university of groningen

COMENIUS UNIVERSITY BRATISLAVA

(SOME) MOLECULAR SEARCHES FOR NEW PHYSICS

INT-24-1 PROGRAM

Lukáš F. Pašteka

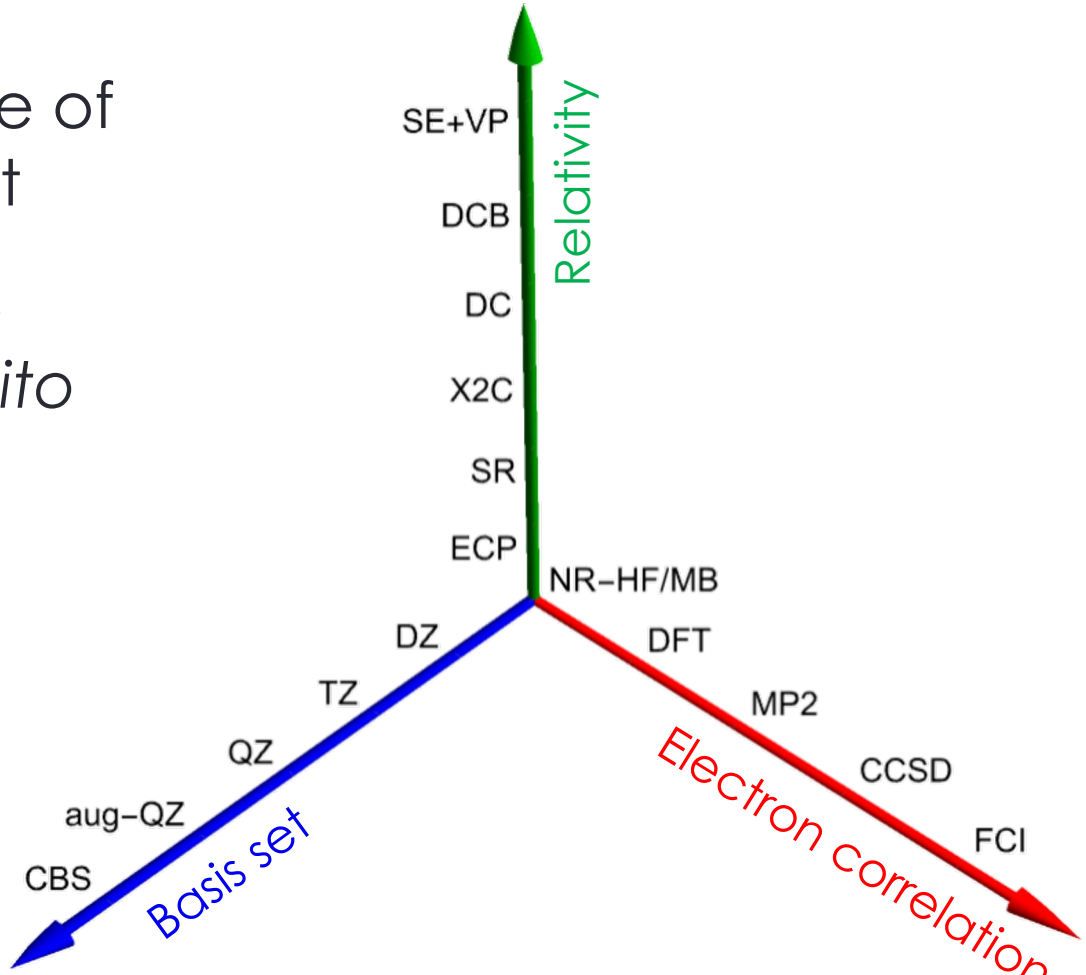
Overview

- Computational methods
- NL-eEDM related applications
- PV in chiral molecules
- Molecular searches for VFC

Computational methods
a general idea

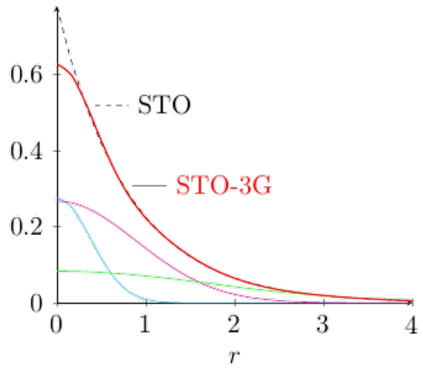
Computational methods

- systematic increase of accuracy and cost
- starting point is the cheapest still *ab inito* method
- computation is a balancing act

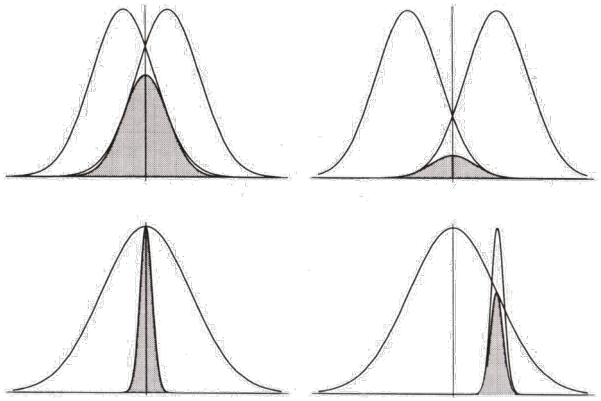


Computational methods

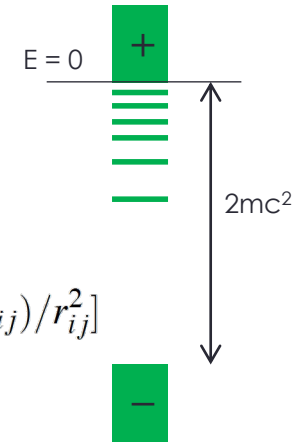
- vector space
- 1-electron expansion
- MO-LCAO
- atom and property specific
- Gaussian (radial) basis sets



$$G_{nlm}(r,\theta,\psi) = N_n \underbrace{r^{n-1}e^{-\alpha r^2}}_{\text{radial part}} \underbrace{Y_l^m(\theta,\psi)}_{\text{angular part}}$$



- i.e. Hamiltonian $H = \sum_i h_i + \sum_{i<j} h_{ij}$
- Schrödinger → Dirac → beyond
- $h_i = -\frac{1}{2}\nabla^2 + V_n \rightarrow h_i = c\alpha \cdot \mathbf{p} + \beta c^2 + V_n$



$$h_C = 1/r_{ij}$$

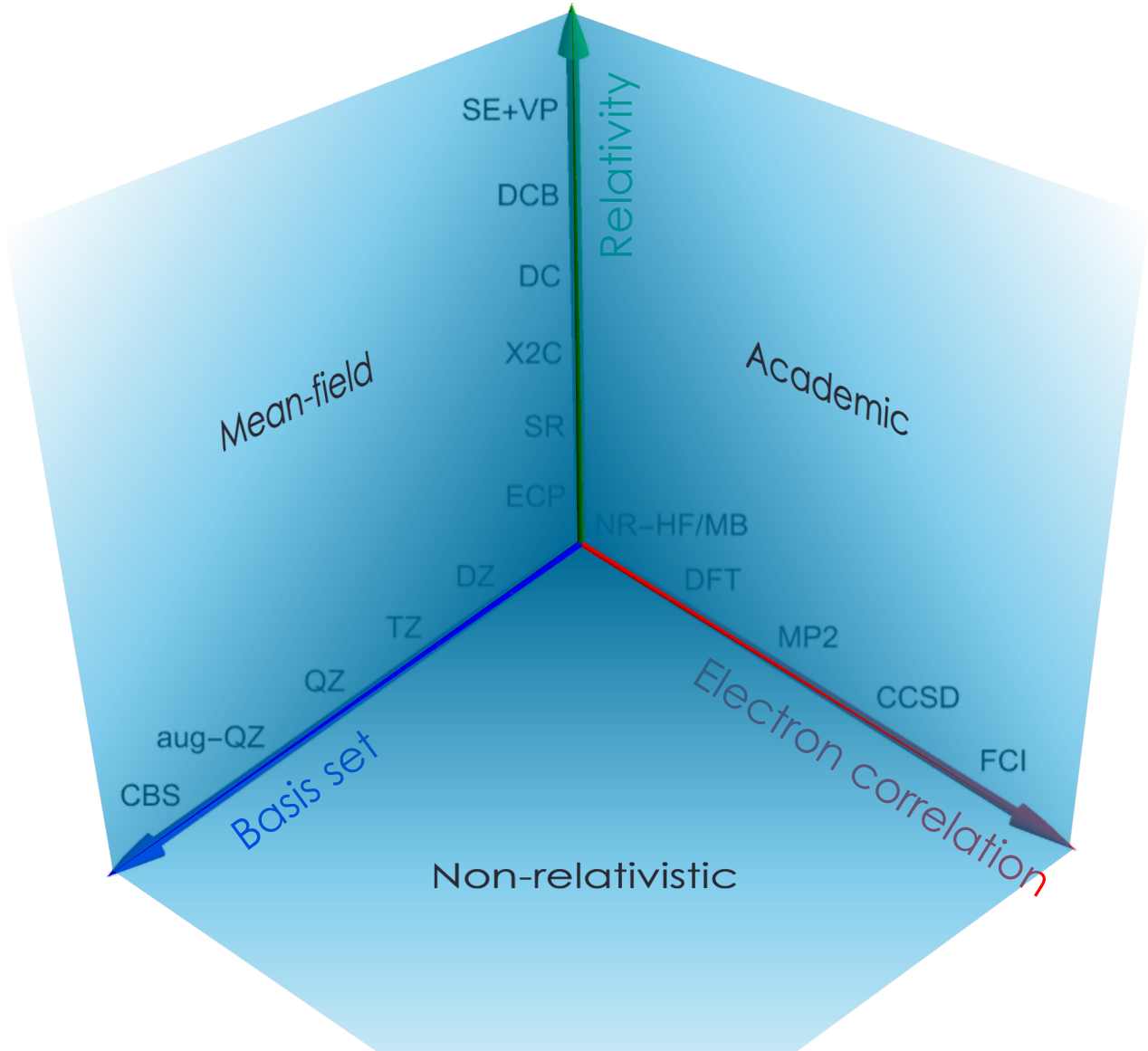
$$h_B = -\frac{1}{2r_{ij}}[\alpha_i \cdot \alpha_j + (\alpha_i \cdot \mathbf{r}_{ij})(\alpha_j \cdot \mathbf{r}_{ij})/r_{ij}^2]$$

- *N*-electron expansion (SD /CSF)
- post-HF methods
  - MP perturbation theory
  - configuration interaction $\psi = \sum_I C_I \Phi_I$
  - coupled cluster

$$\psi = \exp(T)\Phi$$

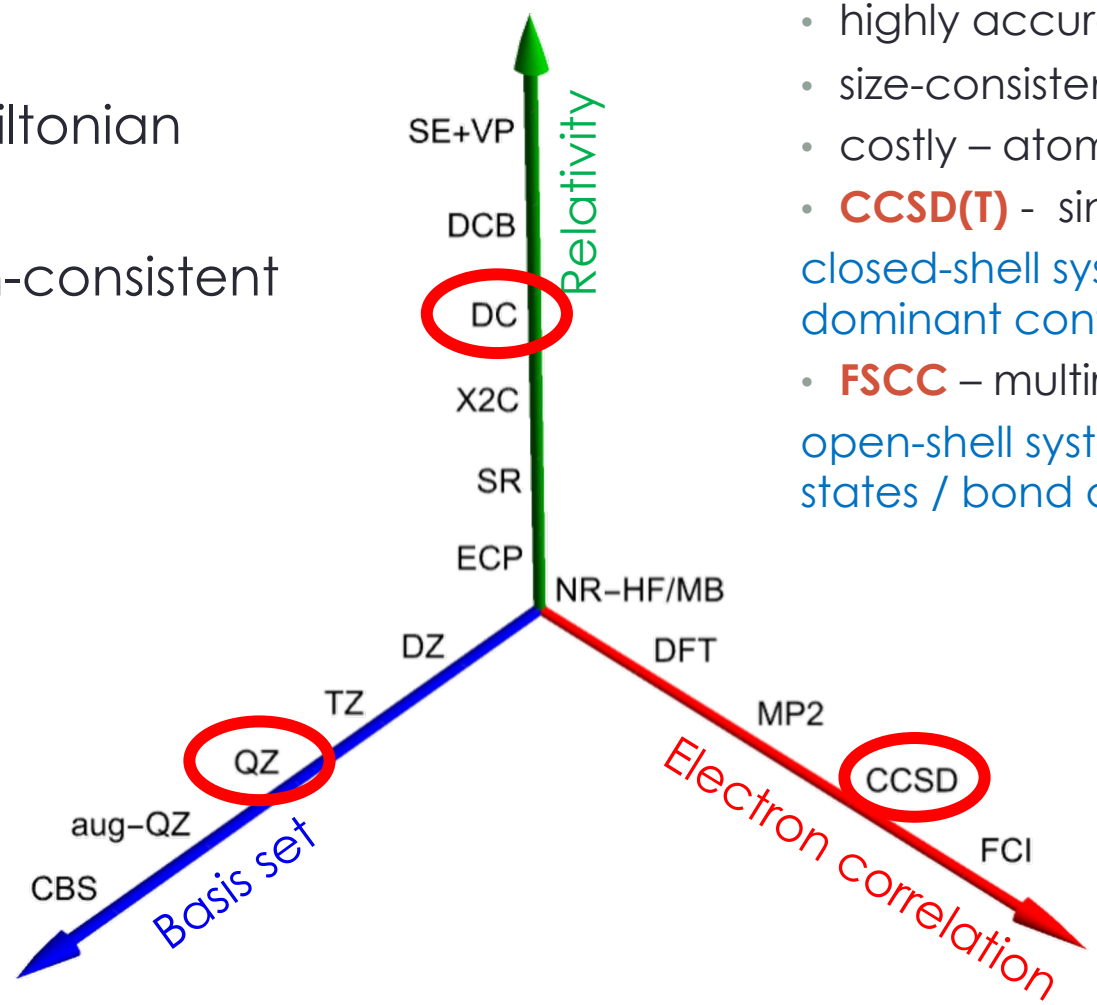
$$T = T_1 + T_2 + T_3 + \ldots + T_N$$

Computational methods



Golden standard

- 4c Dirac-Coulomb Hamiltonian
- large flexible correlation-consistent basis sets
  - CBS extrapolation



- Coupled-Cluster
  - highly accurate
  - size-consistent
  - costly – atoms & small molecules
  - **CCSD(T)** - single reference CC

  closed-shell systems / systems with one dominant configuration (e.g. BaF, $X\ ^2\Sigma$)
  - **FSCC** – multireference Fock-space CC

  open-shell systems / spectrum of excited states / bond dissociation

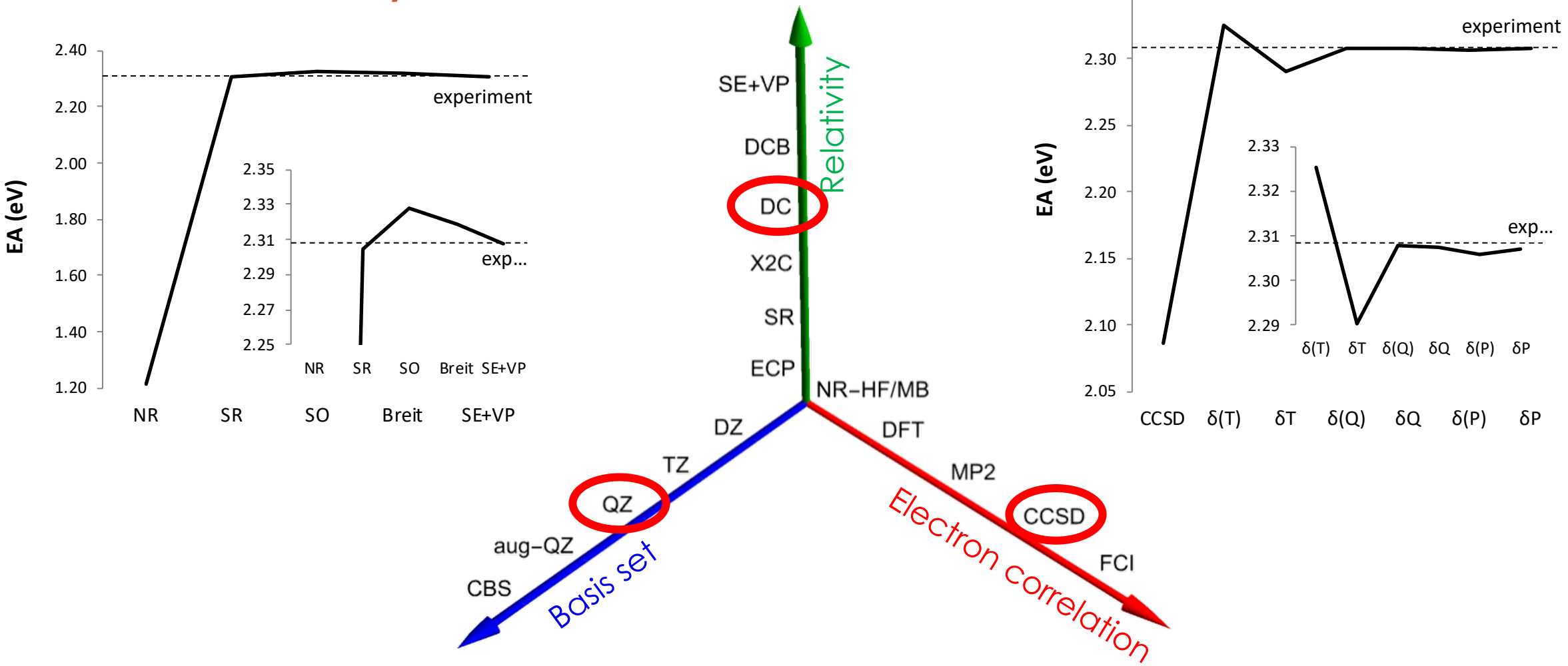
What can we calculate

- Atomic properties
  - energies, IPs, EAs, spectra, HFS parameters, polarizabilities, …
- Molecular properties
  - geometries, spectroscopic constants, laser cooling schemes, …
- Properties for interpretation of precision measurements
  - W_d, Ws (eEDM experiments)
  - W_A (NSD-PV, nuclear anapole moments)
  - W_M (NMQ moments)
  - E_{PV} (parity-violating energy shifts)
  - sensitivity to a-variation
- Expected accuracy
  - ~ 10 meV for energies, ~ 5 % for properties
  - can do better
- Systematic improvement and uncertainty evaluation

