency measurements in the mid-infrared

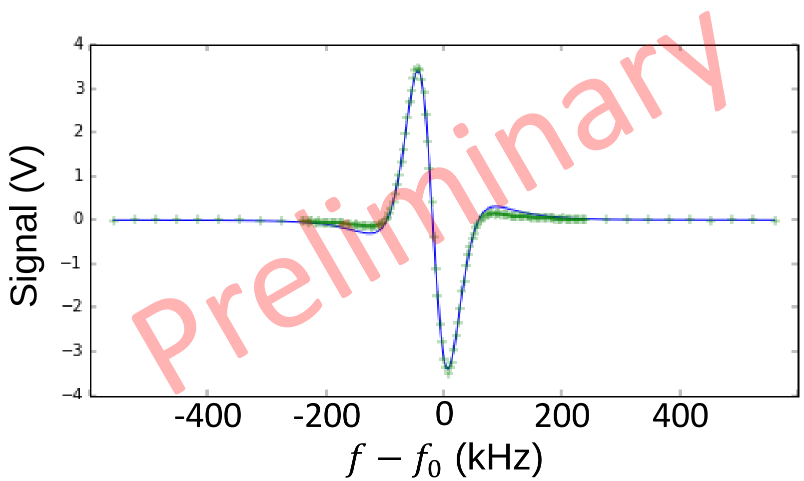
Frequency measurement setup

- ✓ Frequency comb centered at 1.56 µm, locked on ultrastable signal T-REFIMEVE from SYRTE at 1.542 µm
- ✓ Extension around 1.89 µm
- ✓ SFG in $AgGaSe_2$: 1.89 µm + 9.17 µm → 1.56 µm
- ✓ Beat note SFG signal/comb used to lock CO_2 laser
- ✓ QCL locked to CO_2 laser with tunable frequency offset (+/− 2 GHz)

See B. Argence et al., Nature Photon. 2015

Characterization : spectroscopy of formic acid (HCOOH)

Intracavity saturated absorption, 3rd harmonic detection



Repeatability of line center :
± 37 Hz ($\sim 10^{-12}$)

Theoretical methods (1)

- Nonrelativistic Quantum Electrodynamics (NRQED)
  - effective Hamiltonian approach
  - expansion of corrections in powers of $\alpha, Z\alpha, m/M$.

- Resolution of the three-body Schrödinger equation by a variational method

Separation of radial and angular variables:

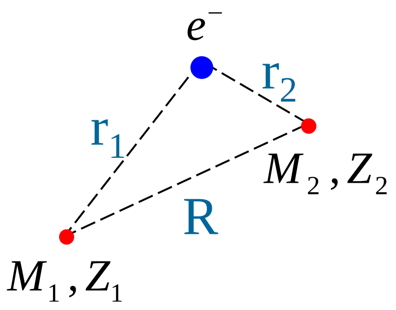
$$\psi_{LM}^{\Pi}(\mathbf{R},\mathbf{r}_1) = \sum_{l_1+l_2=L \text{ or } L+1} \mathcal{Y}_{LM}^{l_1 l_2}(\hat{\mathbf{R}},\hat{\mathbf{r}}_1) F_{l_1}(R,r_1,r_2)$$

C. Schwartz, Phys. Rev. **123**, 1700 (1961)

Radial wavefunctions:

$$F(R,r_1,r_2) = \sum_{n=1}^{N} \left(C_n \operatorname{Re}\left(e^{-\alpha_n R - \beta_n r_1 - \gamma_n r_2}\right) + D_n \operatorname{Im}\left(e^{-\alpha_n R - \beta_n r_1 - \gamma_n r_2}\right)\right)$$

V.I. Korobov, Phys. Rev. A **61**, 064503 (2000)



✓ Extremely accurate energy levels (10^{-15}-10^{-20} or better) and wavefunctions

Theoretical methods (2)

- Some higher-order corrections are evaluated in the adiabatic approximation

$$\Psi^{\mathrm{BO}} = \phi_{\mathrm{el}}(\mathbf{r}; R)\chi_{\mathrm{BO}}(R)$$

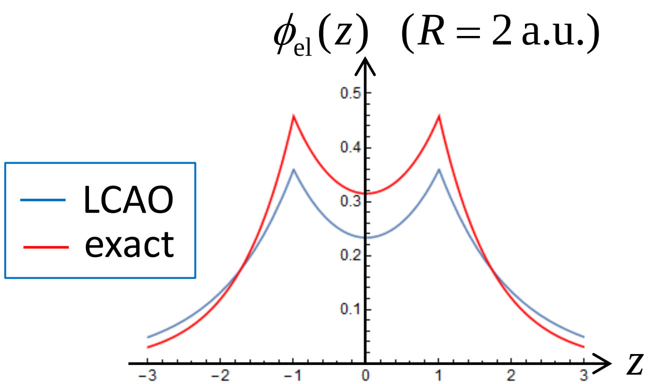
Variational expansion:

$$\phi_{\mathrm{el}}(r_1, r_2) = \sum_{i=1}^{N} C_i \left(e^{-\alpha_i r_1 - \beta_i r_2} + e^{-\beta_i r_1 - \alpha_i r_2} \right)$$

Ts. Tsogbayar and V.I. Korobov, J. Chem. Phys. **125**, 024308 (2006)

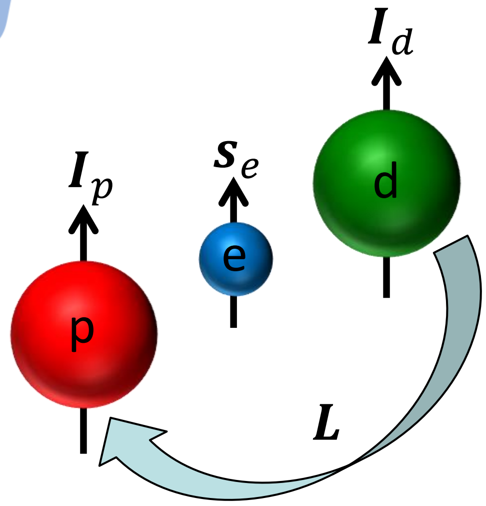
- LCAO approximation :

$$\phi_{\mathrm{LCAO}}(r_1, r_2) = \frac{1}{\sqrt{2(1+S)}} \left[\phi_{1s}(r_1) + \phi_{1s}(r_2) \right]$$

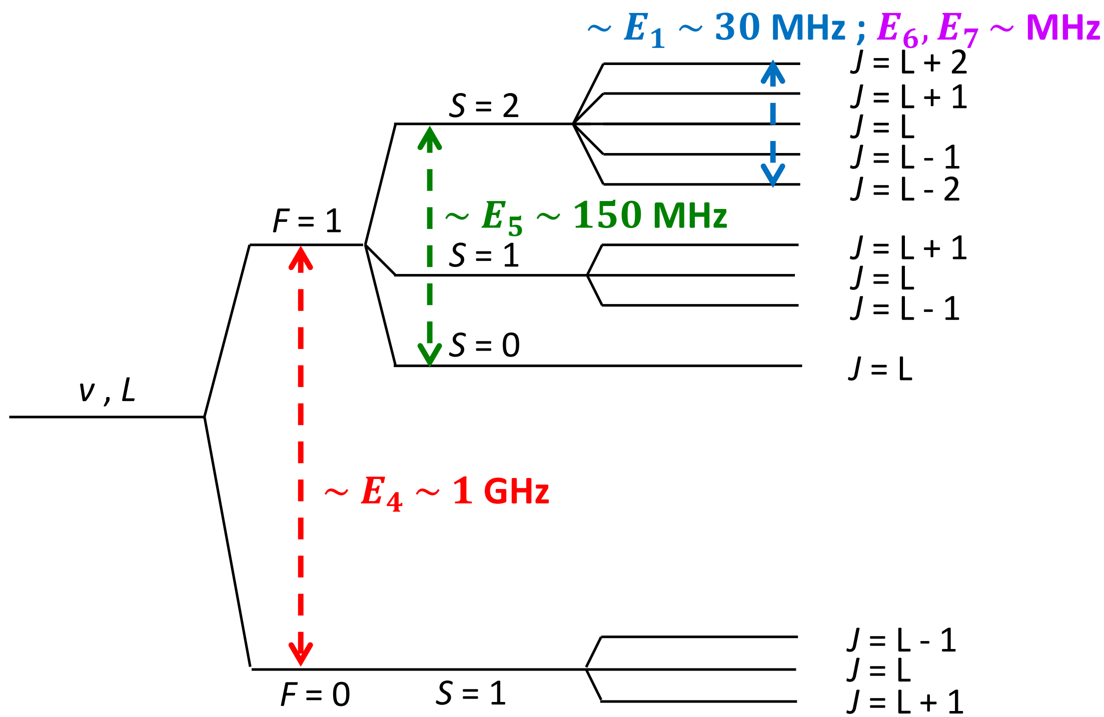


$1s\sigma_g$ electronic wavefunction

Effective spin Hamiltonian: HD^+



$$\mathbf{F} = \mathbf{s}_e + \mathbf{I}_p$$
$$\mathbf{S} = \mathbf{F} + \mathbf{I}_d$$
$$\mathbf{J} = \mathbf{S} + \mathbf{L}$$



Electronic spin-orbit — Nuclear spin-rotation — "Fermi" interaction

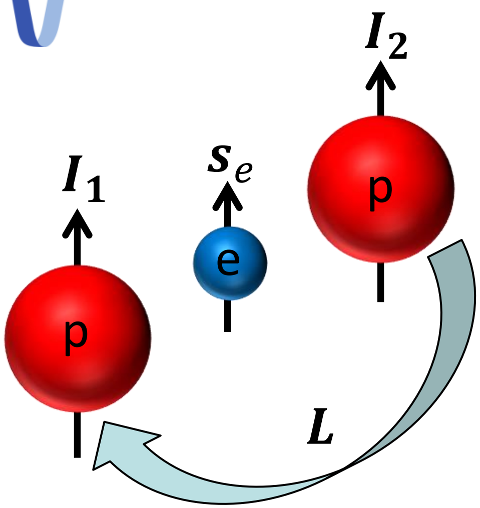
$$H_{\text{eff}} = E_1(\mathbf{L}\cdot\mathbf{s}_e) + E_2(\mathbf{L}\cdot\mathbf{I}_p) + E_3(\mathbf{L}\cdot\mathbf{I}_d) + E_4(\mathbf{I}_p\cdot\mathbf{s}_e) + E_5(\mathbf{I}_d\cdot\mathbf{s}_e)$$
$$+ E_6\left\{2\mathbf{L}^2(\mathbf{I}_p\cdot\mathbf{s}_e) - 3[(\mathbf{L}\cdot\mathbf{I}_p)(\mathbf{L}\cdot\mathbf{s}_e) + (\mathbf{L}\cdot\mathbf{s}_e)(\mathbf{L}\cdot\mathbf{I}_p)]\right\}$$
$$+ E_7\left\{2\mathbf{L}^2(\mathbf{I}_d\cdot\mathbf{s}_e) - 3[(\mathbf{L}\cdot\mathbf{I}_d)(\mathbf{L}\cdot\mathbf{s}_e) + (\mathbf{L}\cdot\mathbf{s}_e)(\mathbf{L}\cdot\mathbf{I}_d)]\right\}$$
$$+ E_8\left\{2\mathbf{L}^2(\mathbf{I}_p\cdot\mathbf{I}_d) - 3[(\mathbf{L}\cdot\mathbf{I}_p)(\mathbf{L}\cdot\mathbf{I}_d) + (\mathbf{L}\cdot\mathbf{I}_d)(\mathbf{L}\cdot\mathbf{I}_p)]\right\}$$
$$+ E_9\left\{\mathbf{L}^2\mathbf{I}_d^2 - (3/2)(\mathbf{L}\cdot\mathbf{I}_d) - 3(\mathbf{L}\cdot\mathbf{I}_d)^2\right\}$$

Spin-spin tensor interactions (E_6, E_7, E_8 terms)