Uncertainty estimation

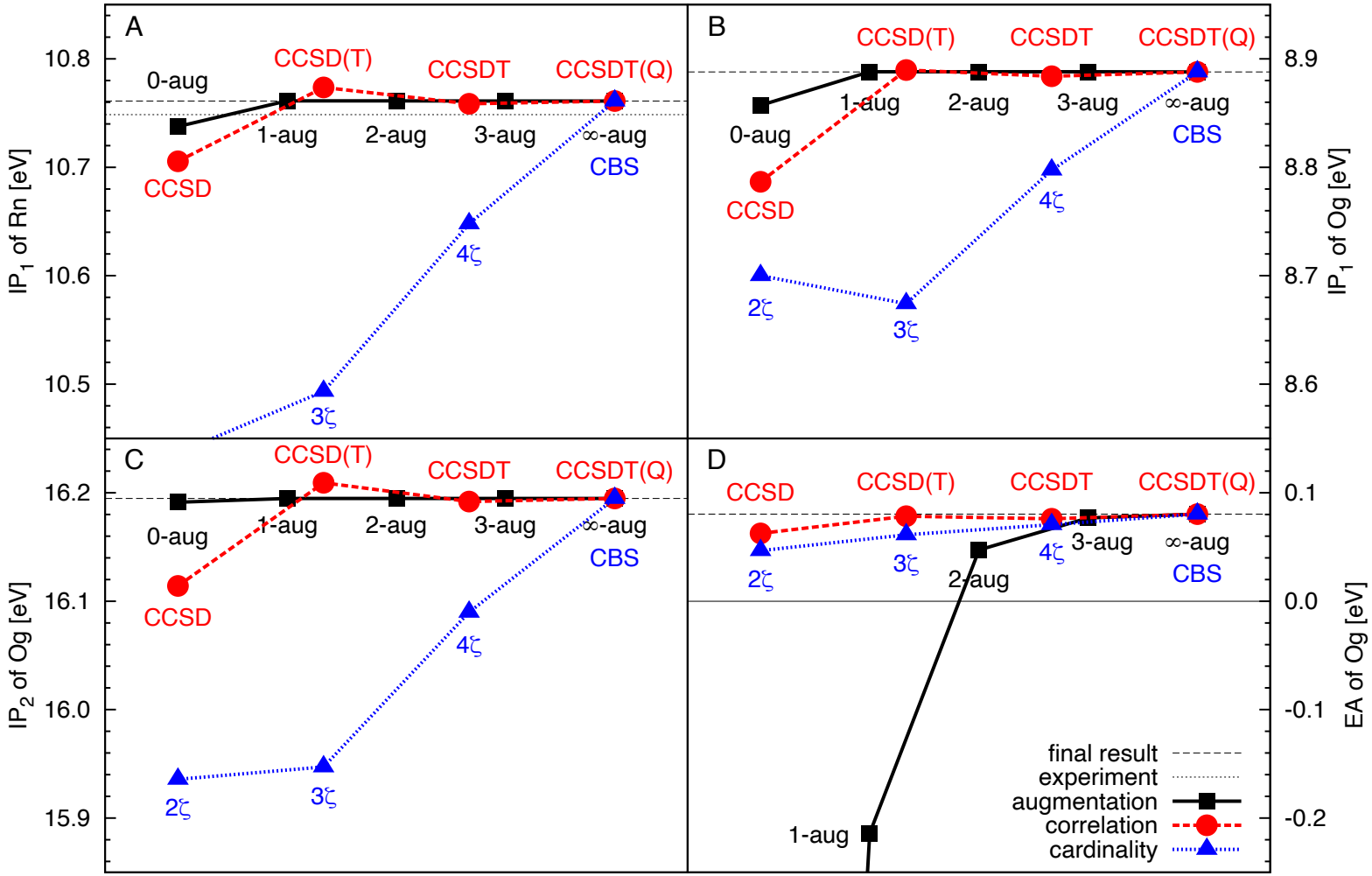
- same property in an experimentally known lighter homologue
- different experimentally known property in the same system
- use systematics trends due to method incompleteness

Uncertainty estimation



Pašteka et al., PRL 118, 023002 (2017)

Uncertainty estimation – IP/EA of Rn/Og



Guo et al., Adv. Quant. Chem. 83, 107 (2021)

In service to NL-eEDM

NL-eEDM collaboration

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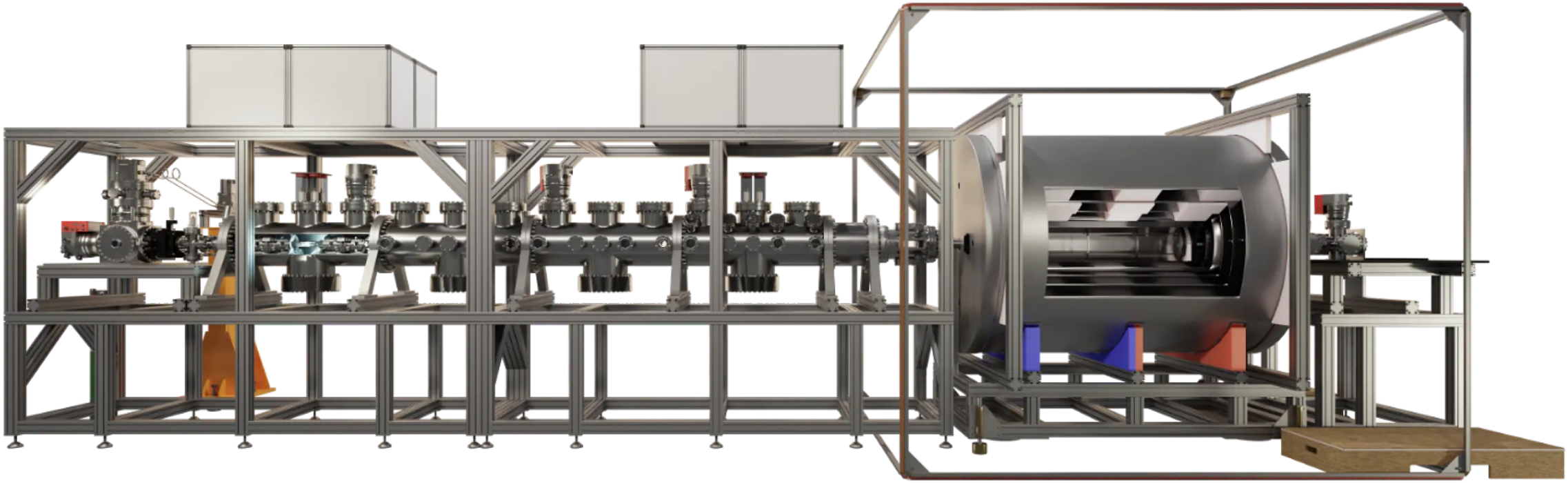
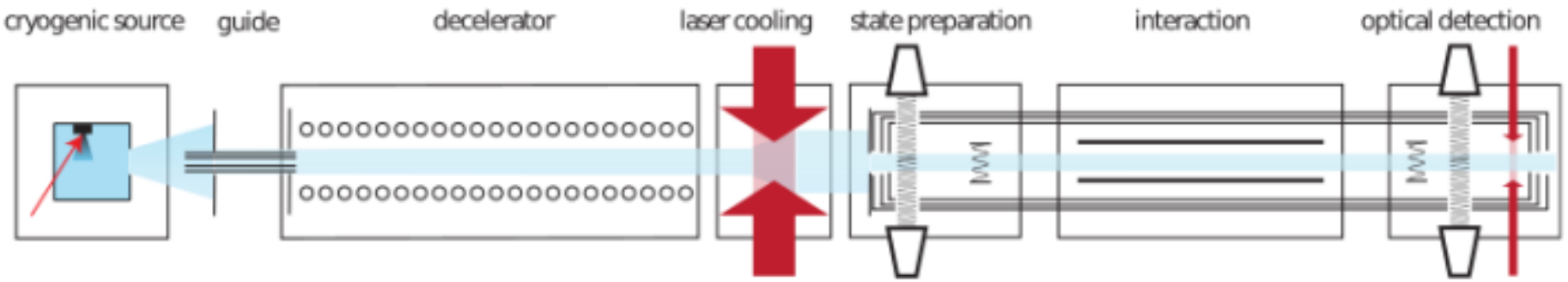
VU VRIJE UNIVERSITEIT AMSTERDAM

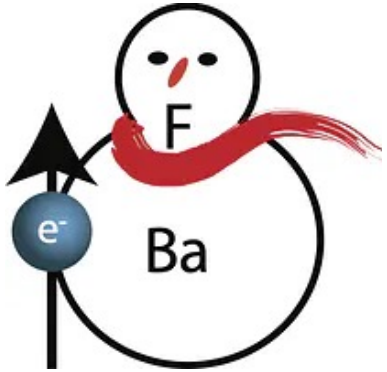
NL-eEDM experiment





Selected applications

- BaF (and friends)
  - coupling constants
  - laser cooling
  - IPs



- Polyatomic molecules
  - $BaCH_3$
  - $YbCH_3$
  - BaOH

Anastasia Borschevsky

Steven Hoekstra

W_d/W_s parameters

$\mathcal{P},\mathcal{T}$-odd scalar pseudoscalar (S-PS) neutral-current electron-nucleon interaction constant

Electron electric dipole moment (eEDM)

$$H_{sr}^{\mathcal{P},\mathcal{T}-\mathrm{odd}} = (W_\mathrm{s}\, k_\mathrm{s} + W_\mathrm{d}\, d_\mathrm{e})\,\Omega$$

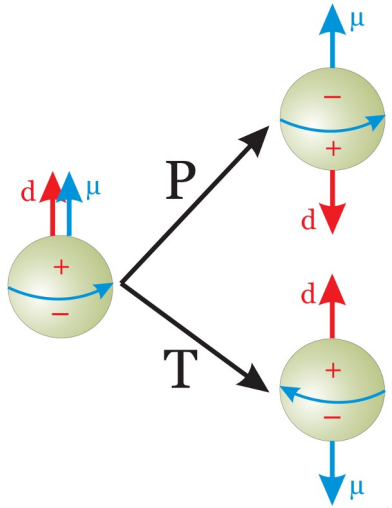
$$W_\mathrm{s} = \frac{1}{\Omega\, k_\mathrm{s}}\langle\Psi^{(0)}|H^{\mathrm{S-PS}}|\Psi^{(0)}\rangle$$

$$H^{\mathrm{S-PS}} = \frac{\imath G_\mathrm{F} k_\mathrm{s}}{e\sqrt{2}}\sum_{i,k}\rho_k(\mathbf{r}_i)\gamma^0\gamma^5$$

$$W_\mathrm{d} = \frac{1}{\Omega\, d_\mathrm{e}}\langle\Psi^{(0)}|H^{\mathrm{eEDM}}|\Psi^{(0)}\rangle$$

$$H^{\mathrm{eEDM-II}} = \frac{2\imath c d_\mathrm{e}}{e\hbar}\sum_i \gamma^0\gamma^5\mathbf{p}_i^2$$

- Use relativistic CC to calculate W_d and W_s.
- Systematically improve the calculation up to convergence
- Perform an extensive computational study to estimate uncertainties

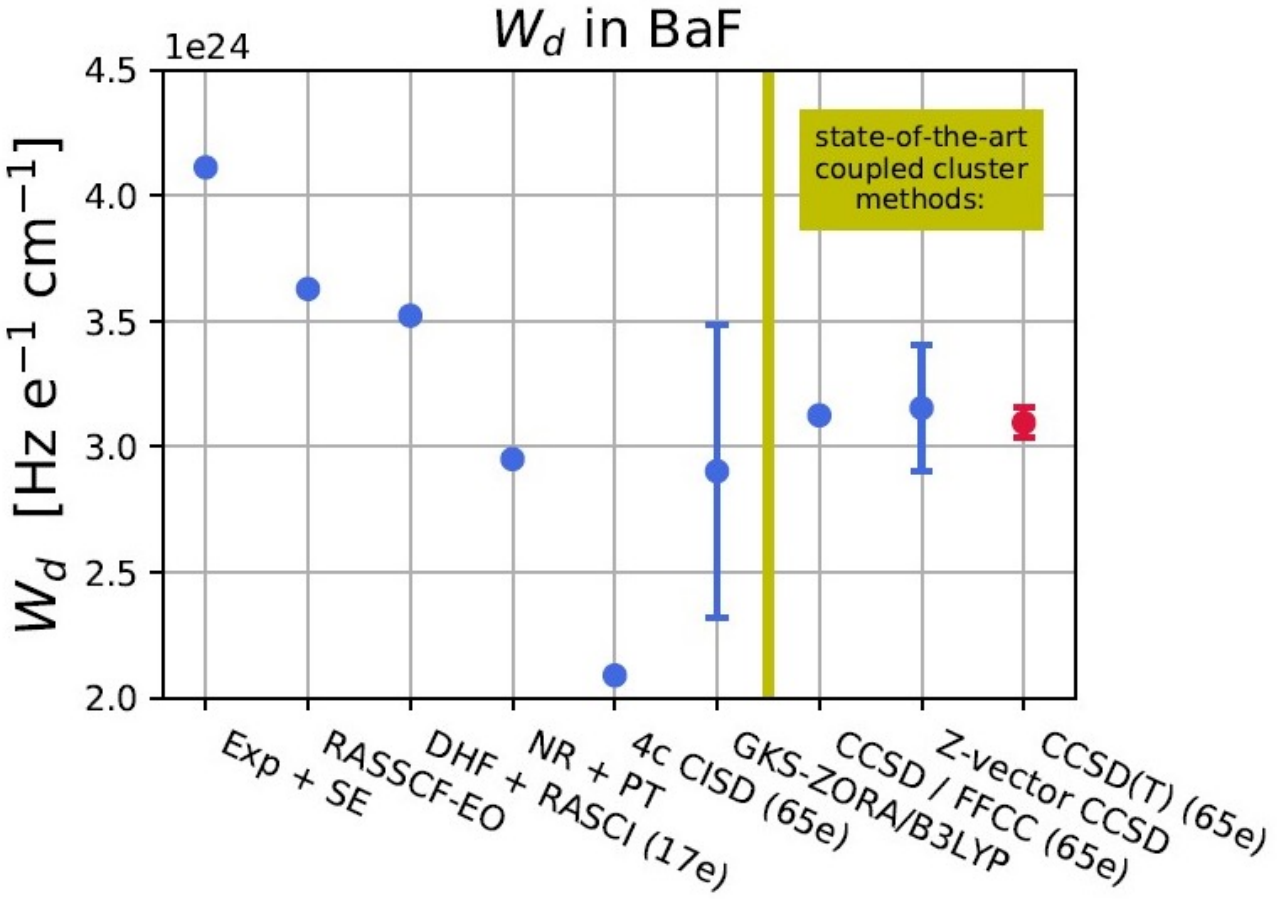


Kriplovich, Nauka (1981), EN trans. G&B (1991)
Kozlov, Zh. Eksp. Teor. Fiz. 89, 1933 (1985)
Dimitriev et al, Phys. Lett. A 167, 280 (1992)

BaF: W_d/W_s parameters

- Calculated values

BaF	W_d^* $[\frac{10^{24}\text{Hz}}{\text{e cm}}]$	W_s [Hz]
DC CCSD(T)	3.13 ± 0.24	8.29 ± 0.12



Haase et al., J. Chem. Phys. 155, 034309 (2021)

BaF: W_d/W_s parameters

- Uncertainties

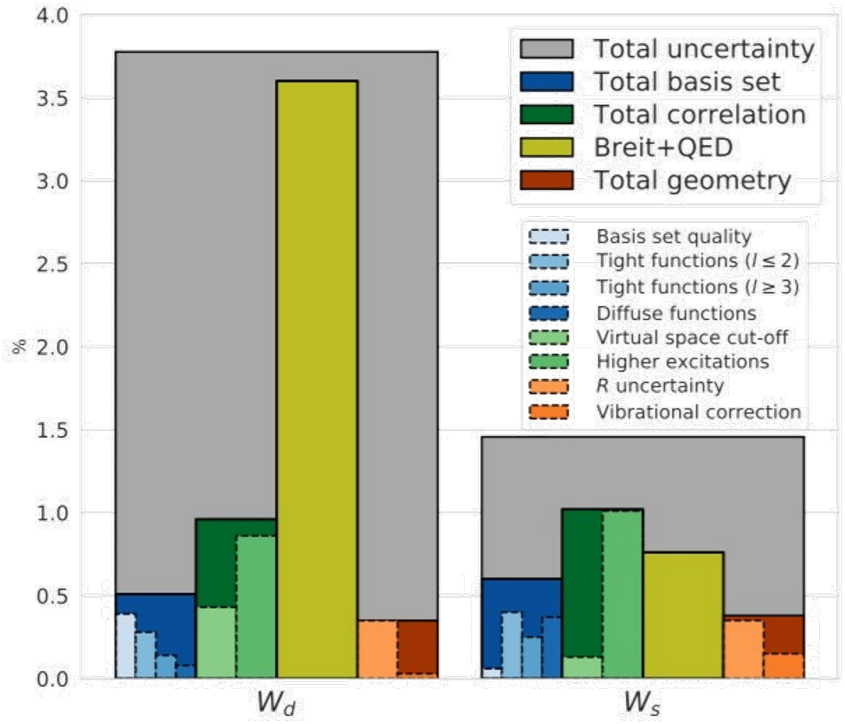


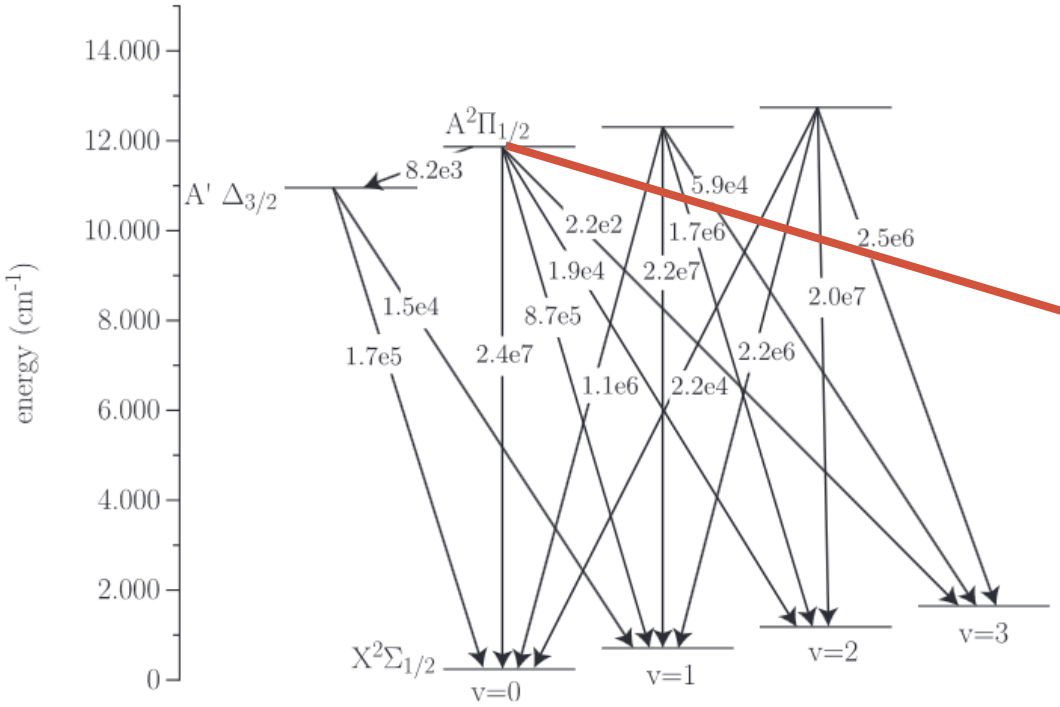
Table 8. $A_\parallel$ and $A_\perp$ of ^{137}Ba in BaF (MHz)