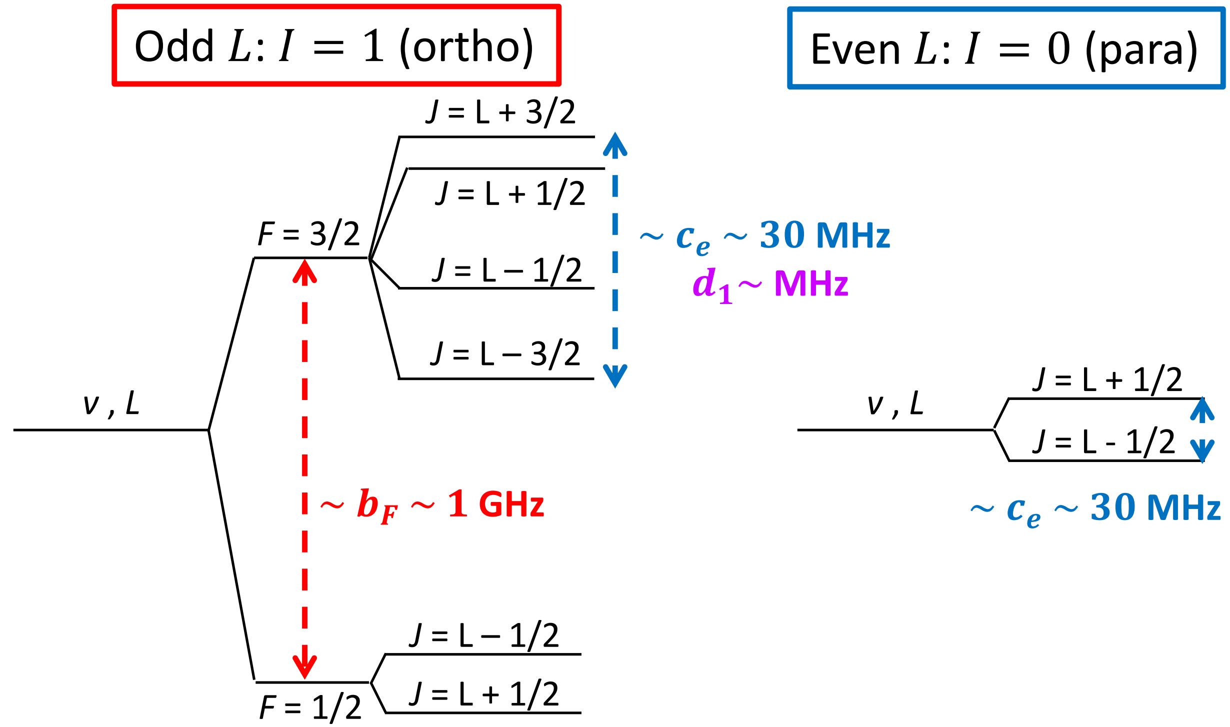
Deuteron Quadrupole moment (E_9 term)

D. Bakalov, V.I. Korobov, S. Schiller, PRL **97**, 243001 (2006)

Effective spin Hamiltonian: H_2^+



$$\mathbf{I} = \mathbf{I}_1 + \mathbf{I}_2$$
$$\mathbf{F} = \mathbf{s}_e + \mathbf{I}$$
$$\mathbf{J} = \mathbf{S} + \mathbf{L}$$



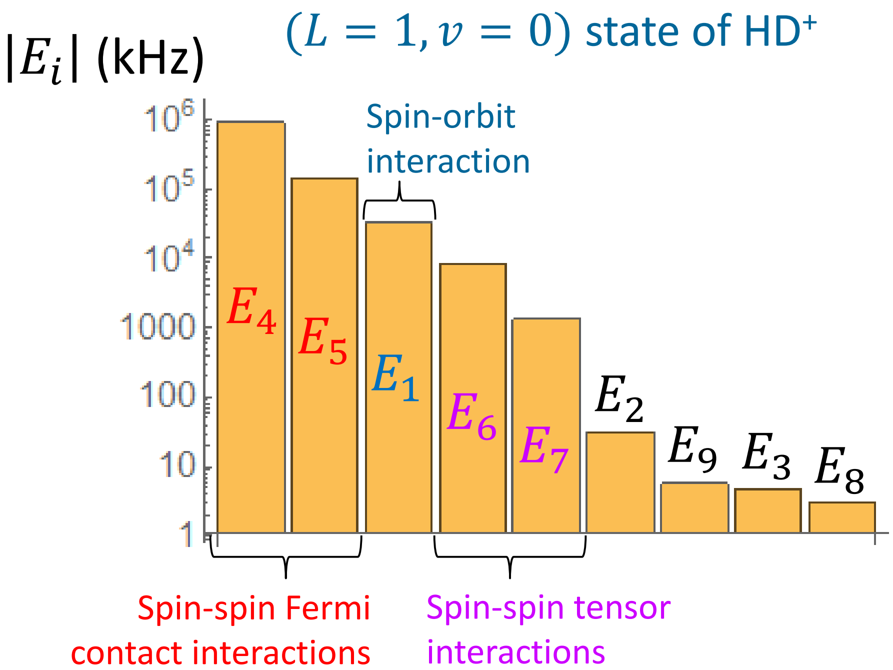
Electronic spin-orbit — Nuclear spin-rotation — "Fermi" interaction

$$H_{\text{eff}} = c_e(\mathbf{L}\cdot\mathbf{s}_e) + c_I(\mathbf{L}\cdot\mathbf{I}) + b_F(\mathbf{I}\cdot\mathbf{s}_e)$$
$$+ \frac{d_1}{3(2L-1)(2L+3)}\left\{2\mathbf{L}^2(\mathbf{I}\cdot\mathbf{s}_e) - 3[(\mathbf{L}\cdot\mathbf{I})(\mathbf{L}\cdot\mathbf{s}_e) + (\mathbf{L}\cdot\mathbf{s}_e)(\mathbf{L}\cdot\mathbf{I})]\right\}$$
$$+ \frac{d_2}{3(2L-1)(2L+3)}\left\{\mathbf{L}^2\mathbf{I}^2 - \frac{3}{2}(\mathbf{L}\cdot\mathbf{I}) - 3(\mathbf{L}\cdot\mathbf{I})^2\right\}$$

Spin-spin tensor interactions

V.I. Korobov, L. Hilico, J.-Ph. Karr, PRA **74**, 040502(R) (2006)

Calculation of hyperfine coefficients



- All coefficients calculated within Breit-Pauli approximation, taking into account electron anomalous magnetic moment
  All terms of order $m\alpha^4$ and $m\alpha^5$ included $\Rightarrow$ relative uncertainty $\sim \alpha^2$
  D. Bakalov et al., PRL 2006

- Sufficient for small coefficients (E_2, E_3, E_8, E_9) at present level of exp. accuracy

- For the largest coefficients, higher-order corrections need to be considered
  $E_4, E_5 \rightarrow$ see next slide
  E_1, E_6, E_7 : V.I. Korobov et al., PRA 2020 ; M. Haidar et al., arXiv:2209.02382, to appear in PRA