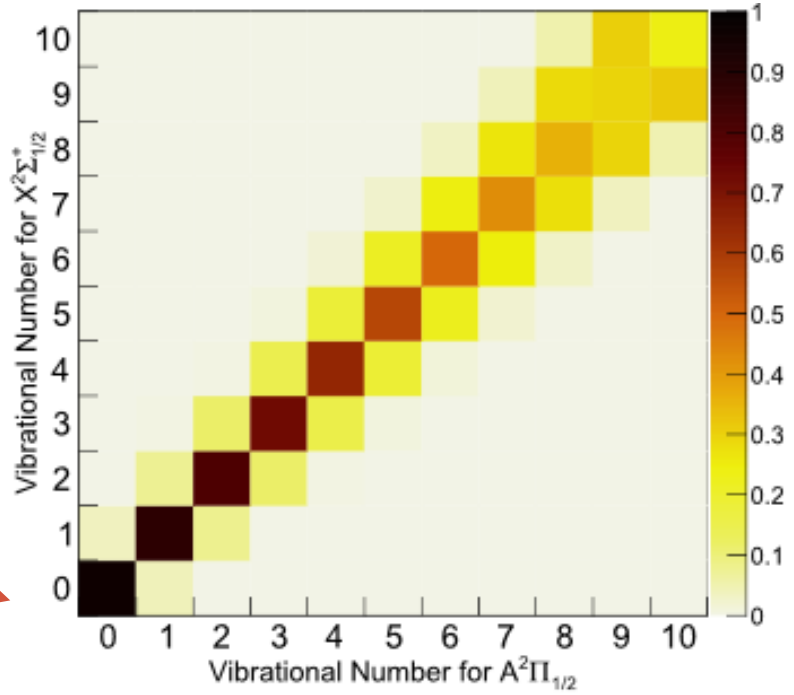
	^{137}BaF			
method	$A_\parallel$	%(exp)	$A_\perp$	%(exp)
GRECP SCF-EO[90]	2264	−4.71	2186	−5.00
GRECP RASSCF-EO[90]	2272	−4.38	2200	−4.39
DF RASCI[91]	2240	−5.72	2144	−6.82
DF MBPT[91]	2314	−2.61	2254	−2.04
DC CCSD (this work)	2383(129)	0.29	2305(132)	0.17
exp[77]	2376(12)		2301(9)	

Haase et al., J. Chem. Phys. 155, 034309 (2021)

BaF: cooling scheme

- transition rates, FCFs, lifetimes

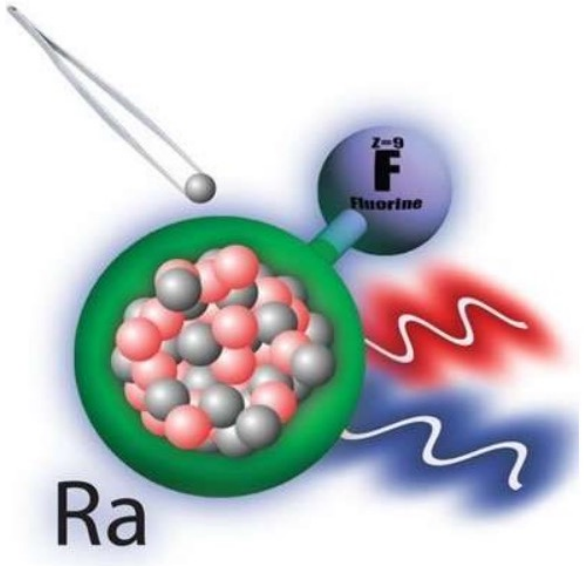




Hao et al., J. Chem. Phys. 151, 034302 (2019)

RaF

- promising candidate for precision measurements
- many (high-impact) experimental studies
- spectra, isotope shifts
- new measurements: IP
- theory before experiment



87. "Precision spectroscopy and laser cooling scheme of a radium-containing molecule".
S.M. Udrescu, S. Wilkins, A. Breier, M. Athanasakis-Kaklamanakis, **R.F. Garcia Ruiz** et al.
Nature Physics (2023).

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Spectroscopy of short-lived radioactive molecules

R. F. Garcia Ruiz, R. Berger, J. Billowes, C. L. Binnersley, M. L. Bissell, A. A. Breier, A. J. Brinson, K. Chrysalidis, T. E. Cocolios, B. S. Cooper, K. T. Flanagan, T. F. Giesen, R. P. de Groote, S. Franchoo, F. P. Gustafsson, T. A. Isaev, Á. Koszorús, G. Neyens, H. A. Perrett, C. M. Ricketts, S. Rothe, L. Schweikhard, A. R. Vernon, K. D. A. Wendt, ... X. F. Yang + Show authors

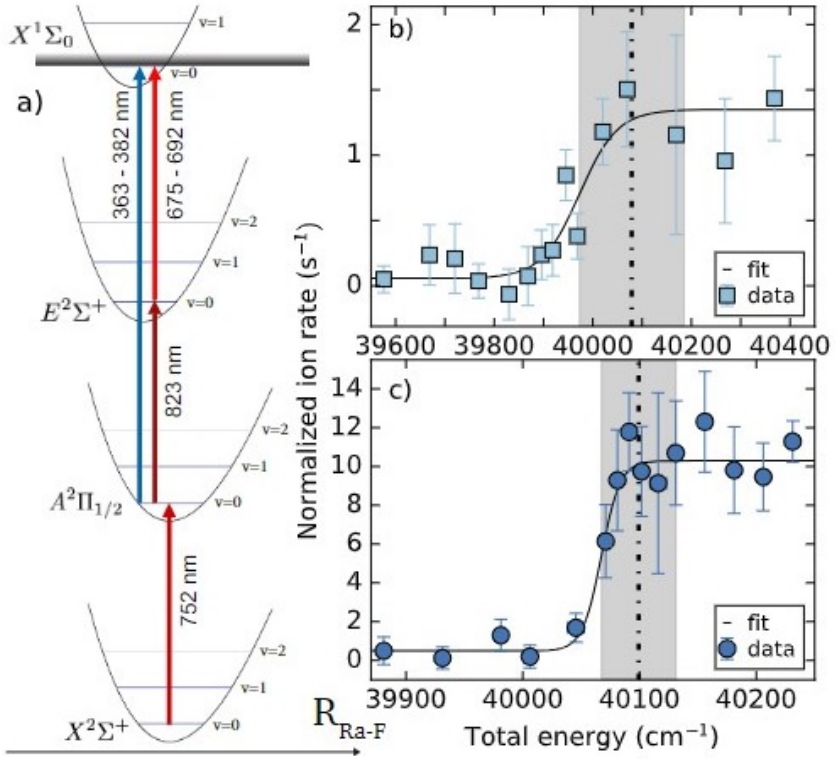
Featured in Physics | Editors' Suggestion | Open Access

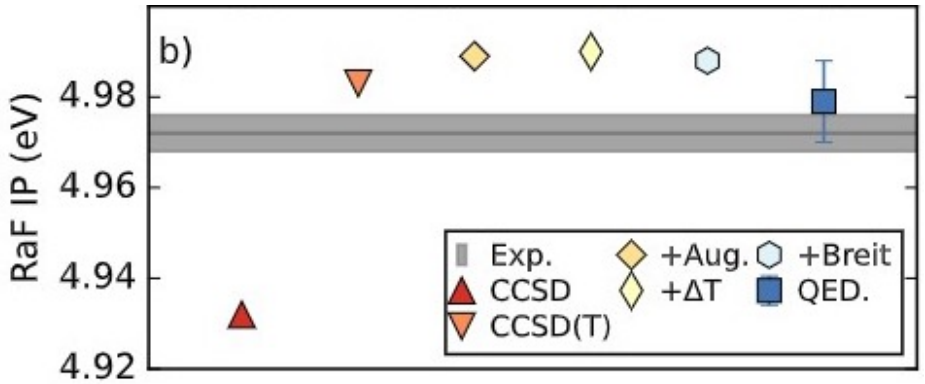
Isotope Shifts of Radium Monofluoride Molecules

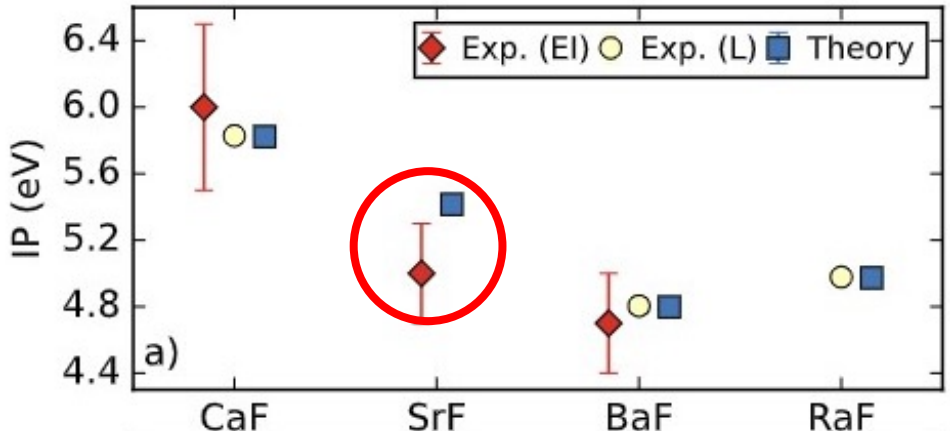
S. M. Udrescu *et al.*
Phys. Rev. Lett. **127**, 033001 – Published 14 July 2021

RaF: ionization potential

- Measurement
  - ionization threshold under multi-step laser excitation
  - both two-step and three-step ionization schemes.
- Theory
  - relativistic CC with higher order corrections

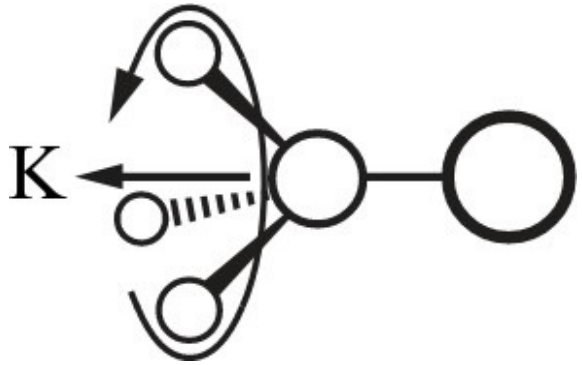






Wilkins et al., in prep. (2024)

Symmetric top molecules



- $BaCH_3$ and $YbCH_3$
- long-lived close-lying opposite parity eigenstates (K-doublets)
- expected to be laser-coolable
- similar W_d/W_s parameters to other Ba/Yb containing molecules

Chamorro et al., Phys. Rev. A 106, 052811 (2022)

Bonding effects

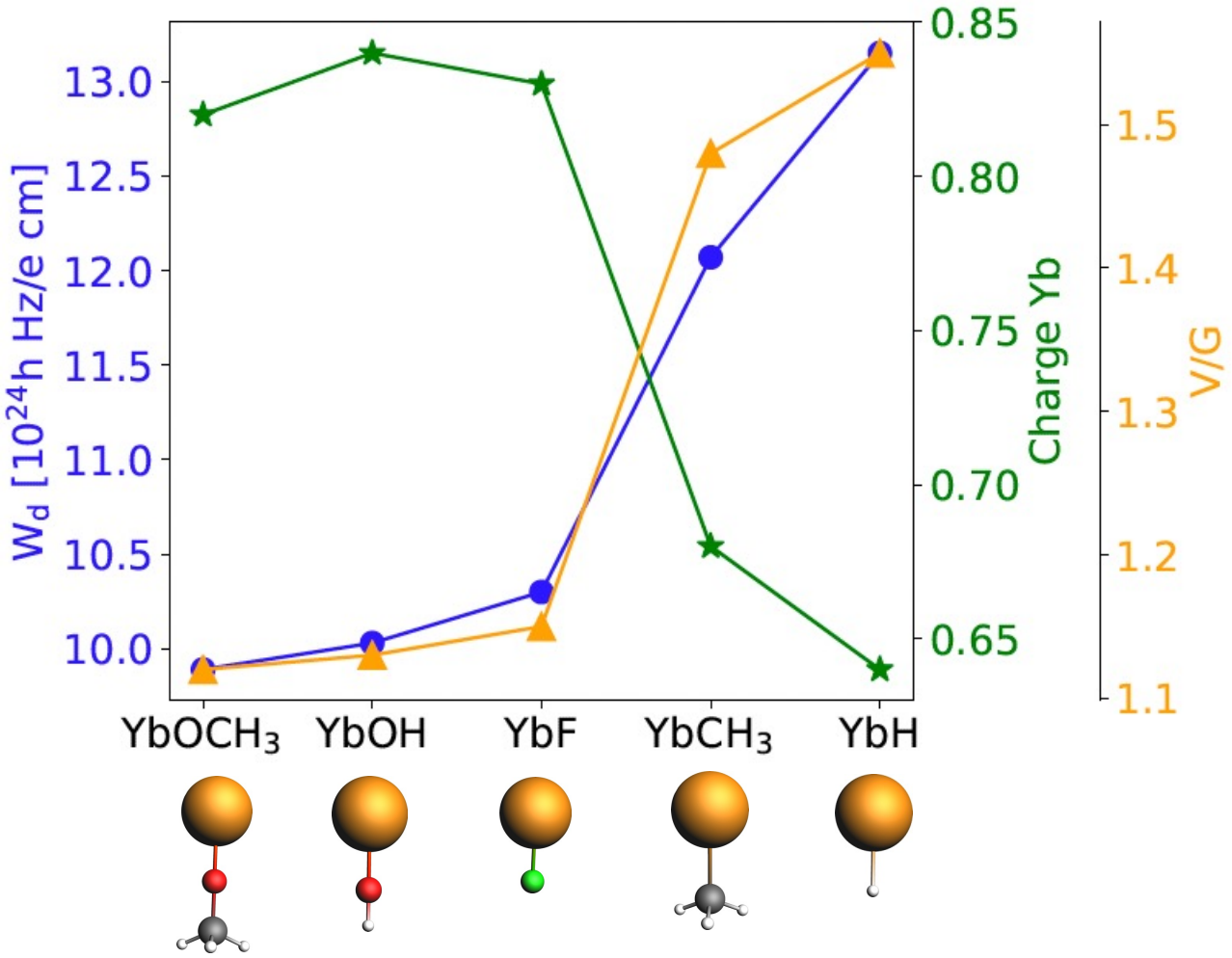
- smaller charge on Yb

  ↓

- less polar = more covalent

- V/G at BCP
  - measure of covalent character
  - <1 ionic, 1-2 polar, >2 covalent

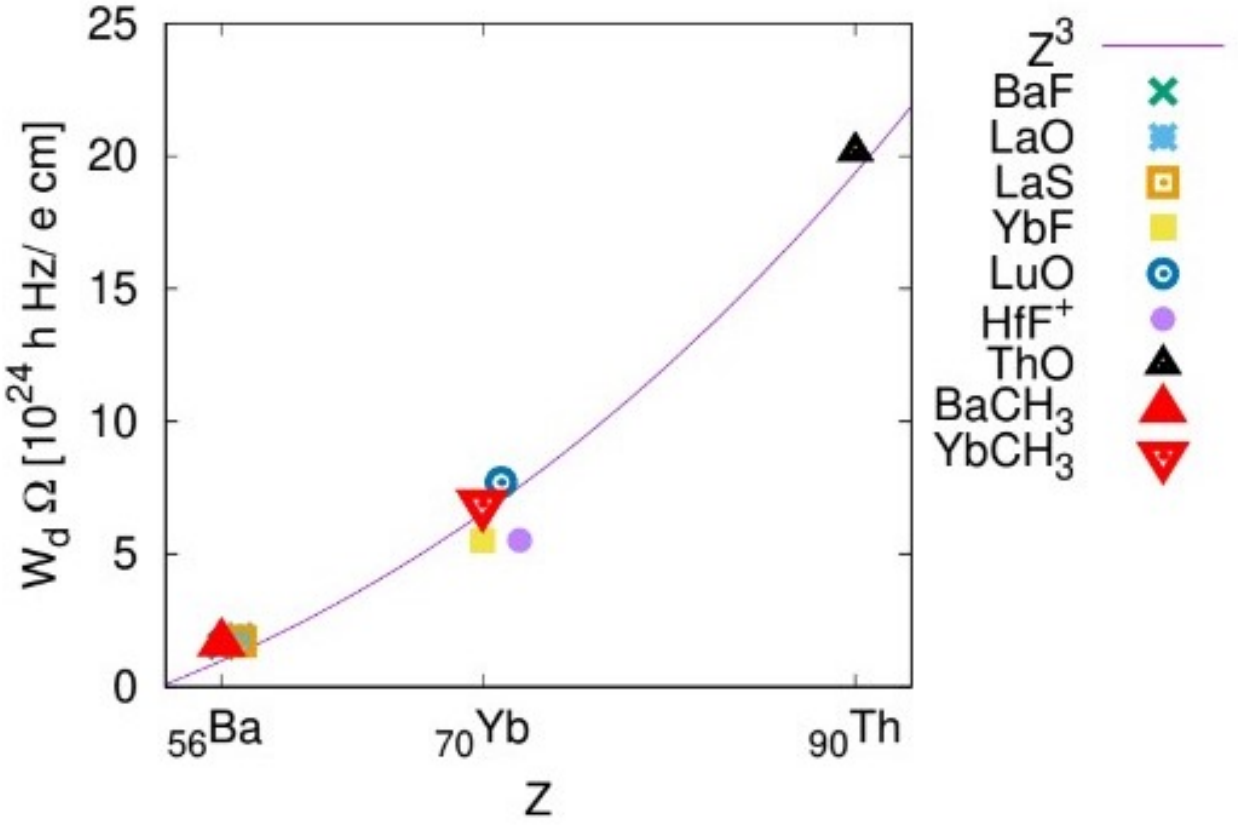
- downside – laser coolability



Chamorro et al., Phys. Rev. A 106, 052811 (2022)