Spin-spin contact interactions

Unit: kHz

Type of contribution	H atom $\Delta E_{hfs}(1S)$	HD+ molecule $E_4(v=0, L=0)$
Fermi splitting E_F [$m\alpha^4$ order]	1 418 840.093	924 383.973
Anomalous magnetic moment [αE_F]	1 645.361	1 071.964
Relativistic ("Breit") correction [$(Z\alpha)^2 E_F$]	113.333	66.936(61)
One-loop radiative correction [$\alpha(Z\alpha)E_F$]	−136.517	-88.942
One-loop radiative correction [$\alpha(Z\alpha)^2 E_F$]	−11.330	-7.381
Higher-order nonrecoil QED	1.089(1)	-2.241(432)
Nuclear correction $= E_{hfs}^{exp} - E_{hfs}^{QED}$	-46.276(1)	-30.150(424)
TOTAL	1 420 405.752 (exp.)	925 394.159(860)

Breit-Pauli (Fermi splitting, Anomalous magnetic moment)

State-independent (One-loop radiative corrections)

0.93 ppm

J.-Ph. Karr et al., PRA **102**, 052827 (2020)

- $(Z\alpha^2)E_F$ relativistic correction calculated in the adiabatic approximation.
- Nuclear correction in H atom determined from the difference between experimental value and total nonrecoil QED prediction.
- Higher-order QED & nuclear correction added in HD+ theory under the approximation that they are entirely described by a **delta function**.

Comparison with experiments : H_2^+

- Complete measurements of the hyperfine splitting
  K. B. Jefferts, PRL **23**, 1476 (1969)

$\Rightarrow$ spin-spin contact interaction coefficient b_F ($\leftrightarrow$ E_4 in HD⁺)

✓ Good agreement at ~ 1 ppm level

Unit: MHz L = 1

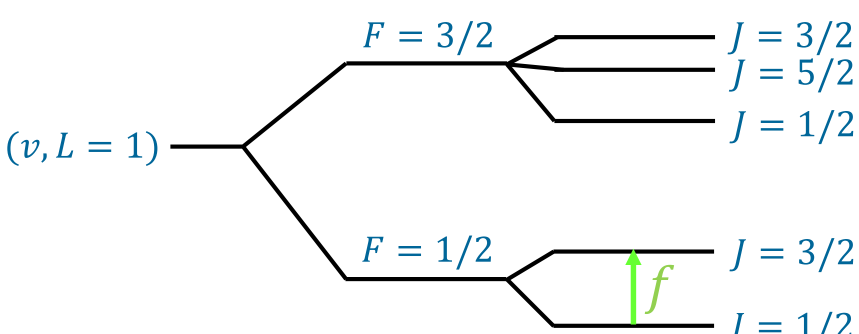
v	b_F (theory)	b_F (experiment)
4	836.7287(8)	836.7292(8)
5	819.2267(8)	819.2273(8)
6	803.1745(7)	803.1751(8)
7	788.5075(7)	788.5079(8)
8	775.1712(7)	775.1720(8)

J.-Ph. Karr et al., PRA **102**, 052827 (2020)

- High-precision measurements (~ 10^{-7}) for a few hyperfine intervals
  S. C. Menasian and H. G. Dehmelt, Bull. Am. Phys. Soc. **18**, 408 (1973)

  Sensitive to c_e,d_1 ($\leftrightarrow$ E_1,E_6 in HD^+)

✓ Small deviations of 60-80 Hz (3-5 ppm) ~ 1.2-1.6 σ_c



Unit: MHz

(L, v)	f (theory)	f (experiment)
(1,4)	15.371 316(56)	15.371 407(2)
(1,5)	14.381 453(52)	14.381 513(2)
(1,6)	13.413 397(48)	13.413 460(2)

M. Haidar et al., PRA **106**, 022816 (2022)

Comparison with experiments : HD^+

Unit: kHz

Transition	f_{hfs}^{exp}	f_{hfs}^{theor}	Δf	$\Delta f/\sigma_c$	
$(v=0,L=0) \rightarrow (v'=1,L'=1)$	41 294.06(32)	41 293.66(12)	0.40	1.2	E_1,E_6
$(v=0,L=0) \rightarrow (v'=5,L'=1)$	126 092.6(1.2)	126 092.02(10)	0.58	0.5	E_4,E_5
$(v=0,L=3) \rightarrow (v'=9,L'=3)$	178 254.4(9)	178 245.89(28)	8.5	9.0	E_4,E_5

➢ Rotational transition : 6 hyperfine components measured $\rightarrow$ extract E_1, E_6, E_7

coefficient	E_k^{exp}	E_k^{theor} (this work)	ΔE_k	$\Delta E_k/\sigma_c$
E_1	31 984.9(1)	31 985.41(12)	-0.5	-3.3
E_6	8 611.17(5)	8 611.299(18)	-0.13	-2.4
E_7	1 321.72(4)	1 321.7960(28)	-0.08	-2.0

- No contribution(s) identified that could have the required order of magnitude to explain discrepancies
- Take discrepancies into account by expanding error bars

M. Haidar et al., arXiv:2209.02382, to appear in PRA

HD+ energy levels: overview and comparison with H atom

- Unit: kHz, CODATA 2018 values of FC
- Only theoretical uncertainties are shown

Type of contribution	H atom $\Delta E(1S)$	HD+ molecule $\Delta E(v=0, L=0)$
1. Relativistic energy	-3 288 095 029 857.92	-3 934 027 681 033.9(1.1)
2. Relativistic-recoil	2 402.35	2 229.6(0.6)
3. One-loop self-energy	8 383 339.47	10 891 032.6(17.4)
4. One-loop vacuum polarization Muonic VP Hadronic VP	- 214 816.61 -5.07 -3.40(8)	-280 113.6 -6.6 -4.4(0.1)
5. Two-loop radiative corrections	727.19(66)	944.6(11.8)
6. Three-loop radiative corrections	1.72(34)	2.4(0.6)
7. Nuclear finite size and polarizability (+ rad. corr.)	1 107.98(39)	5 330.2(0.5)
8. Radiative-recoil corrections	-12.32(74)	-13.5(2.2)
9. Nuclear self-energy	4.62(16)	3.8(0.1)
TOTAL	-3 288 086 857 111.4(1.1)	-3 934 017 061 629(21)
	3.5×10^{-13}	5.3×10^{-12}