Z-scaling

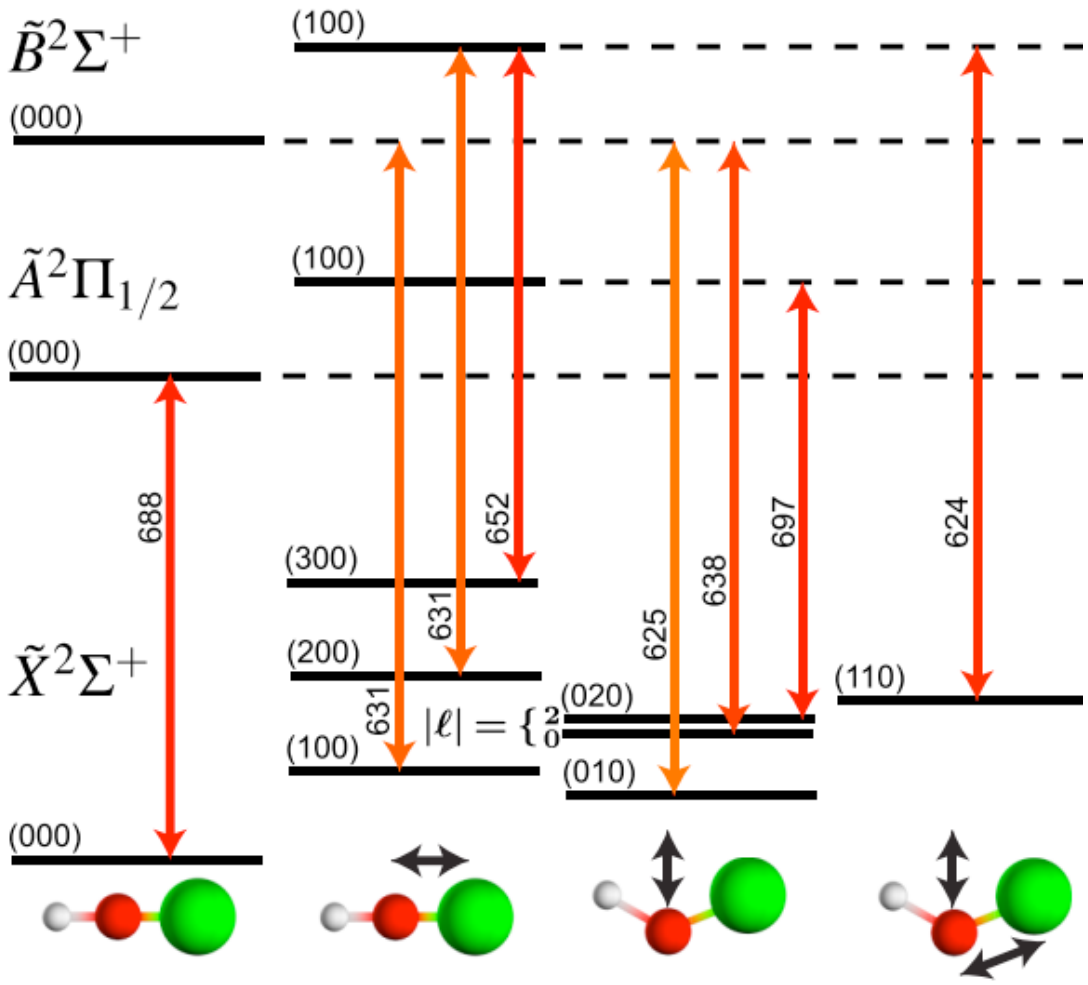
- W_d scales as Z^3



Bouchiat et Bouchiat, J. Phys. France 35, 899 (1974)

BaOH: work in progress

- bending mode lifetime
- cooling scheme
- polarizability and scattering tensors



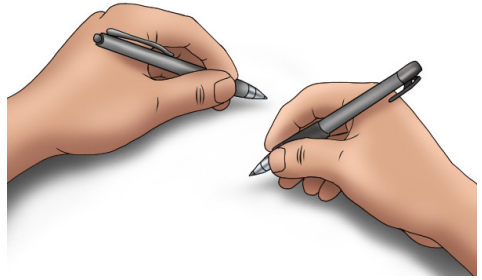
(this is fake news – actually SrOH)

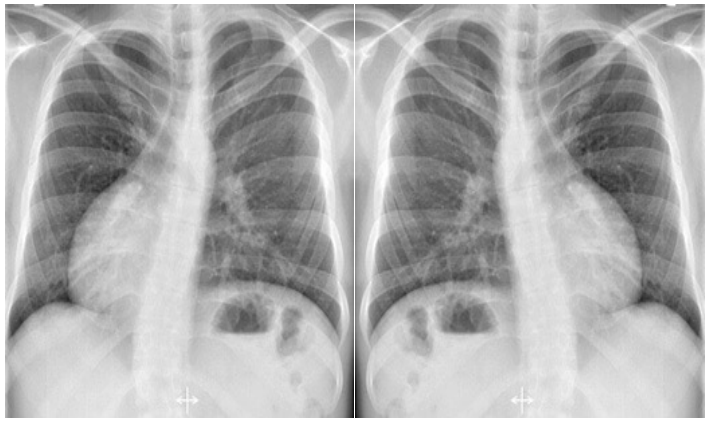
Parity violation in chiral molecules

Is universe right or left handed?

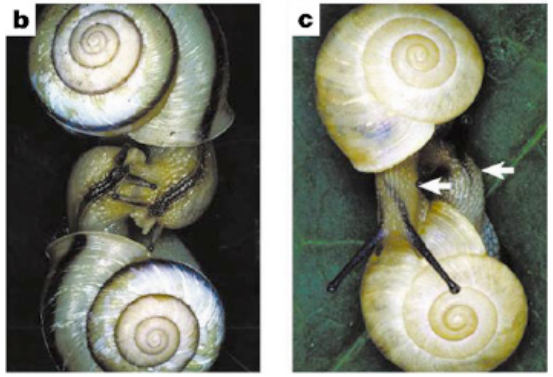
Symmetry breaking in nature

- left-/right-handedness (1:10)

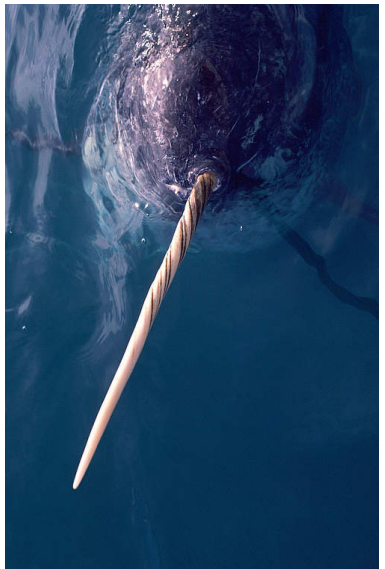




- dextro-/levo-cardia (1:12 000)

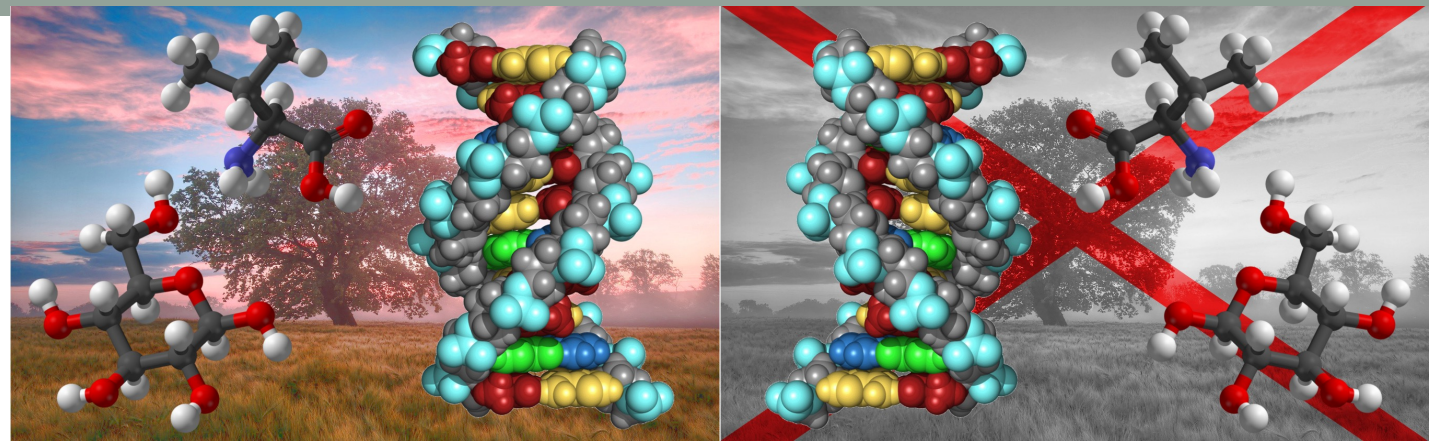


- left/right snail shells (1:20 000)



- right/left-twisting narwhal tusks (1:?)

Biohomochirality



- Only one enantiomer appears in live organisms
- D-sugars, L-proteins, D-DNA, …
- Arthur C. Clarke – Technical Error
- Condition for life?
- Origin
  - parity violation
  - circularly polarized light
  - chiral surfaces
  - panspermia
- Amplification mechanisms
  - asymmetric autocatalysis

Planet	Earth	Saturn	Arion	Hypatia	Pirx
Homochiral life?	✓	?	?	?	?
Racemic life?	✗	?	?	?	?

Biohomochirality

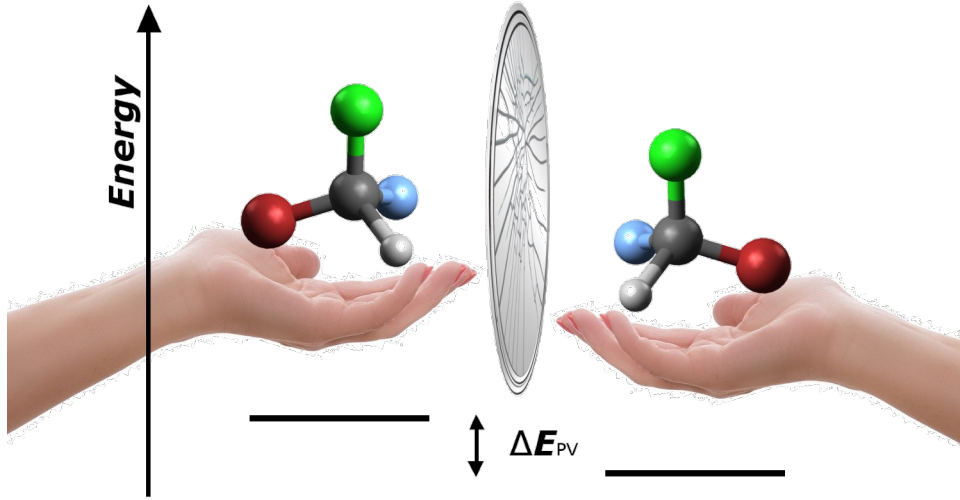
- Racemic drug
  Cetirizine (Zyrtec)
  Ibuprofen (Advil)

Enantiopure drug
Levocetirizine (Xyzal)
Dexibuprofen (Seractil)

- Thalidomide cautionary tale
  - (S) is sedative (morning sickness)
  - (R) is teratogenic (birth defects)
  - *in vivo* conversion

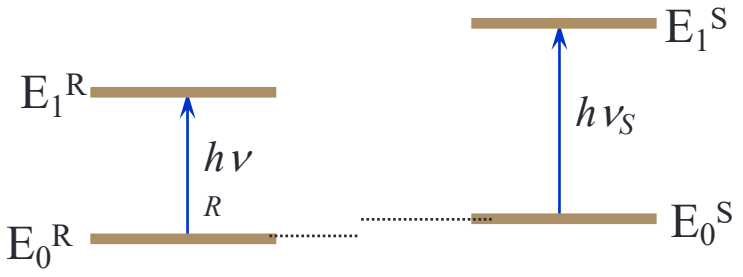
PV in molecules

- chiral molecules
  - inherent parity violation effects
  - unseen experimentally



- attempts
  - camphor $|\Delta\nu/\nu| < 10^{-8}$ theory: $|\Delta\nu/\nu| \sim 10^{-19}$
  - CHFClBr $|\Delta\nu/\nu| < 10^{-13}$ theory: $|\Delta\nu/\nu| \sim 10^{-17}$

- sensitive molecules and predictions needed



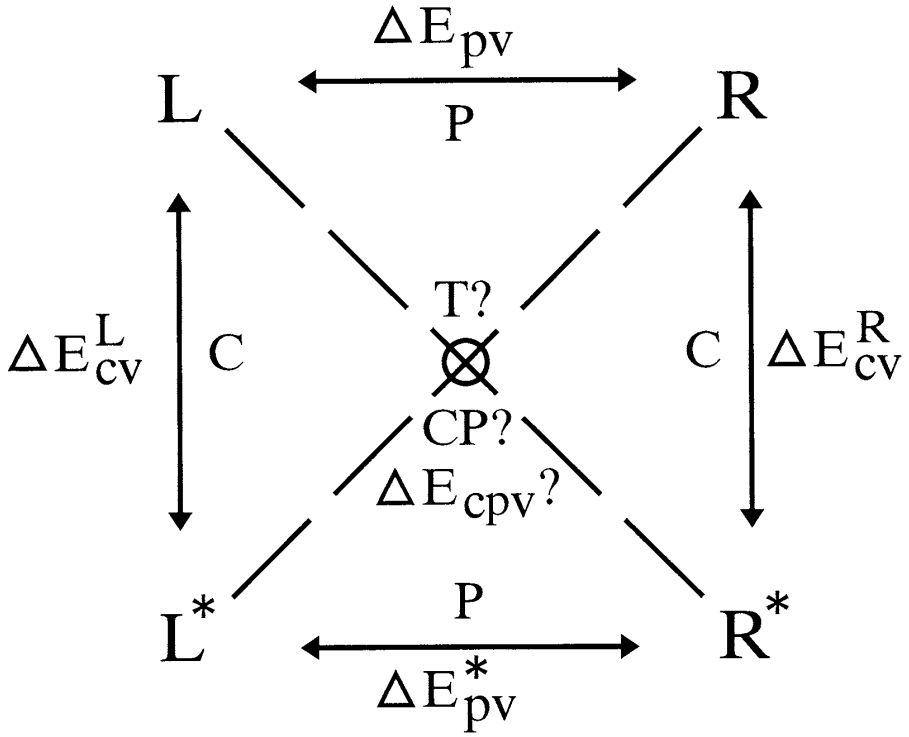
$$\nu_R \neq \nu_S$$

$$\Delta\nu_{PV} = \nu_R - \nu_S \neq 0$$

Letokhov, Phys. Lett. 53A, 275 (1975)
Glorieux, Oka, Opt. Commun. 23, 369 (1977); .Schwerdtfeger, et al., Chem. Phys. Lett. 383, 496 (2004)
Daussy et al., PRL 83, 1554 (1999); Ziskind et al., Euro. Phys. J. D 20, 219 (2002)
Quack, Stohner, J. Chem. Phys. 119, 11228–11240 (2003); Rauhut, Schwerdtfeger, PRA 103, 042819 (2021)

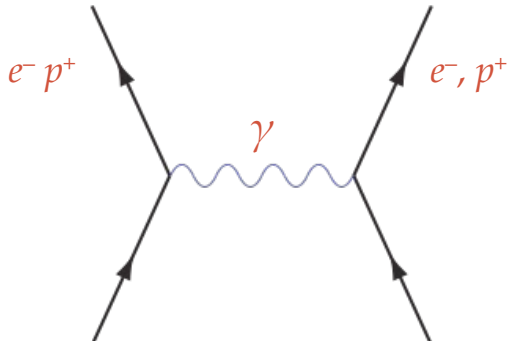
PV in molecules

- CP violation test
- $E_{\mathrm{PV}}^{*} \stackrel{?}{=} E_{\mathrm{PV}}$



Quack, in Progress in Theoretical Chemistry and Physics Vol. 26 (Eds. Nishikawa, et al.), p 47, Springer (2012)

PV from EW theory



- Interaction Lagrangian between fermions and EW bosons

$$\mathcal{L}_{\text{int}} = \sum_{k=1}^{3} \{ -e \left((-1)\bar{\mathrm{e}}_k \gamma^\mu \mathrm{e}_k + (2/3)\bar{\mathrm{u}}_k \gamma^\mu \mathrm{u}_k + (-1/3)\bar{\mathrm{d}}_k \gamma^\mu \mathrm{d}_k \right) A_\mu$$

γ boson (photon)

$$- \frac{e}{2\sqrt{2}\sin\theta_{\mathrm{w}}} \left[\left(\bar{\nu}_{\mathrm{e}k} \gamma^\mu (1-\gamma^5) \mathrm{e}_k + \bar{\mathrm{u}}_k \gamma^\mu (1-\gamma^5) \mathrm{d}'_k \right) W_\mu^+ \right.$$

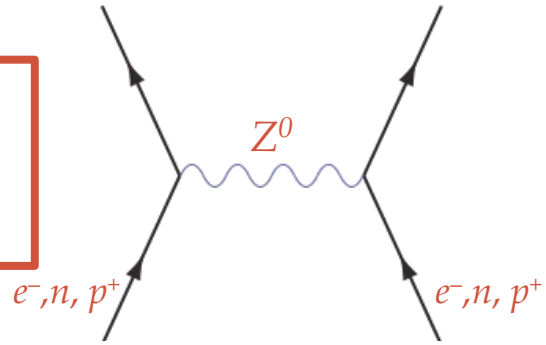
W^+ boson

$$\left. + \left(\bar{\mathrm{e}}_k \gamma^\mu (1-\gamma^5) \nu_{\mathrm{e}k} + \bar{\mathrm{d}}'_k \gamma^\mu (1-\gamma^5) \mathrm{u}_k \right) W_\mu^- \right]$$

W^- boson

$$- \frac{e}{2\sin\theta_{\mathrm{w}}\cos\theta_{\mathrm{w}}} \left(\sum_{f=1}^{4} \bar{f}_k \gamma^\mu (g_{\mathrm{V}}^f - g_{\mathrm{A}}^f \gamma^5) f_k \right) Z_\mu \Bigg\}$$

Z^0 boson



- Weinberg mixing angle θ_{W}

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_{\mathrm{W}} & \sin\theta_{\mathrm{W}} \\ -\sin\theta_{\mathrm{W}} & \cos\theta_{\mathrm{W}} \end{pmatrix} \begin{pmatrix} B \\ W_3 \end{pmatrix} \qquad \cos\theta_{\mathrm{W}} = \frac{m_{\mathrm{W}}}{m_{\mathrm{Z}}}$$

Berger in Relativistic Electronic Structure Theory. Part 2: Applications (ed. Schwerdtfeger), p 188 (2007)

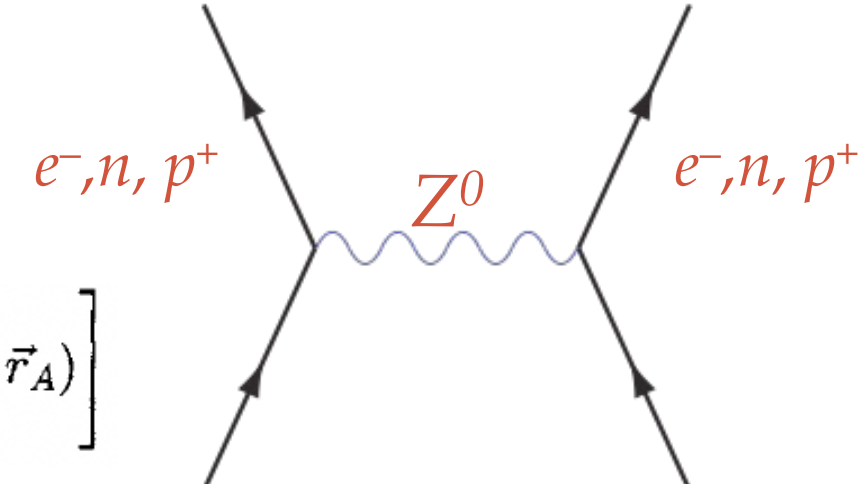
PV from EW theory

- Effective PV Hamiltonian

$$\hat{H}_{\mathrm{pv}}^{(\mathrm{e-nucl})} = \hat{H}_{\mathrm{pv}}^{(\mathrm{e-nucl},1)} + \hat{H}_{\mathrm{pv}}^{(\mathrm{e-nucl},2)}$$

$$= \sum_{i=1}^{n} \left[\hat{h}_{\mathrm{pv}}^{(1)}(i) + \hat{h}_{\mathrm{pv}}^{(2)}(i) \right]$$

$$= \frac{G_{\mathrm{F}}}{2\sqrt{2}} \sum_{i=1}^{n} \left[\sum_{A=1}^{N} Q_{\mathrm{w}}(A) \gamma_i^5 \rho(\vec{r}_i - \vec{r}_A) + \sum_{A=1}^{N} \kappa_A \vec{\alpha}_i \cdot \hat{\vec{I}} \rho(\vec{r}_i - \vec{r}_A) \right]$$



spin-independent (SI, V_nA_e) ≫ spin-dependent (SD, V_eA_n)

$$Q_{\mathrm{w}} = -N + Z\,(1 - 4\sin^2\theta_{\mathrm{W}}) \approx -N$$

$$\kappa_A = \lambda_A(1 - 4\sin^2\theta_{\mathrm{W}})/2 \approx 0.038\,\lambda_A$$

$$\sin^2\theta_{\mathrm{W}} \approx 0.231$$

Berger in Relativistic Electronic Structure Theory. Part 2: Applications (ed. Schwerdtfeger), p 188 (2007)

Properties of H_{PV}

- Effective Hamiltonian H_{PV} – perturbation to H_{DC}

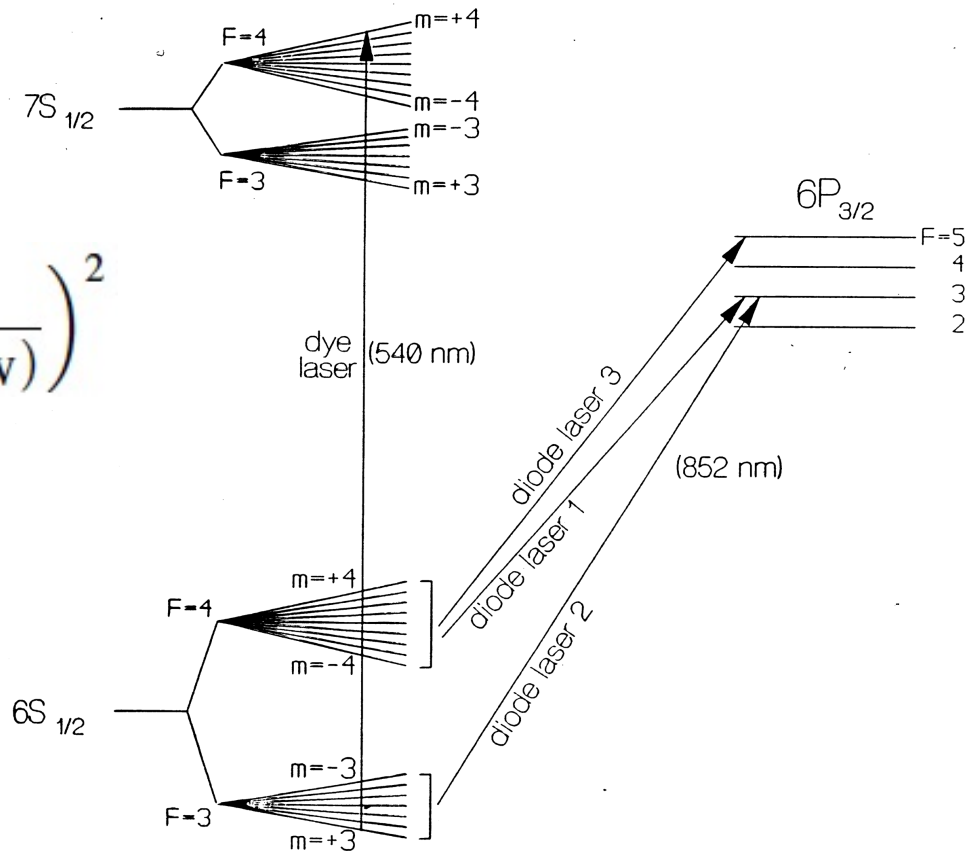
$$H_{\mathrm{PV}} = \sum_A H_{\mathrm{PV}}^A \qquad H_{\mathrm{PV}}^A = \frac{G_{\mathrm{F}}}{2\sqrt{2}} Q_{\mathrm{w}}^A \sum_i \gamma_5(i)\rho^A(\mathbf{r}_i)$$

- Small prefactor

$$G_F = 2.22255 \times 10^{-14} E_h a_0^3 \approx 2\sqrt{2}\left(\frac{4\pi\hbar^2}{4\pi\varepsilon_0 M_Z^2 c^4}\right)\left(\frac{ec}{2\sin(2\theta_{\mathrm{w}})}\right)^2$$

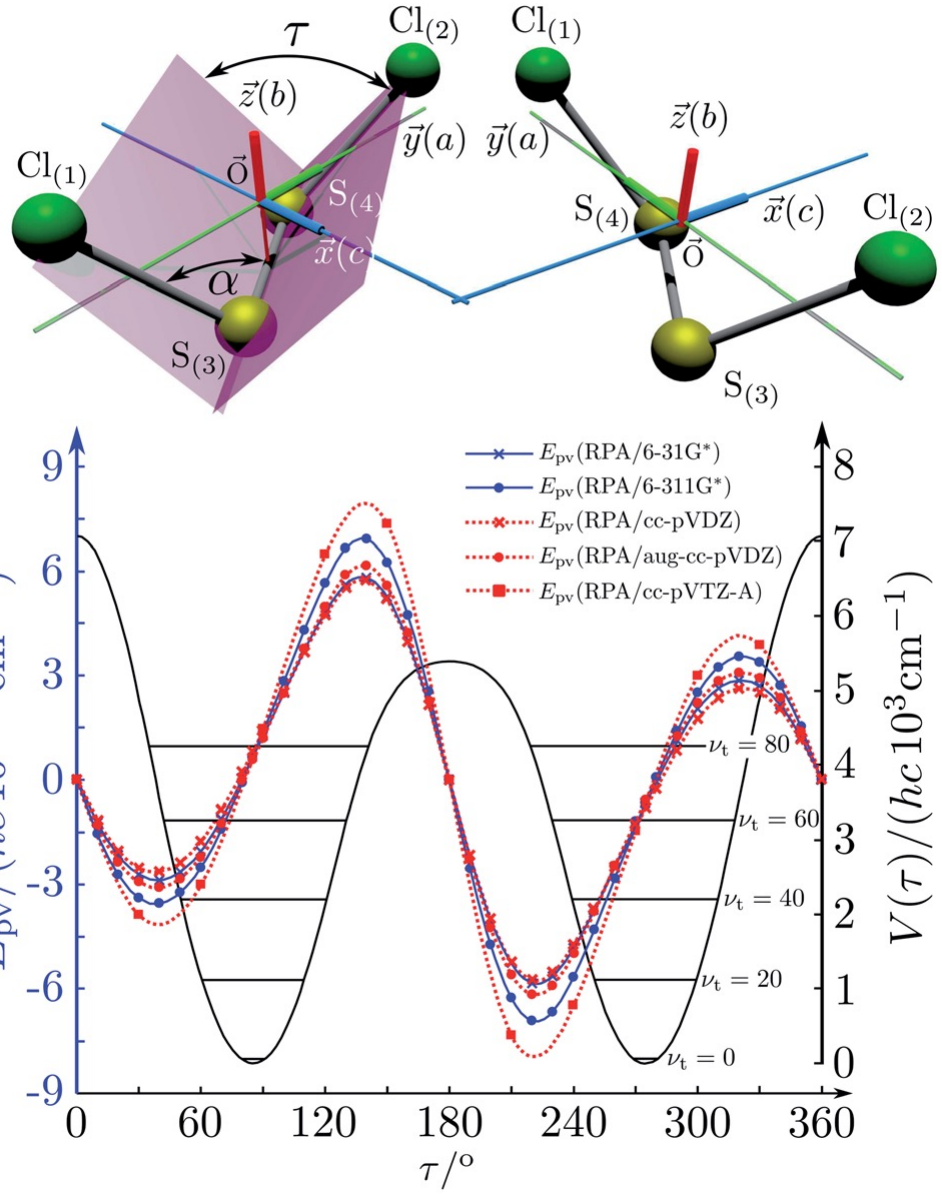
- H_{DC} + H_{PV} commutes with J
  - mixing of orbitals with same J, but different L
  - notably s-p mixing
  - Laporte rule violation (e.g. Cs 6s-7s E1 transition)

$$\Psi_{s_{1/2}}^{PV} = \Psi_{s_{1/2}} + \varepsilon_{PV}\Psi_{p_{1/2}} \qquad \varepsilon = \frac{i\langle\Psi_{2s_{1/2}}|H_{\mathrm{PV}}|\Psi_{2p_{1/2}}\rangle}{E_{2s_{1/2}} - E_{2p_{1/2}}}$$



PV in molecules

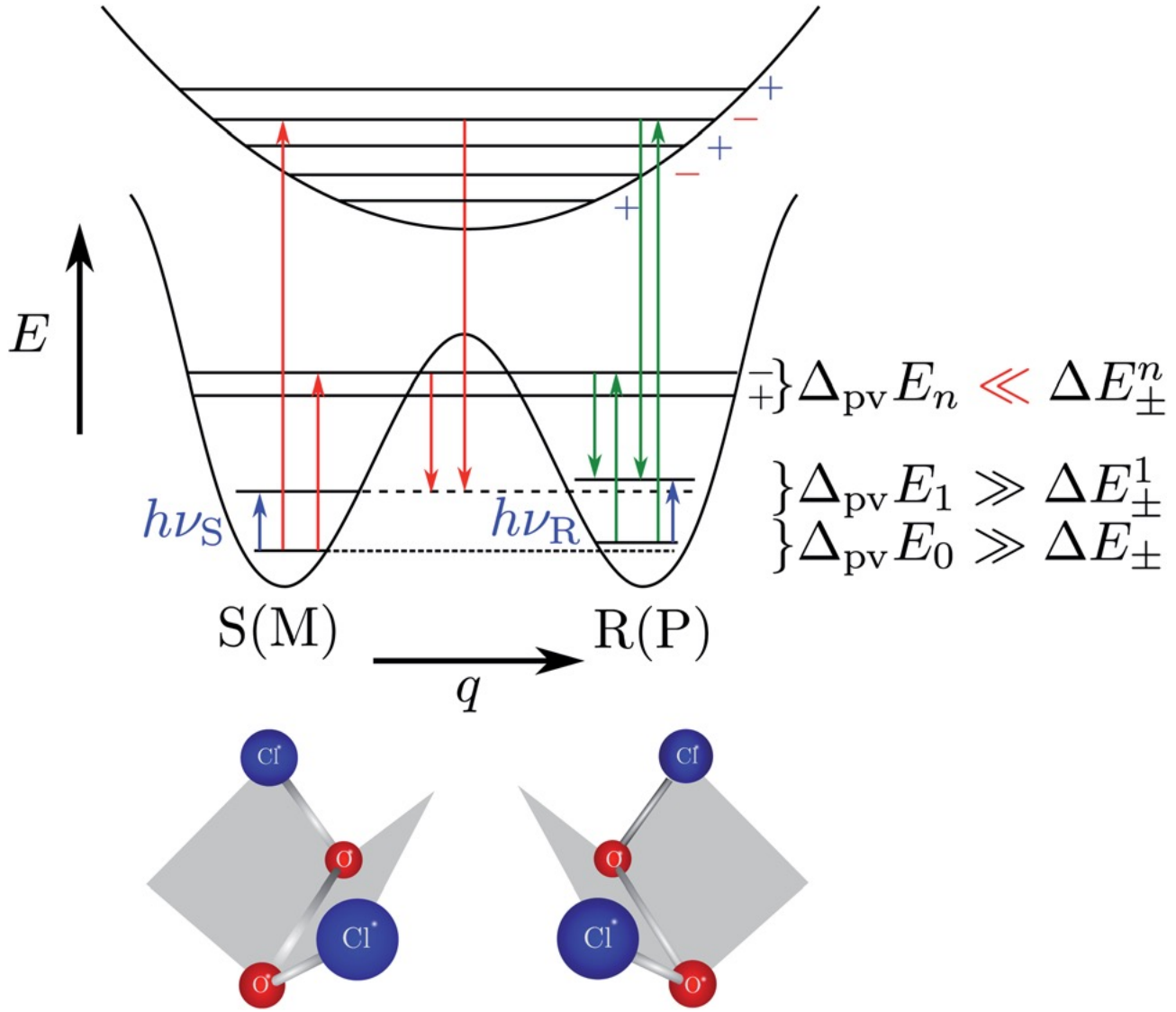
- Torsion of X_2Y_2 (here S_2Cl_2)
- E_{pot} even
- E_{PV} odd



Quack, Seyfang, Wichmann, Chem. Sci., 2022, 13, 10598 (2022)

PV in molecules

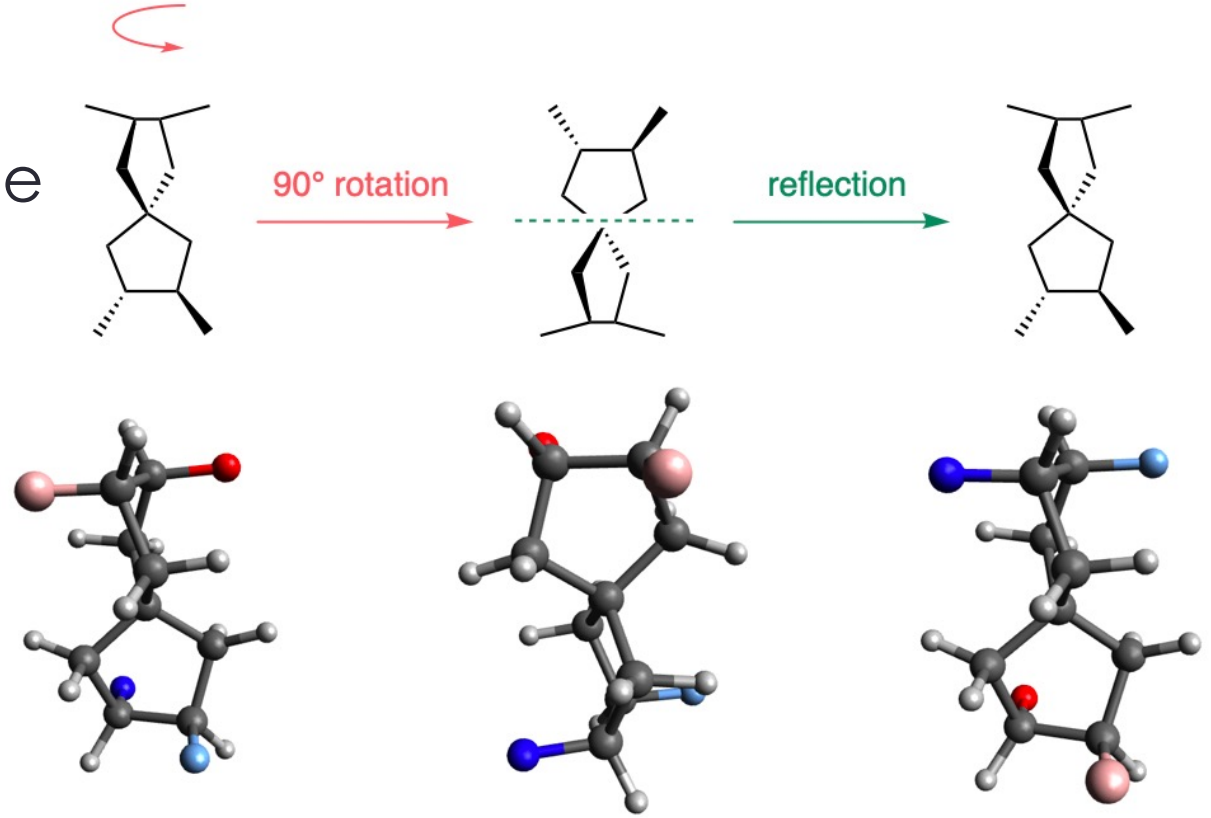
- PV measurement schemes
  - direct vibrational
  - via electronically excited state