E. Tiesinga et al., Rev. Mod. Phys. **93**, 025010 (2021)
S. Karshenboim et al., Phys. Lett. B **795**, 432 (2019)

One-loop self-energy

$$E_{se} = m\alpha^5\Big[\left(A_{41}\ln\left(\alpha^{-2}\right) + A_{40}\right)\langle Z_1\delta(\mathbf{r_1}) + Z_2\delta(\mathbf{r_2})\rangle \\ + A_{50}\alpha\left\langle Z_1^2\delta(\mathbf{r_1}) + Z_2^2\delta(\mathbf{r_2})\right\rangle \\ +\left(A_{62}\ln^2\left(\alpha^{-2}\right) + A_{61}\ln\left(\alpha^{-2}\right) + A_{60}\right)\alpha^2\left\langle Z_1^3\delta(\mathbf{r_1}) + Z_2^3\delta(\mathbf{r_2})\right\rangle \\ +\left(A_{71}\ln\left(\alpha^{-2}\right) + A_{70}\right)\alpha^3\left\langle Z_1^4\delta(\mathbf{r_1}) + Z_2^4\delta(\mathbf{r_2})\right\rangle + \cdots\Big]$$

- Some coefficients (A_{41}, A_{50}, A_{62}, A_{71}) are state-independent and can be taken from H-like atom theory.
- $m\alpha^5$ order: Bethe logarithm calculated with 8-9 significant digits

  V.I. Korobov, PRA **85**, 042514 (2012) ; V.I. Korobov and Z.-X. Zhong, PRA **86**, 044501 (2012)
- $m\alpha^7$ order: calculated in the adiabatic approximation

  V.I. Korobov, L. Hilico, J.-Ph. Karr, PRL **112**, 103003 and PRA **89**, 032511 (2014)
- Higher-order remainder ($m\alpha^8$ and above): estimated from H(1S) results using the LCAO approximation

  $$E_{se}^{(8+)} = m\alpha^7\left(G_{SE}(1S) - A_{60}(1S)\right)\left\langle Z_1^3\delta(\mathbf{r_1}) + Z_2^3\delta(\mathbf{r_2})\right\rangle$$

  V.I. Korobov and J.-Ph. Karr, PRA **104**, 032806 (2021)

Comparison with experiments

$(L, v) \to (L', v')$	Theory	Experiment
$(0,0) \to (1,0)$	1 314 925 752.932(19)(61)	1 314 925 752.910(17)
$(0,0) \to (1,1)$	58 605 052 163.9(0.5)(1.3)	58 605 052 164.24(86)
$(3,0) \to (3,9)$	415 264 925 502.8(3.3)(6.7)	415 264 925 501.8(1.3)

V.I. Korobov and J.-Ph. Karr, PRA **104**, 032806 (2021)

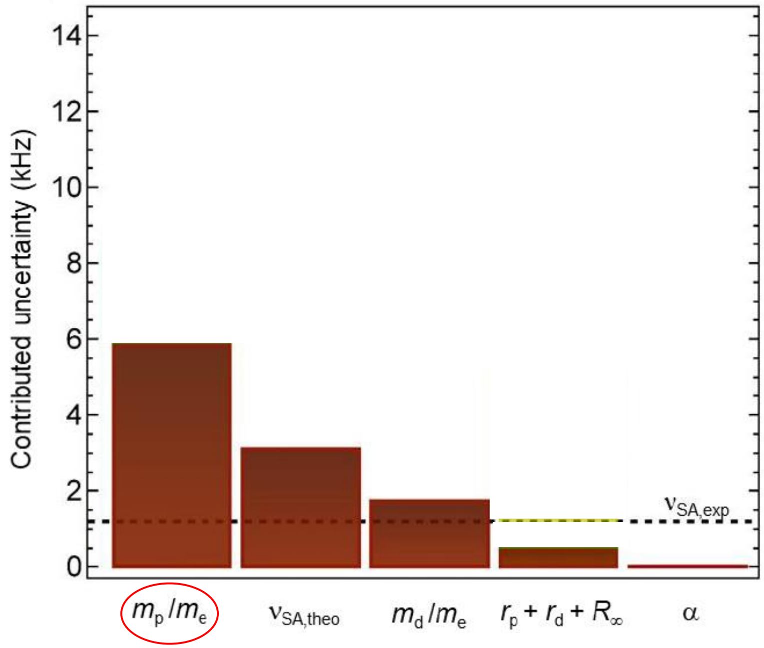
Theoretical uncertainties

Uncertainties from FC (CODATA 2018)

Uncertainty contributions

Example : $v = 0 \to 9$ transition

S. Patra et al., Science **369**, 1238 (2020)



Theory: status and next steps

- Theoretical uncertainty ∼ 7.5 10^{-12} (1.5 10^{-11}) for vibrational (rotational) transitions
- Satisfactory agreement with experimental data
- Next step : nonperturbative calculation of the one-loop self-energy using highly precise solutions of two-center Dirac equation:

  H.D. Nogueira, V.I. Korobov, J.-Ph. Karr, PRA **105**, L060801 (2022)
  O. Kullie, S. Schiller, PRA **105**, 052801 (2022)

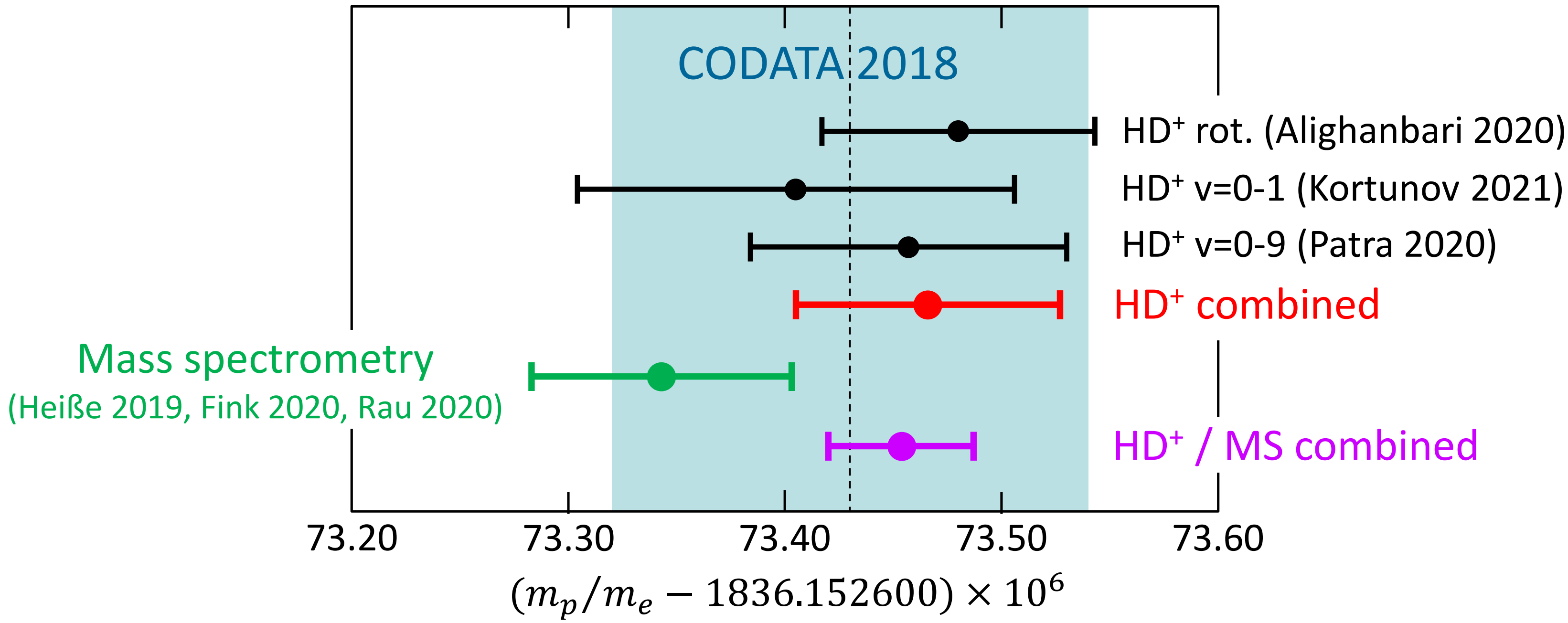
  } 10^{-20} accuracy (in agreement!)