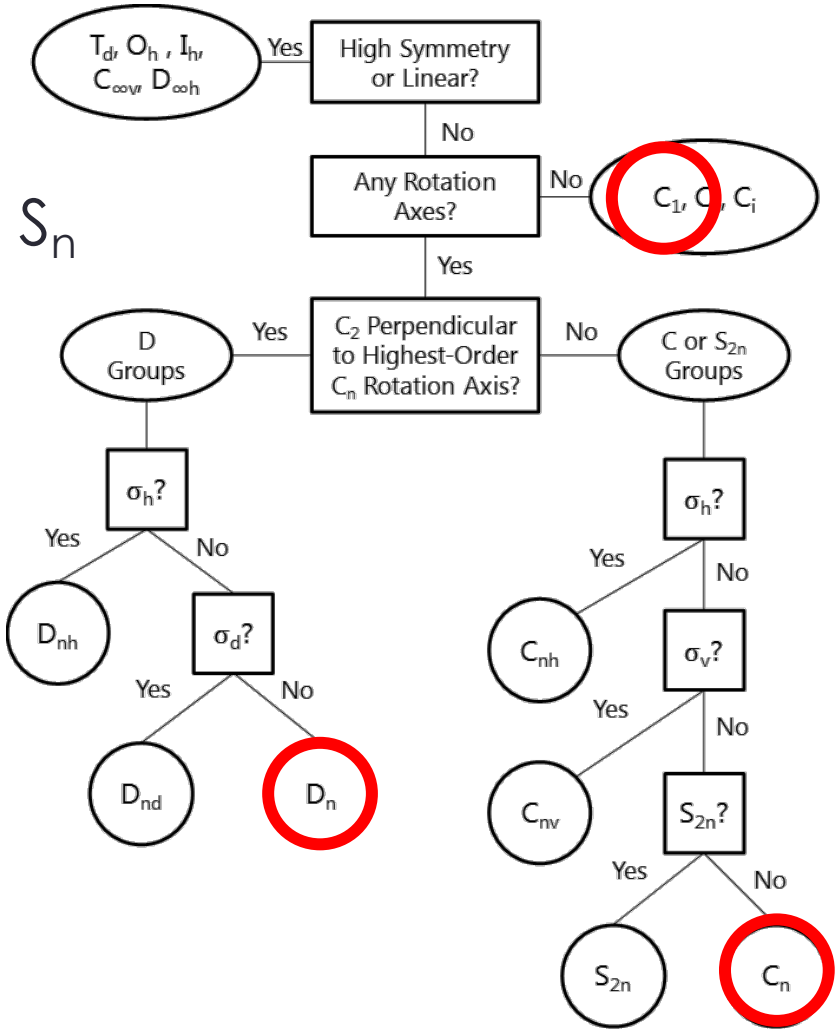


Quack, Seyfang, Wichmann, Chem. Sci., 2022, 13, 10598 (2022)

Molecular chirality

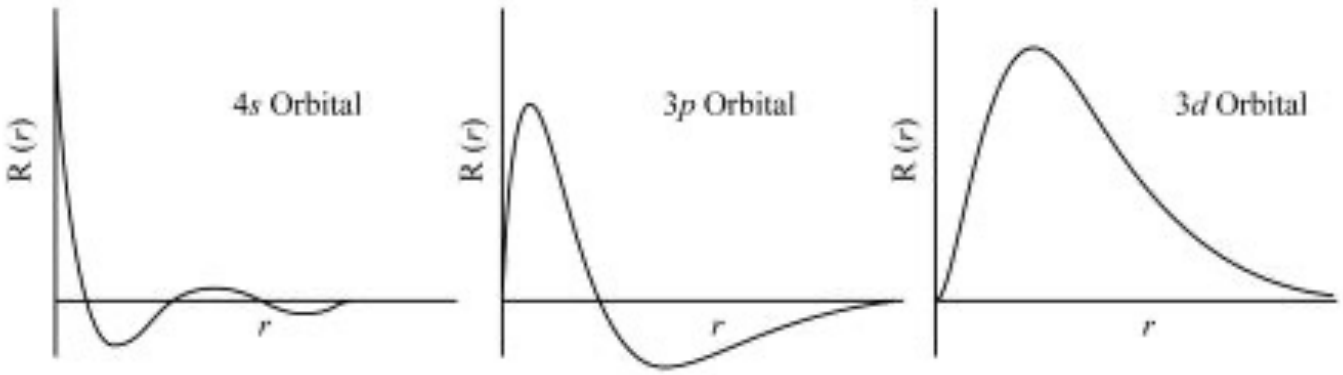
- General definition – lack of improper rotation axis S_n
- $S_1 = i$, $S_2 = \sigma$
- S_4 example





Some trends

- H_2Po_2 PV matrix elements
  - PN vs FN model
  - core vs valence contributions
  - $s_{1/2}$ | $p_{1/2}$ vs $p_{3/2}$ | $d_{3/2}$

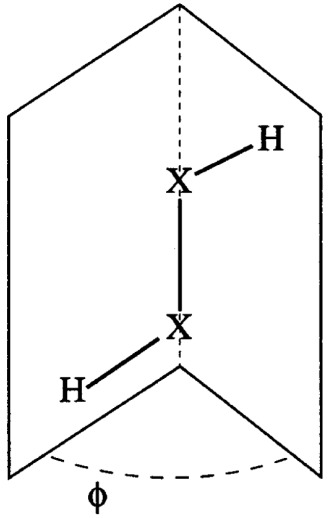


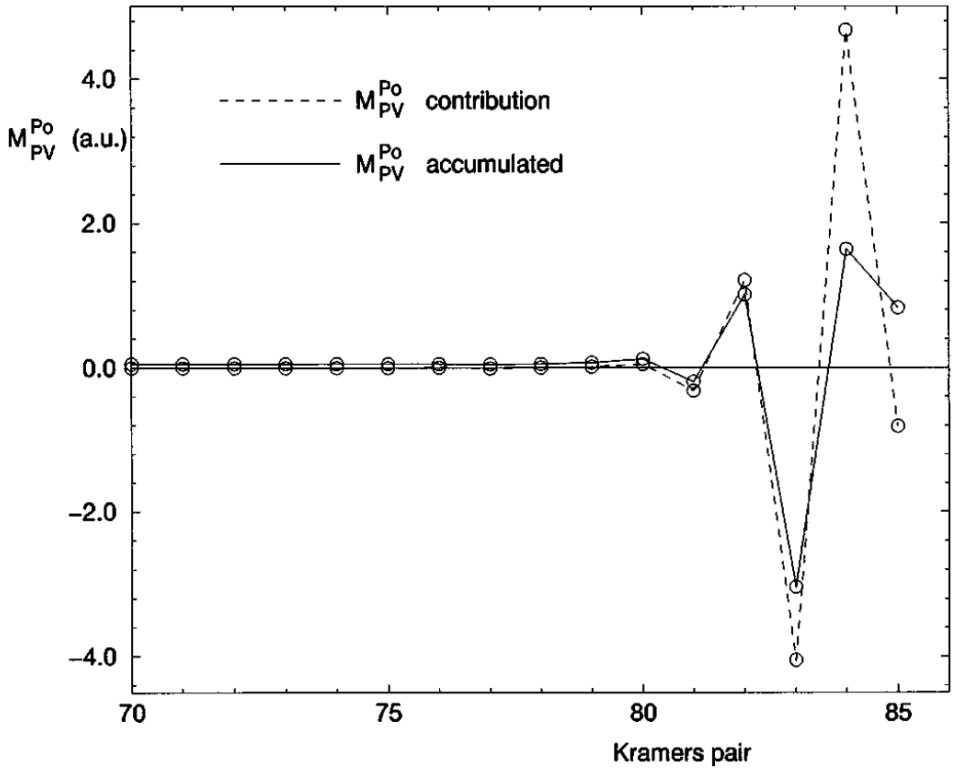
	$2p_{1/2}$	$3p_{1/2}$	$4p_{1/2}$	$5p_{1/2}$	$6p_{1/2}$
$1s_{1/2}$	1.385[+5]	–7.082[+4]	3.583[+4]	1.573[+4]	–4.904[+3]
	(1.551[+5])	(–7.942[+4])	(4.018[+4])	(1.764[+4])	(–5.499[+3])
$2s_{1/2}$	5.486[+4]	–2.806[+4]	1.419[+4]	6.233[+3]	–1.943[+3]
	(6.148[+4])	(–3.148[+4])	(1.593[+4])	(6.992[+3])	(–2.180[+3])
$3s_{1/2}$	–2.646[+4]	1.354[+4]	–6.847[+3]	–3.007[+3]	9.372[+2]
	(–2.966[+4])	(1.519[+4])	(–7.683[+3])	(–3.373[+3])	(1.051[+3])
$4s_{1/2}$	1.345[+4]	–6.881[+3]	3.481[+3]	1.529[+3]	–4.765[+2]
	(1.508[+4])	(–7.720[+3])	(3.906[+3])	(1.715[+3])	(–5.346[+2])
$5s_{1/2}$	–6.182[+3]	3.162[+3]	–1.600[+3]	–7.024[+2]	2.190[+2]
	(–6.929[+3])	(3.548[+3])	(–1.795[+3])	(–7.881[+2])	(2.457[+2])
$6s_{1/2}$	2.260[+3]	–1.156[+3]	5.849[+2]	2.568[+2]	–8.006[+1]
	(2.534[+3])	(–1.297[+3])	(6.562[+2])	(2.881[+2])	(–8.982[+1])

Bast et al., Phys. Chem. Chem. Phys. 13, 864 (2011)

Some trends

- H_2Po_2 at 45°





- s/p mixing

$$\begin{bmatrix} \psi_+ \\ \psi_- \end{bmatrix} = \begin{bmatrix} \cos\theta & e^{i\phi}\sin\theta \\ -e^{-i\phi}\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} s^X_{1/2} \\ p^X_{1/2} \end{bmatrix}; \quad \theta \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$$

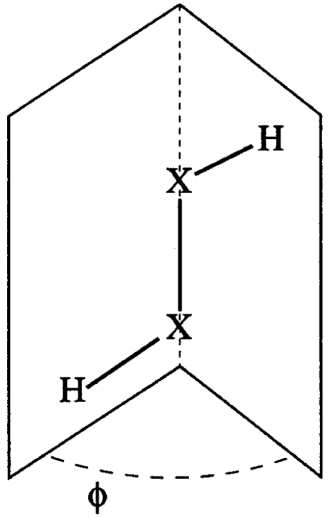
$$\langle\psi_+|\gamma_5\rho^X|\psi_+\rangle = 2\cos\theta\cos\phi\sin\theta\langle s^X_{1/2}|\gamma_5\rho^X|p^X_{1/2}\rangle = -\langle\psi_-|\gamma_5\rho^X|\psi_-\rangle$$

- spherically symmetric core MOs ⇒ ψ_- and ψ_+ contribute equally ⇒ core cancellation

Bast et al., Phys. Chem. Chem. Phys. 13, 864 (2011)
Laerdahl, Schwerdtfeger, PRA 60, 4439 (1999)

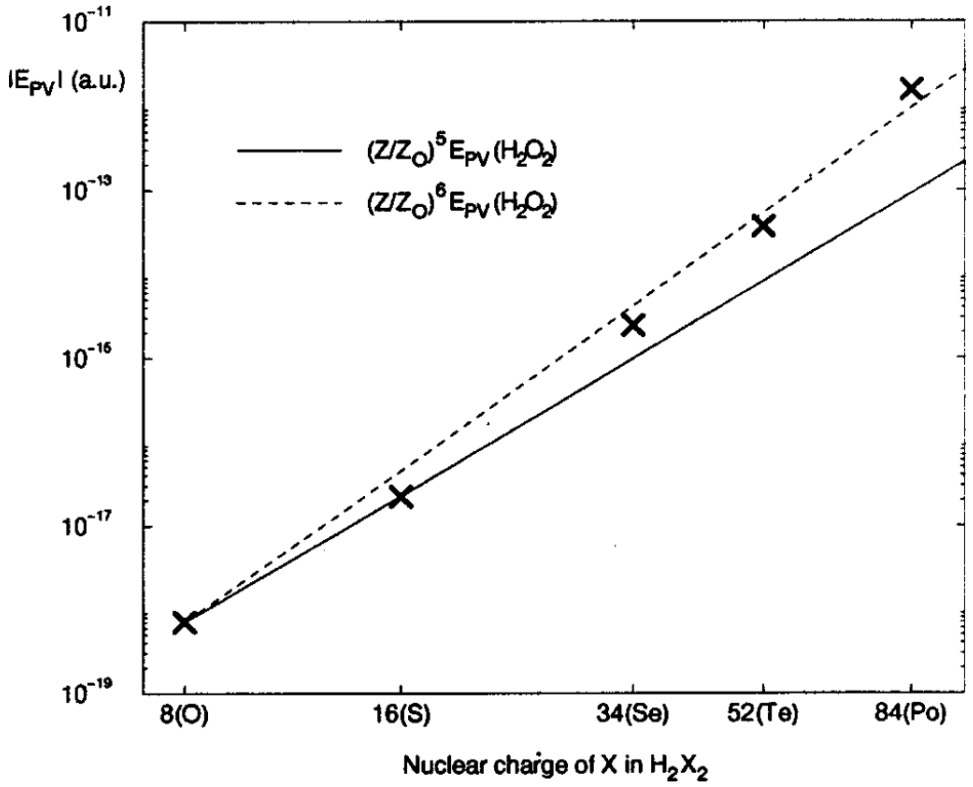
Some trends

- H_2X_2
- Z^5 scaling
- 1c-RSPT2



$$E_{\mathrm{pv}} = 2\,\mathrm{Re}\left\{ \sum_j \frac{\langle 0|\hat{H}_{\mathrm{pv}}|\Psi_j\rangle\langle\Psi_j|\hat{H}_{\mathrm{SO}}|0\rangle}{E_0 - E_j} \right\}$$

$\sim Z^2\alpha N$
$\sim Z^2\alpha Q_{\mathrm{w}}$
$\sim (Z\alpha)^2$



H_2X_2	M^X_{PV} (a.u.)	$M^{\mathrm{H}}_{\mathrm{PV}}$ (a.u.)	N	$Q_{W,X}$	E_{PV} (a.u.)
H_2O_2	6.057×10^{-6}	9.5×10^{-9}	8	-7.421	-7.06×10^{-19}
H_2S_2	9.581×10^{-5}	9.1×10^{-8}	16	-14.84	-2.24×10^{-17}
H_2Se_2	3.586×10^{-3}	2.1×10^{-7}	46	-43.54	-2.45×10^{-15}
H_2Te_2	3.149×10^{-2}	3.7×10^{-7}	78	-74.24	-3.67×10^{-14}
H_2Po_2	8.279×10^{-1}	3.2×10^{-7}	125	-118.9	-1.55×10^{-12}

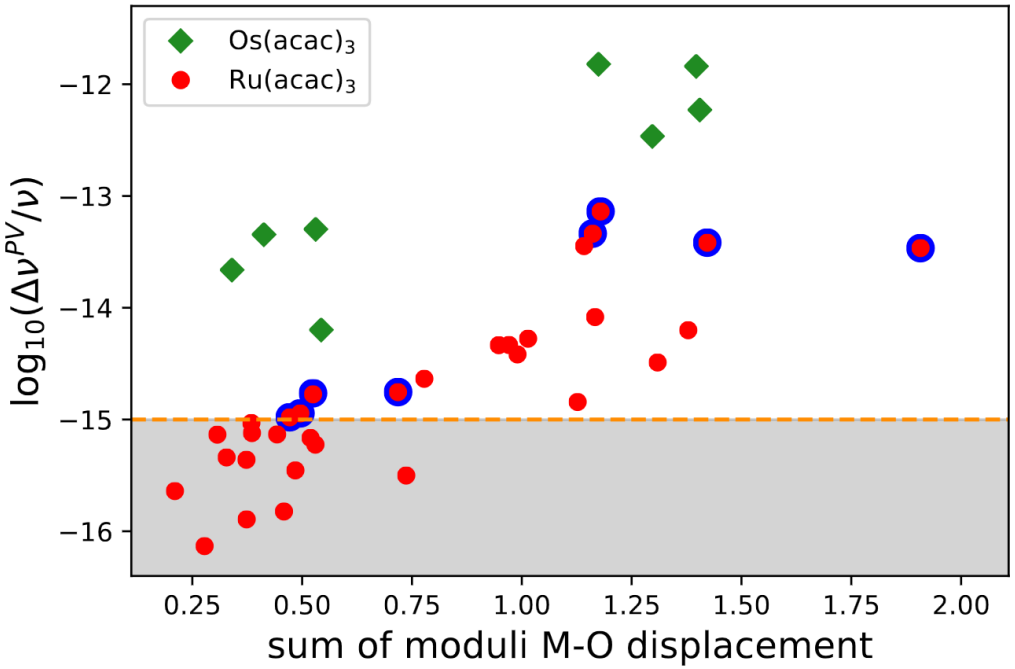
Bouchiat[2], PRB 48, 111 (1974)
Harris, Stodolsky, PRB 78, 313 (1978)
Hegstrom, Rein, Sandars, JCP 73, 2329 (1980)
Laerdahl, Schwerdtfeger, PRA 60, 4439 (1999)

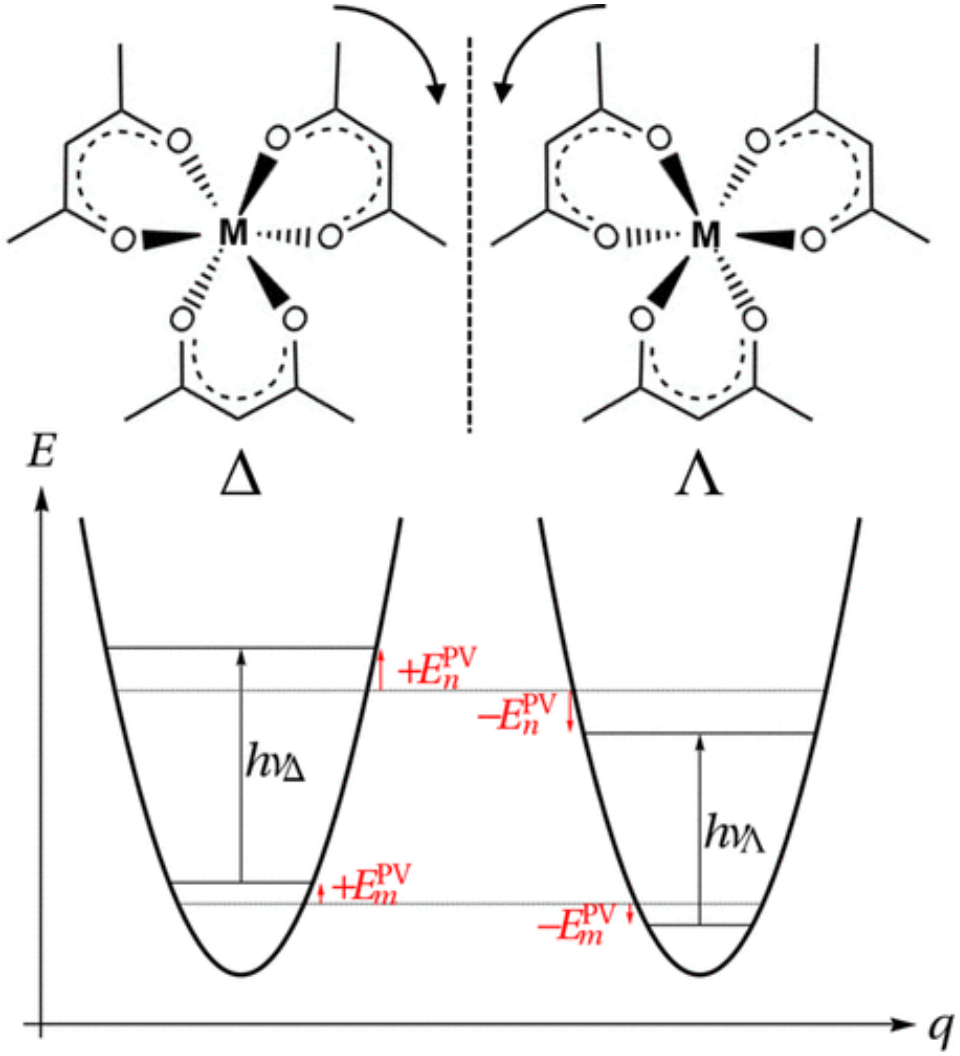
Experiments under construction

PI		Type	Target species	Projected accuracy
	Benoît Darquié, LPL Paris	beam	neutral	0.1 Hz
	David Leibrandt, UCLA	trap	cation	1 Hz
	Yuval Shagam, Technion, Israel	trap	cation	1 Hz

$M(acac)_3$ propellers

- M = Ru, Os, Ir
- methodology tests
- beyond Z^5

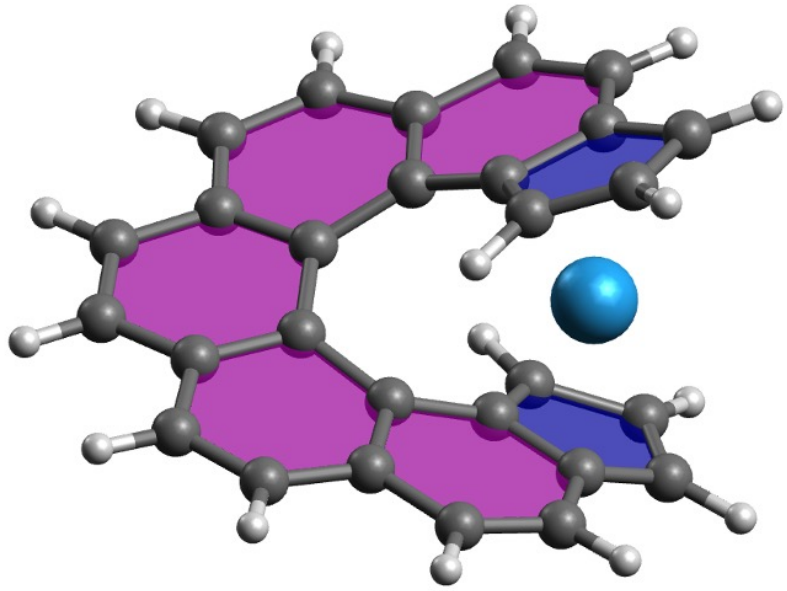




Fiechter et al., J. Phys. Chem. Lett. 13, 10011(2022)

Metalohelicenes

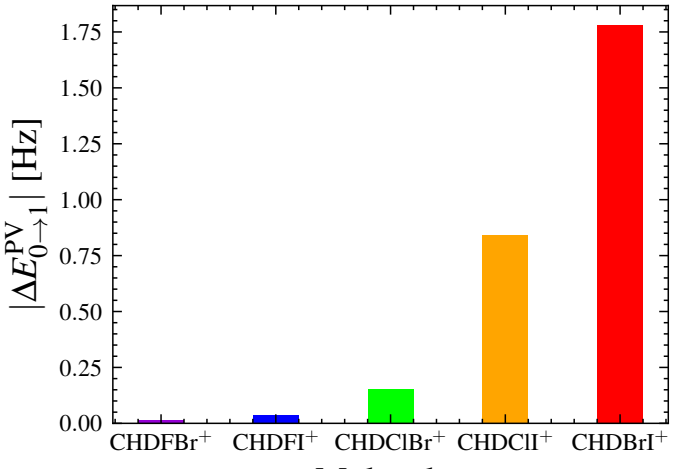
- organometallic complexes
- helical ferocene known
- Ru/Os analogues need to be synthesised
- shifts up to 3Hz

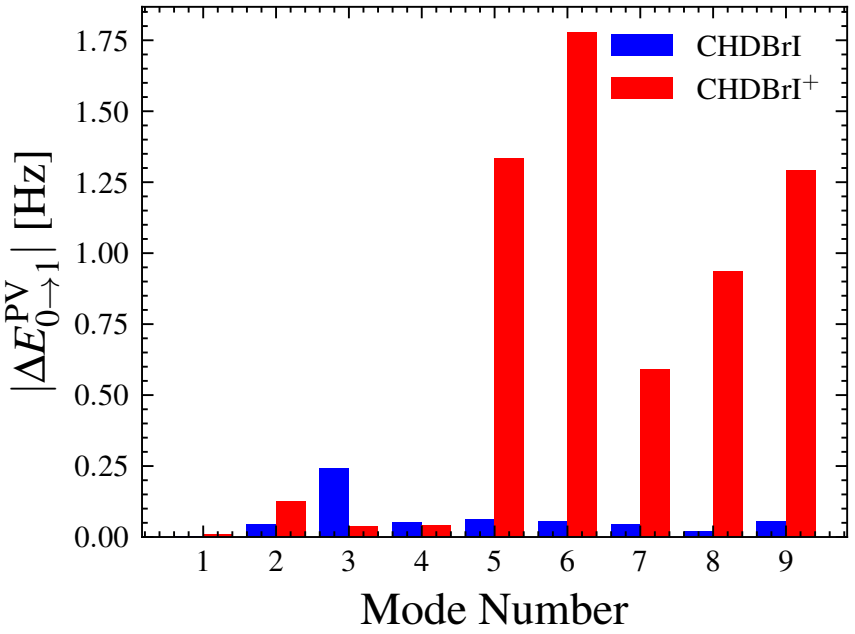


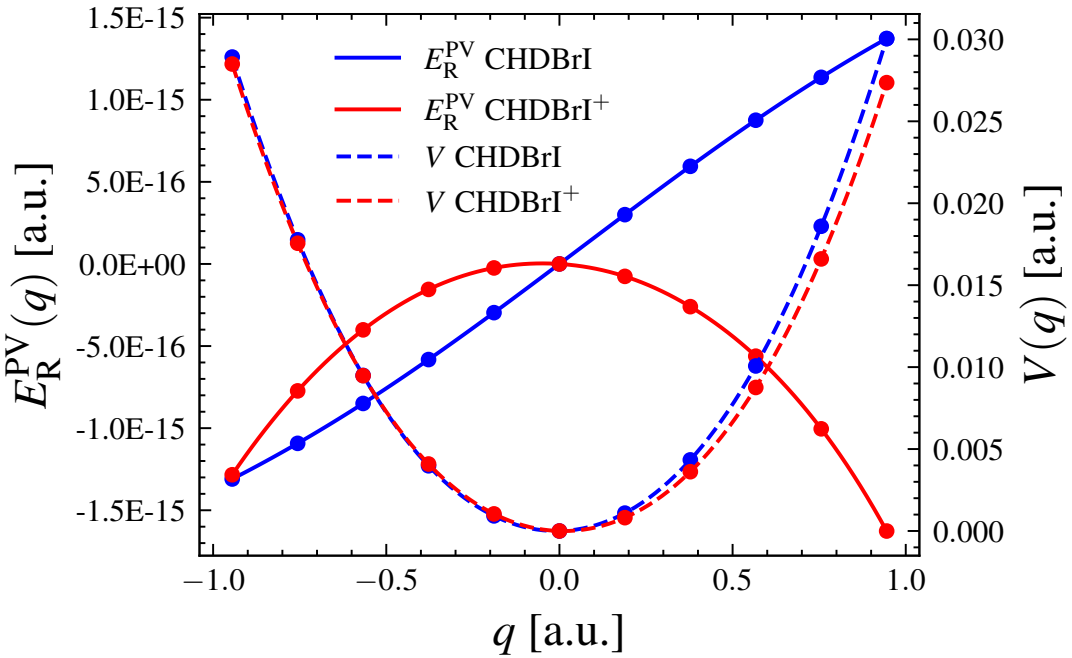
Eduardus et al., in prep (2024)

Isotopically chiral ions

- $CHDBrI^+$
- amplification





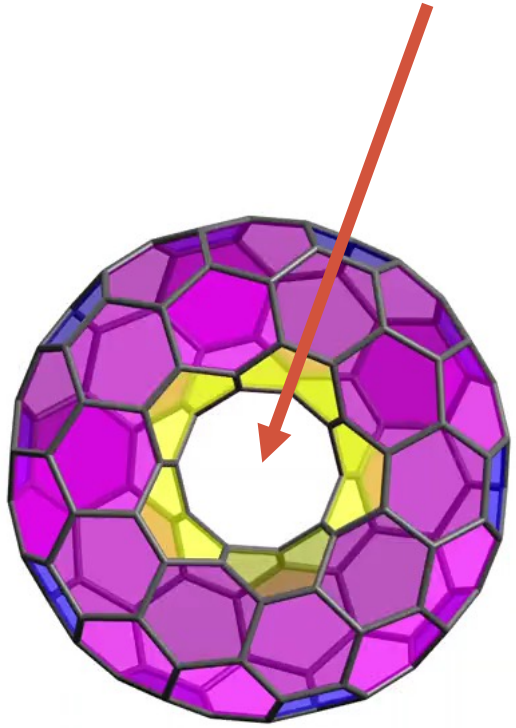


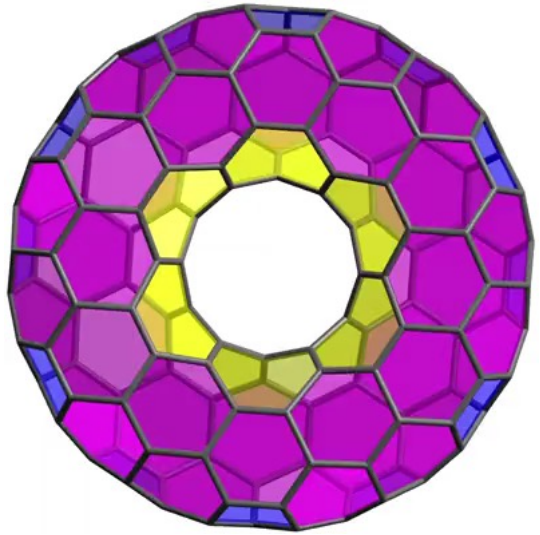
$$\Delta P_{0\to1} = 2(P_1 - P_0) \approx \frac{\hbar}{\mu\omega_e}\left[P^{[2]} - \frac{1}{\mu\omega_e^2}P^{[1]}V^{[3]}\right]$$

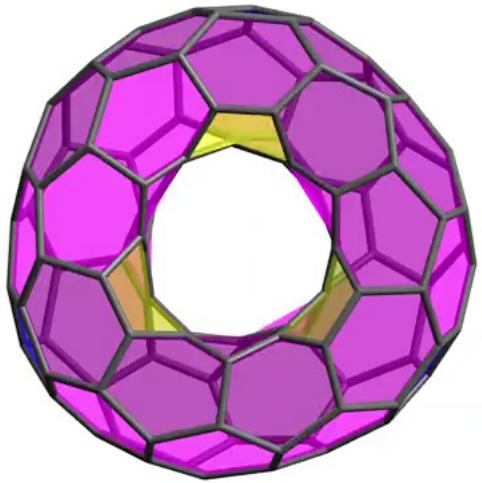
Eduardus et al., Chem. Comm. 59, 14579 (2023)

Carbon nanotoroids

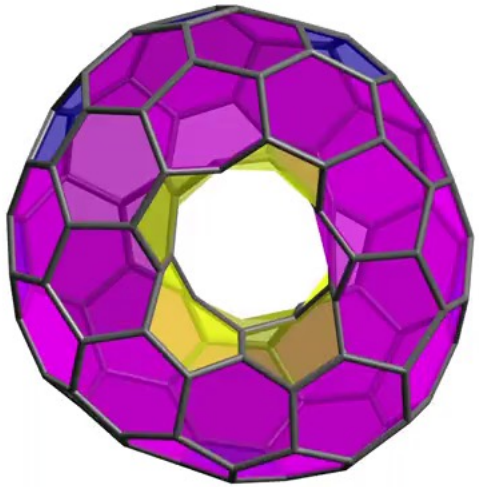
- carbon allotropes - fullerenes, nanotubes, nanotori
- complex with metals



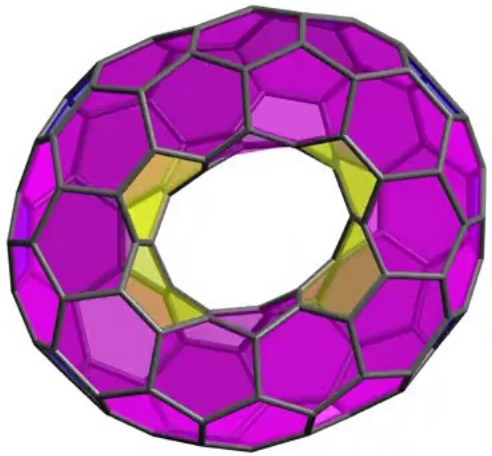




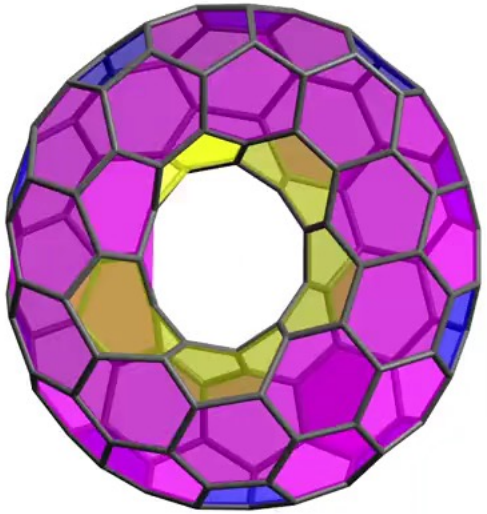
D_3



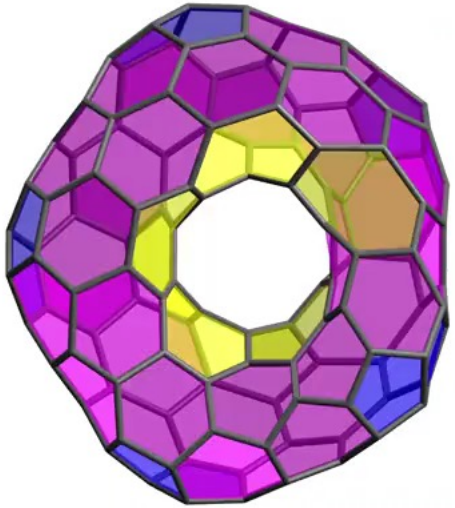
C_2



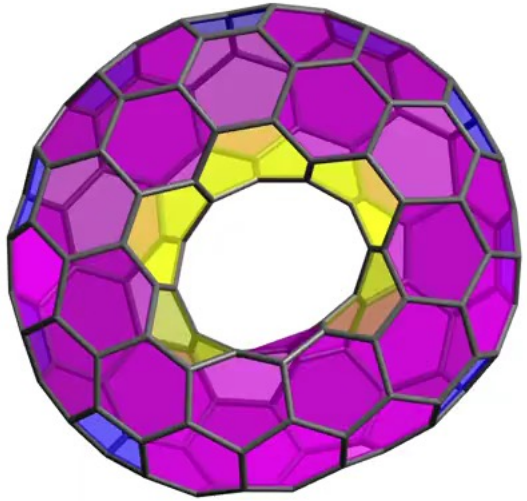
D_2



C_2



C_2

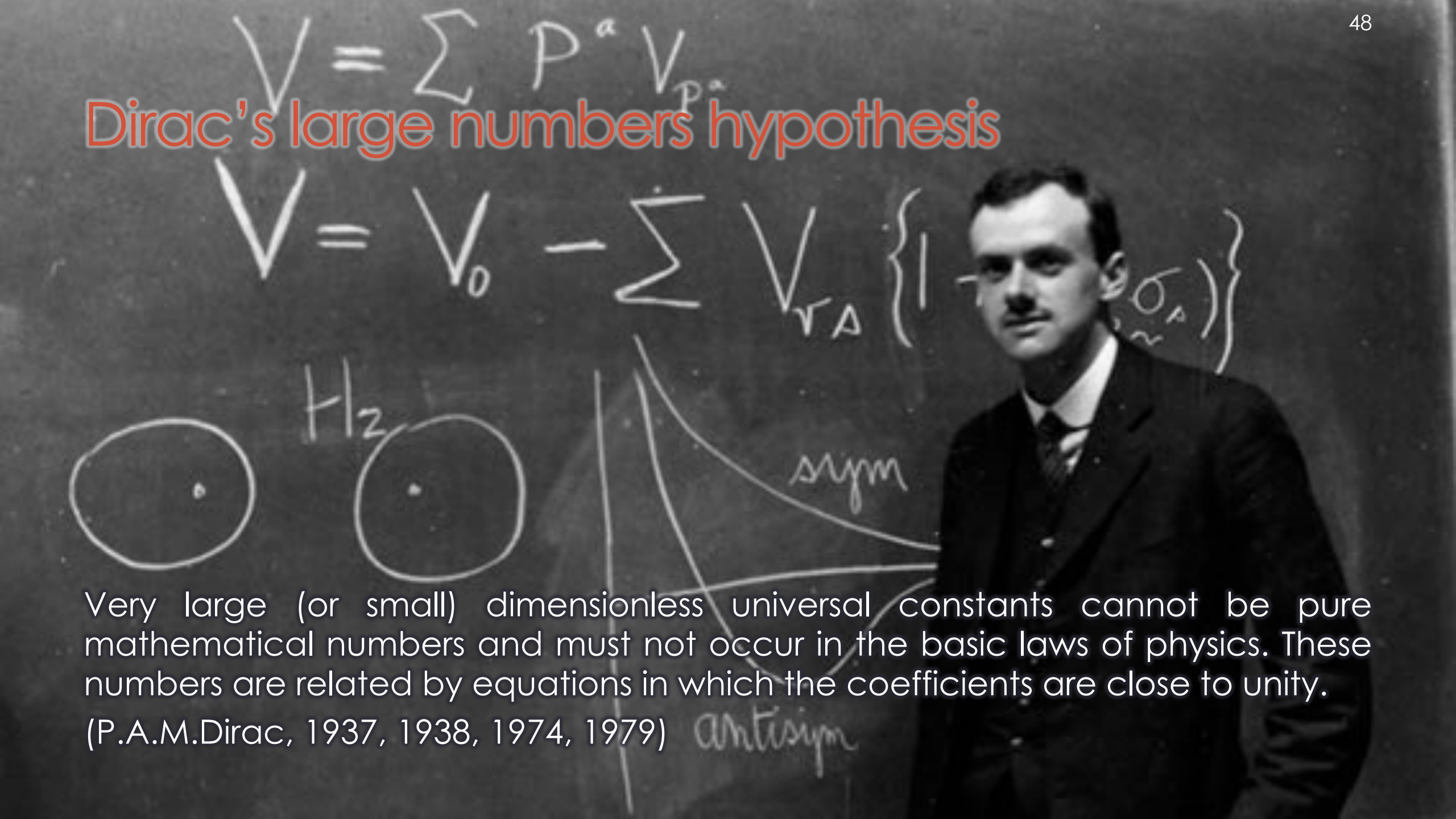


C_2

Searching for variation of fundamental constants

(with molecules and solids)

Dirac's large numbers hypothesis



Very large (or small) dimensionless universal constants cannot be pure mathematical numbers and must not occur in the basic laws of physics. These numbers are related by equations in which the coefficients are close to unity.