  ⇒ reduce uncertainty by a factor of ∼ 2.

Applications

- ➢ Determination of fundamental constants
- ➢ Constraining "new physics"

Determination of the proton-electron mass ratio



- From HD^+ data alone:

$$m_p/m_e = 1836.152\,673\,466(61) \quad [3.3 \times 10^{-11}]$$

Good agreement with CODATA 2018 and recent mass spectrometry results.

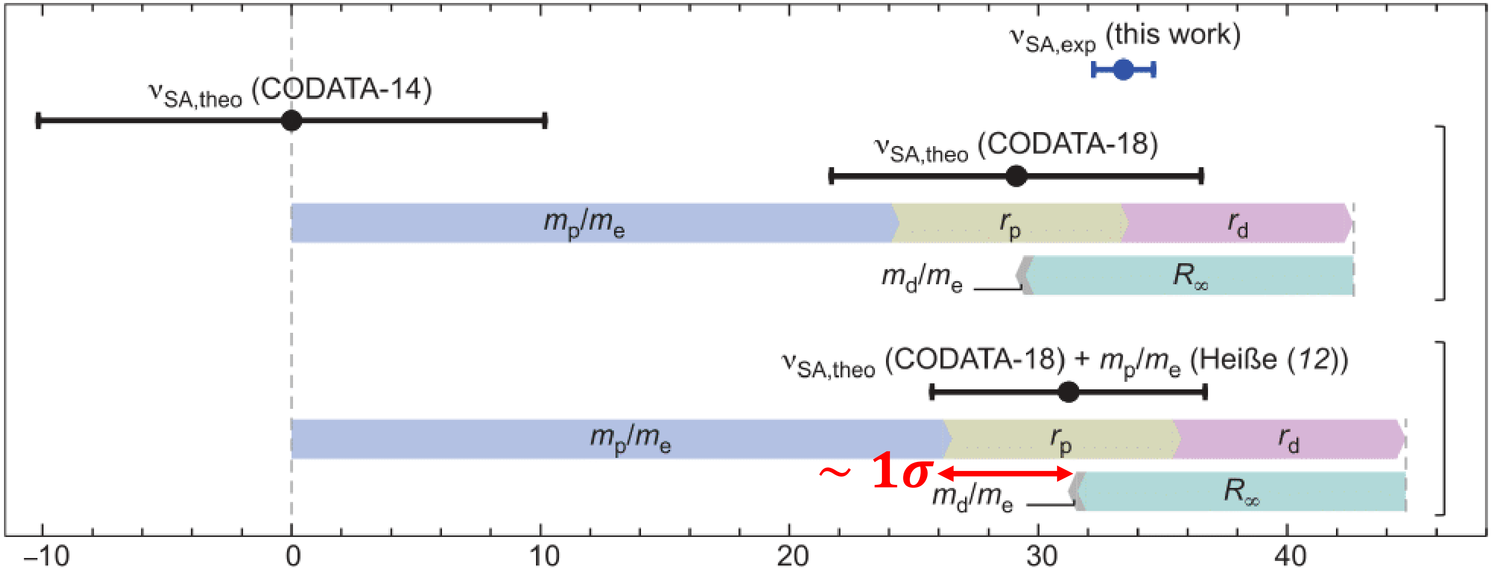
- From HD^+ and mass spectrometry combined:

$$m_p/m_e = 1836.152\,673\,454(33) \quad [1.8 \times 10^{-11}]$$

V.I. Korobov and J.-Ph. Karr, PRA **104**, 032806 (2021)

Is HD$^+$ spectroscopy sensitive to the proton radius ?

Example : $(v = 0, L = 3) \rightarrow (v' = 9, L' = 3)$ transition

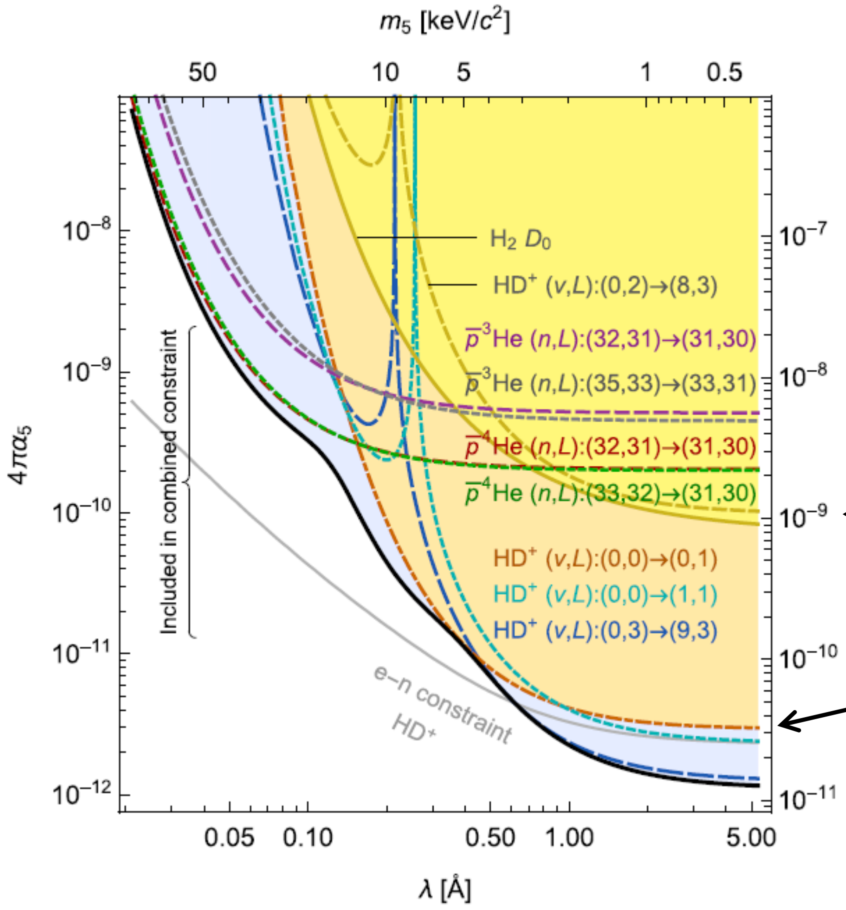


S. Patra et al., Science 2020

- r_p, r_d, R_∞ are strongly correlated (H/D 1S-2S)
- With measurements at 10^{-12} precision level, theory improvement to 3 10^{-12} : $u(r_p) < 0.01$ fm

J.-Ph. Karr et al., PRA 94, 050501(R) (2016)

Constraint on "fifth force" between hadrons



Previous best constraint
(H_2 dissociation limit, Hölsch 2019)

HD^+ rotational transition
(Alighanbari 2020)

Combined: 3 transitions in HD^+ and
4 transitions in antiprotonic helium

M. Germann et al., Phys. Rev. Research **3**, L022028 (2021)

Self-consistent approach to constrain new physics (NP)

LKB

C. Delaunay, JPK, T. Kitahara, J. Koelemeij, Y. Soreq , J. Zupan (soon on arXiv)

- Precision measurements (e.g. spectroscopy of simple atoms/molecules) can be used for NP searches by comparing with Standard Model (SM) prediction.
- SM predictions use accepted (CODATA) values of fundamental constants, which are obtained under the assumption that no NP exists. The presence of NP would affect the extraction of fundamental constants !
- Self-consistent approach: global fit of precision data in the presence of NP, simultaneously extracting fundamental constants and NP parameters.

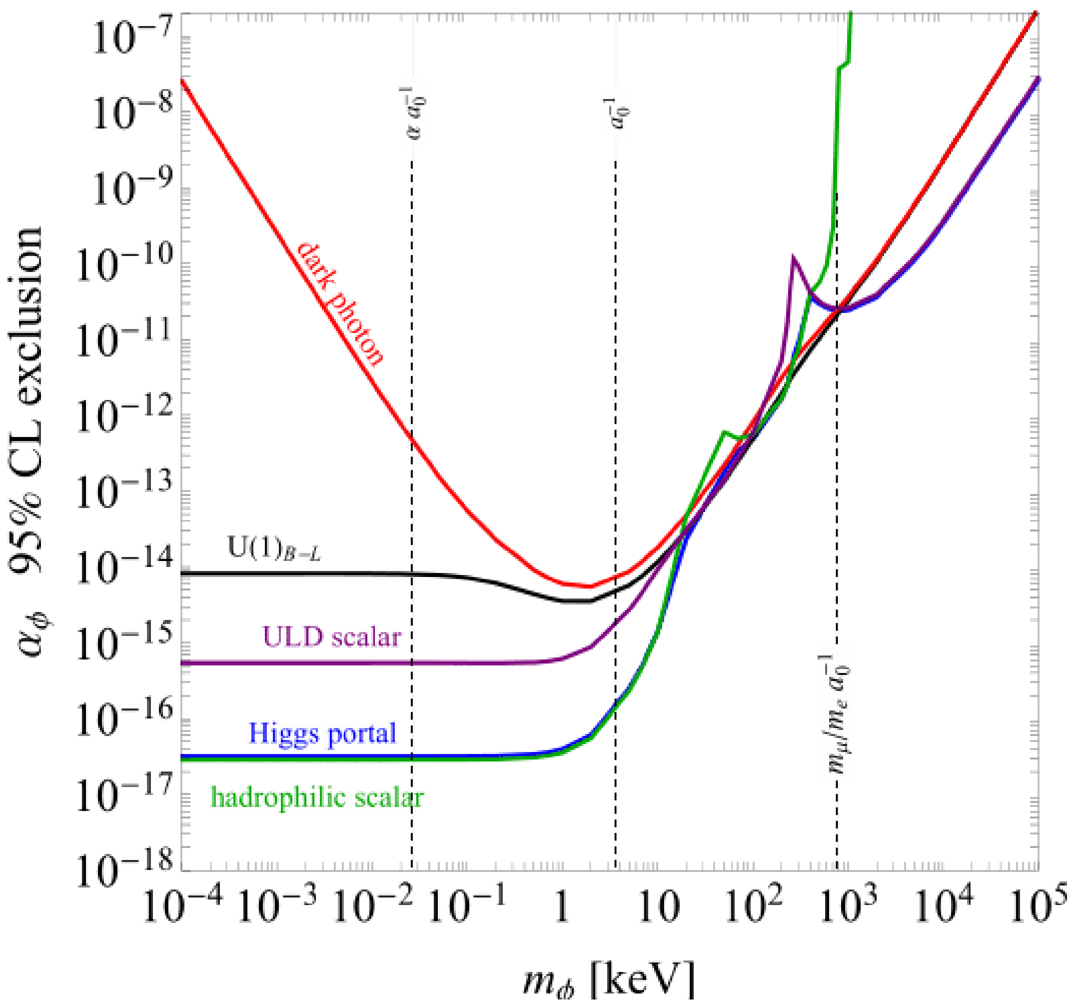
Datasets

1) "Control" dataset = subset of CODATA 2018
   - H, D, μH, μD spectroscopy (R_∞, r_p, r_d)
   - a_e, $h/\mathrm{m_X}$, bound electron g-factors, mass spectrometry (α, m_e, m_p, m_d)
   - 78 observational equations, 44 adjusted constants (CODATA 2018: 105/62 without G and d_{220})

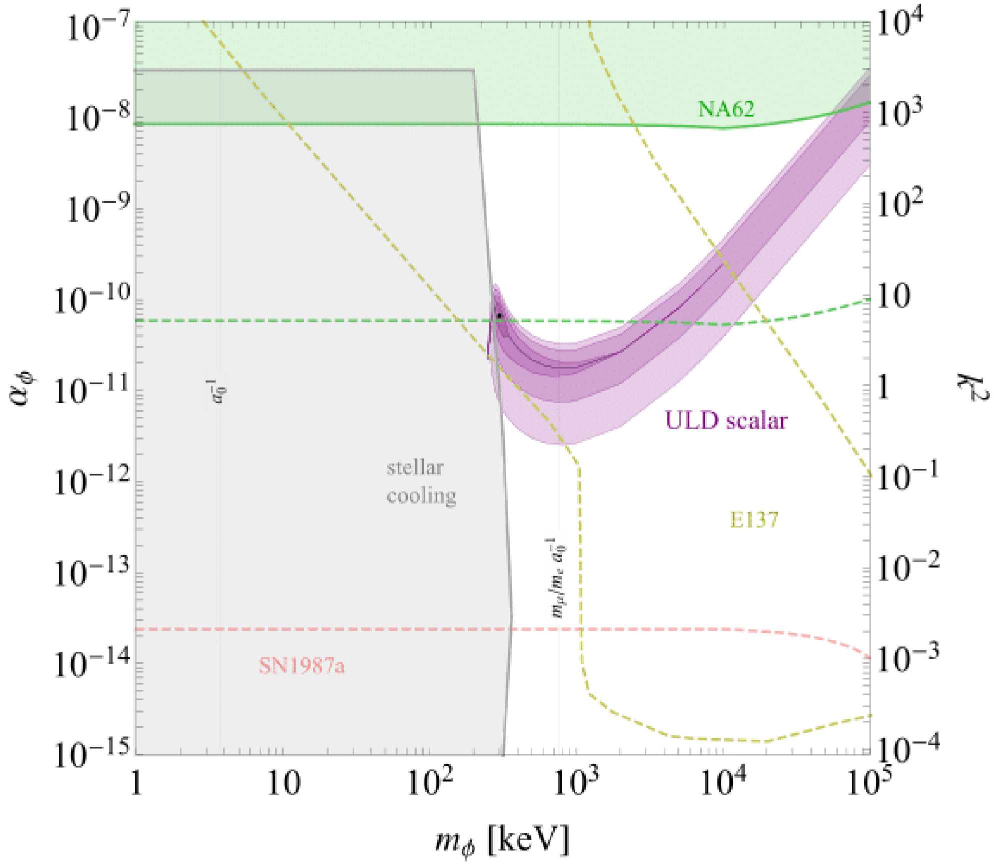
2) 2022 dataset: with most recent data and theory improvements
   and HD^+, $\bar{p}He$ spectroscopy (more sensitive to some NP models)

Bounds on NP coupling constant

$$V_{NP}^{ij}(r) = (-1)^{s+1}\alpha_\phi q_i q_j \frac{e^{-m_\phi r}}{r}$$



NP model favored over SM



- Tensions related to the proton radius favor nonzero e-p coupling
- "Up-Lepto-Darko-philic" scalar model statistically favored at $\sim 5\sigma$ level, not excluded by other constraints

Summary

- Several HD^+ rovibrational transitions measured with $10^{-11}/10^{-12}$ precision
  More - and more precise - data to come.

- Improved hyperfine structure theory
  - Good agreement in H_2^+
  - HD^+ : good agreement or big discrepancy, depending on transition
  - Affects the precision of extracted spin-averaged transition frequencies, but no big impact on m_p/m_e determination.

- Theoretical precision : 7.5 10^{-12} (1.5 10^{-11}) for vibrational (rotational) transitions
  Next step: nonperturbative calculation of the one-loop self-energy, using accurate solutions of the two-center Dirac equation.

- Final data for CODATA 2022 adjustment under study
  Preliminary estimate : m_p/m_e uncertainty reduced to $\sim 2\ 10^{-11}$, combining HD^+ spectroscopy with mass spectrometry.

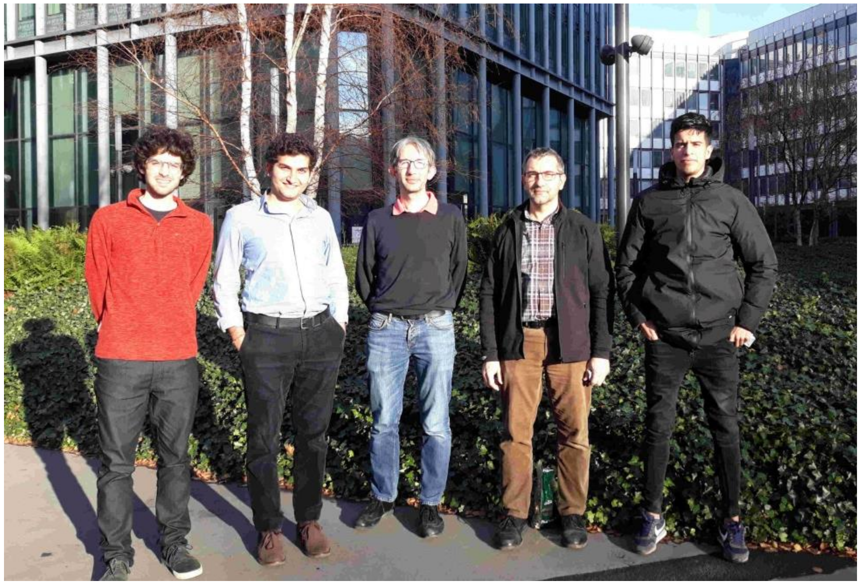
- Self-consistent bounds on NP : check arXiv !

Acknowledgements

LKB Paris

Bérangère Argence

Hugo Nogueira, Mohammad Haidar, Laurent Hilico, Abdessamad Mbardi



Albane Douillet
Johannes Heinrich
Nicolas Sillitoe
Julian Schmidt
Thomas Louvradoux

JINR Dubna

Vladimir Korobov

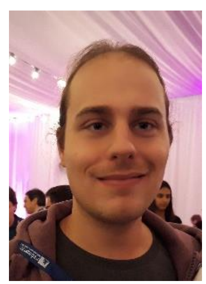
WIPM Wuhan

Zhen-Xiang Zhong

VU Amsterdam

Jeroen Koelemeij

Sayan Patra



Matthias Germann

Frank Cozijn, Kjeld Eikema, Wim Ubachs

ANR
îledeFrance
COST Tipicqa
FIRST TF