(P.A.M.Dirac, 1937, 1938, 1974, 1979)

Dirac's large number hypothesis

- ratio of EM and gravitational force (in H):

$$F_{em}/F_g = e^2/4\pi\varepsilon_0 G m_e m_p = 2.27 \times 10^{39}$$

- age of the universe in units of fundamental constants:

$$t_{universe} \approx 13.7 \times 10^9 \text{ years} = 5.12 \times 10^{39}\ e^2/4\pi\varepsilon_0 m_e c^3$$

- Coincidence or $F_{em}/F_g \sim t_{universe}$?

$G = 6.67384 \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2}$	$e = 1.602176634 \times 10^{-19}\ C$
$m_e = 9.10938291 \times 10^{-31}\ kg$	$m_p = 1.67262178 \times 10^{-27}\ kg$
$c = 2.99792458 \times 10^8\ m/s$	$k_e = 1/4\pi\varepsilon_0 = 8.98755179 \times 10^9\ N\ m^2\ C^{-2}$

Dirac's large number hypothesis

Physical Constants Involved	Large Numbers
1. Electrostatic force F_E and gravitational force F_G between a proton and an electron	$F_E/F_G \simeq 10^{40}$
2. Radius of the universe R and the radius of an electron r	$R/r \simeq 10^{40}$
3. Intensity of electromagnetic and gravitational interaction of elementary particles	$\frac{e^2/\bar{h}c}{Gm_e{}^2/\bar{h}c} \simeq 10^{40}$
4. Mass of a typical star $M_\star$ and electron mass m_e	$M_\star/m_e \simeq 10^{60} = (10^{40})^{3/2}$
5. Mass of the universe M_U and proton mass m_p	$M_U/m_p \simeq 10^{80} = (10^{40})^2$
6. Mass of the universe M_U and Planck mass m_P	$M_U/m_P \simeq 10^{61}$
7. Hubble radius R_H and Planck length l_P	$R_H/l_P \simeq 10^{60}$
8. Planck mass density ρ_P and the observed matter density of the universe ρ	$\rho_P/\rho \simeq 10^{120} = N_1{}^{1/3}$
9. Planck energy E_P and CMBR temperature T_γ	$(E_P/T_\gamma)^2 \simeq 10^{60}$

Roy et al., Int. J. Mod. Phys. D 28, 1930014 (2019)

Shortest article ever

The Ratio of Proton and Electron Masses

FRIEDRICH LENZ
Düsseldorf, Germany
(Received April 5, 1951)

THE most exact value at present[1] for the ratio of proton to electron mass is 1836.12 ± 0.05. It may be of interest to note that this number coincides with $6\pi^5 = 1836.12$.

[1] Sommer, Thomas, and Hipple, Phys. Rev. **80**, 487 (1950).

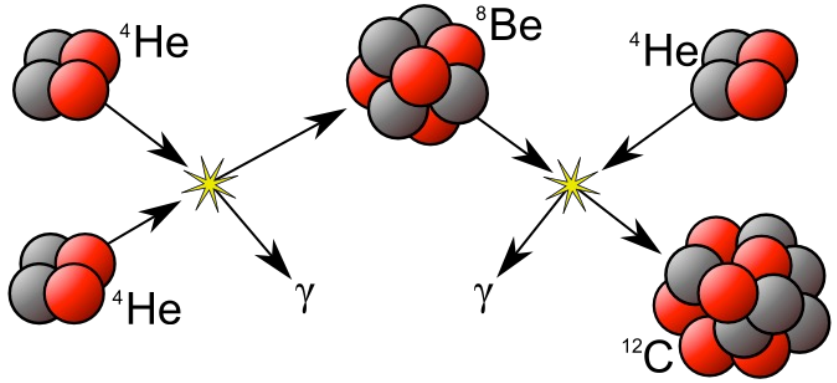
Lenz, Phys. Rev. 82, 554 (1951)

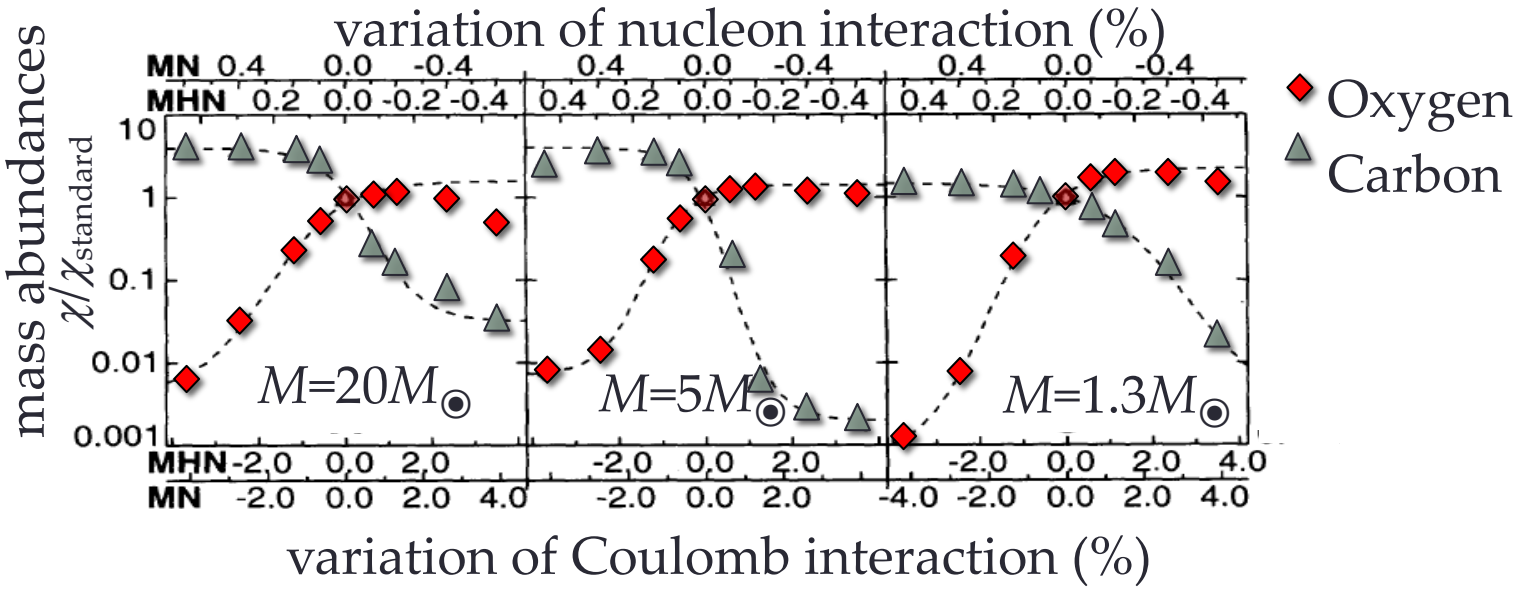
Fine tuning and anthropic principle

- fine-tuning of the fundamental constants is required for life to exist
- observation selection effect/bias

Carbon production

- If α_s varies by 0.5% and α_{EM} by 4%, the stellar production of carbon or oxygen will be reduced by a factor 30–1000





Oberhummer, Csótó, Schlattl, Science 289, 88 (2000)

p^+/n mass difference

- m_n = 939.565378 MeV/c^2, m_p = 938.272046 MeV/c^2
- neutron-proton mass difference Δm = 1.2933 MeV/c^2
- (Λ-QCD 2.52 MeV/c^2 and QED –1.00 MeV/c^2)

- $0.5 < \Delta m < 1.0$ MeV/c^2 → BBN would produce much more ^{4}He and far less H

- $\Delta m < 0.45$ MeV/c^2 → protons would undergo inverse β-decay (electron capture) resulting in predominantly neutrons

- $\Delta m > 1.3$ MeV/c^2 → much faster β-decay for neutrons → far fewer neutrons → difficult synthesis of the heavy elements

Borsanyi et al. Science 347, 1452 (2015)

Variation of fundamental constants

- new physics beyond the Standard Model
- unitless constants
- fine-structure constant $\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c}$
- proton-to-electron mass ratio $\mu = \frac{m_p}{m_e}$

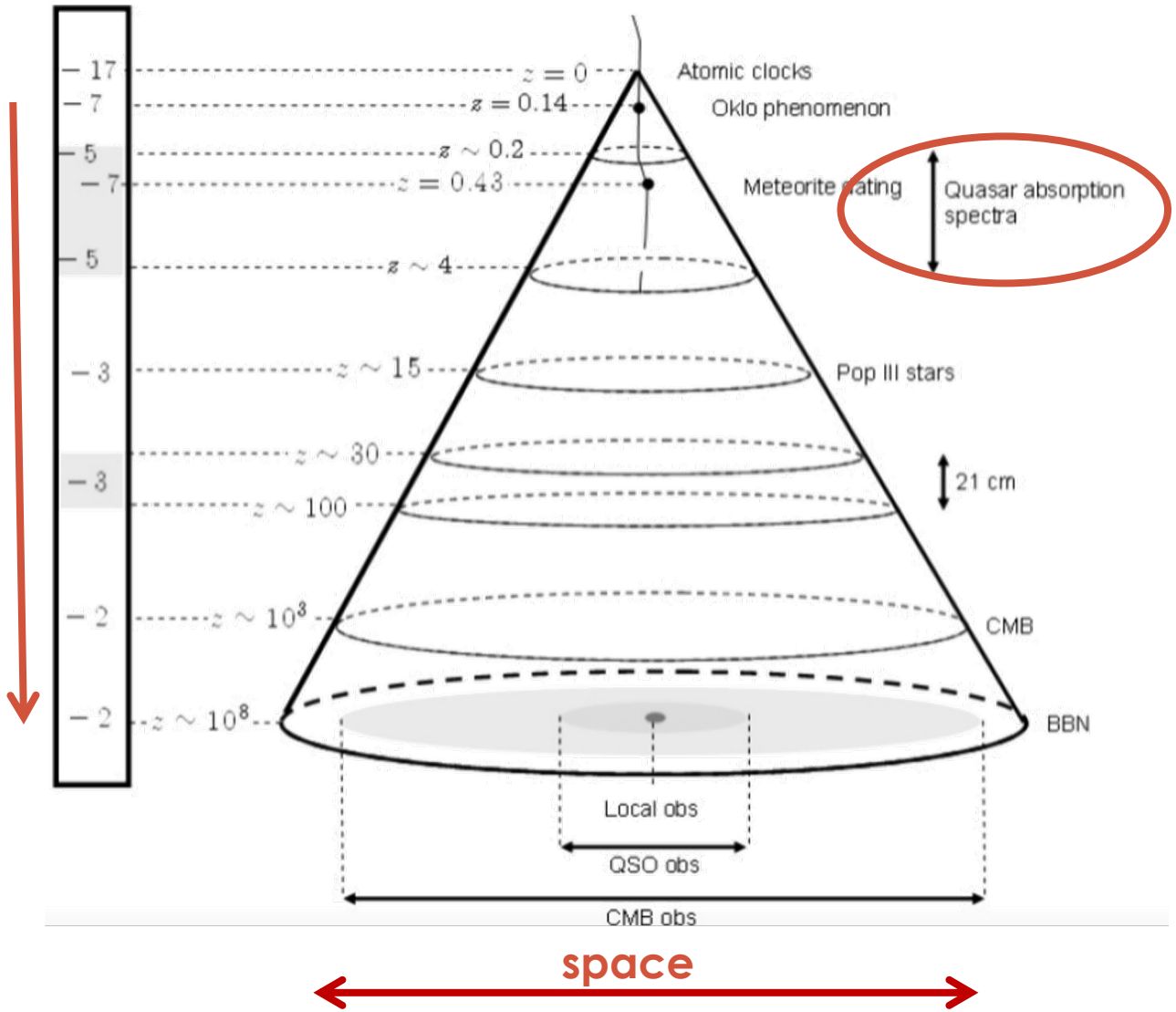
Why α and μ?

- α is the EM coupling constant directly
- μ related to strong coupling constant α_s indirectly
- $\mu \sim m_p \sim \Lambda_{QCD}$ (energy scale)
- α_s running constant (not the same as VFC)
- $$\alpha_s = -\frac{2\pi}{\beta_0 \ln(E/\Lambda_{QCD})}$$

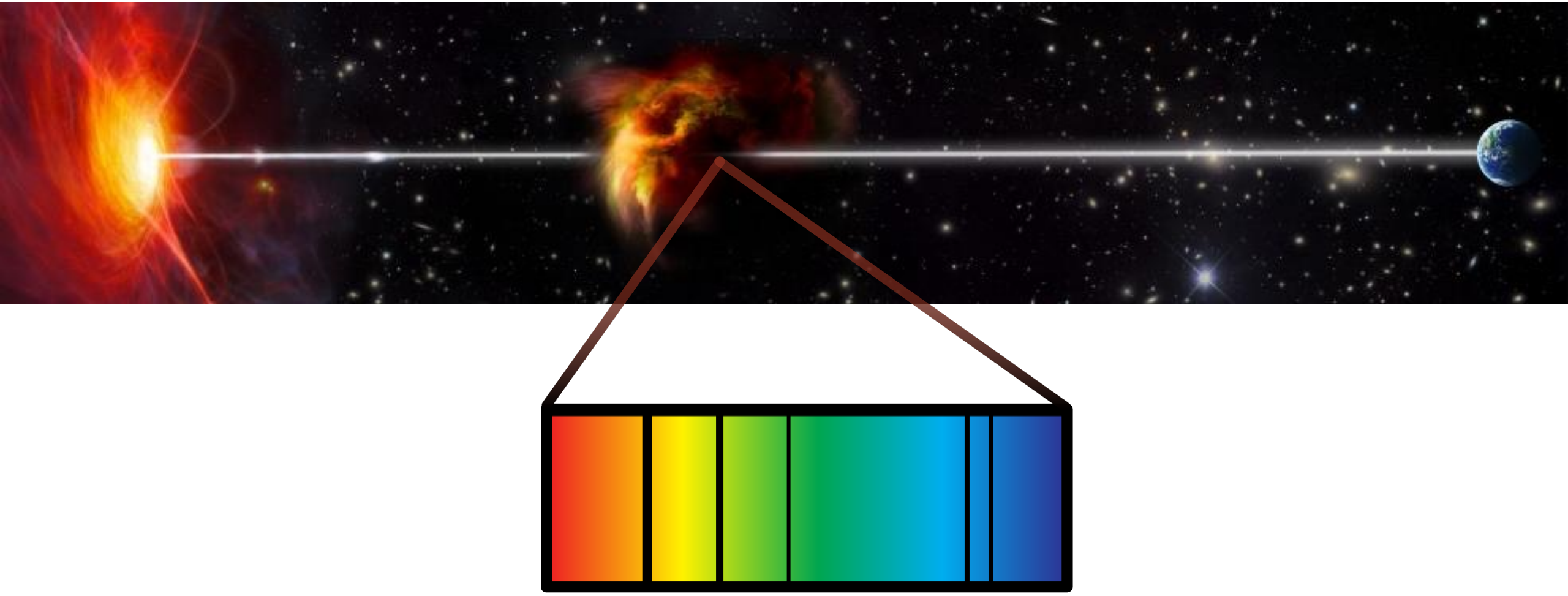
Searching for VFC

$$z = \frac{f_{ref}}{f_{obs}} - 1$$

$$t \approx \frac{ln(z+1)}{H_0} = \frac{ln(\frac{f_{ref}}{f_{obs}})}{H_0}$$

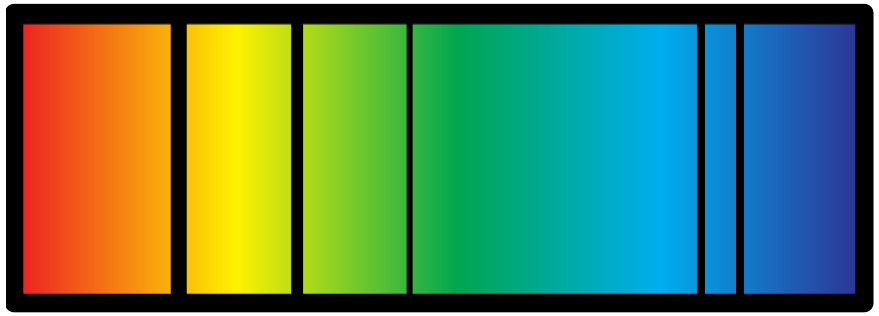


Quasar spectra



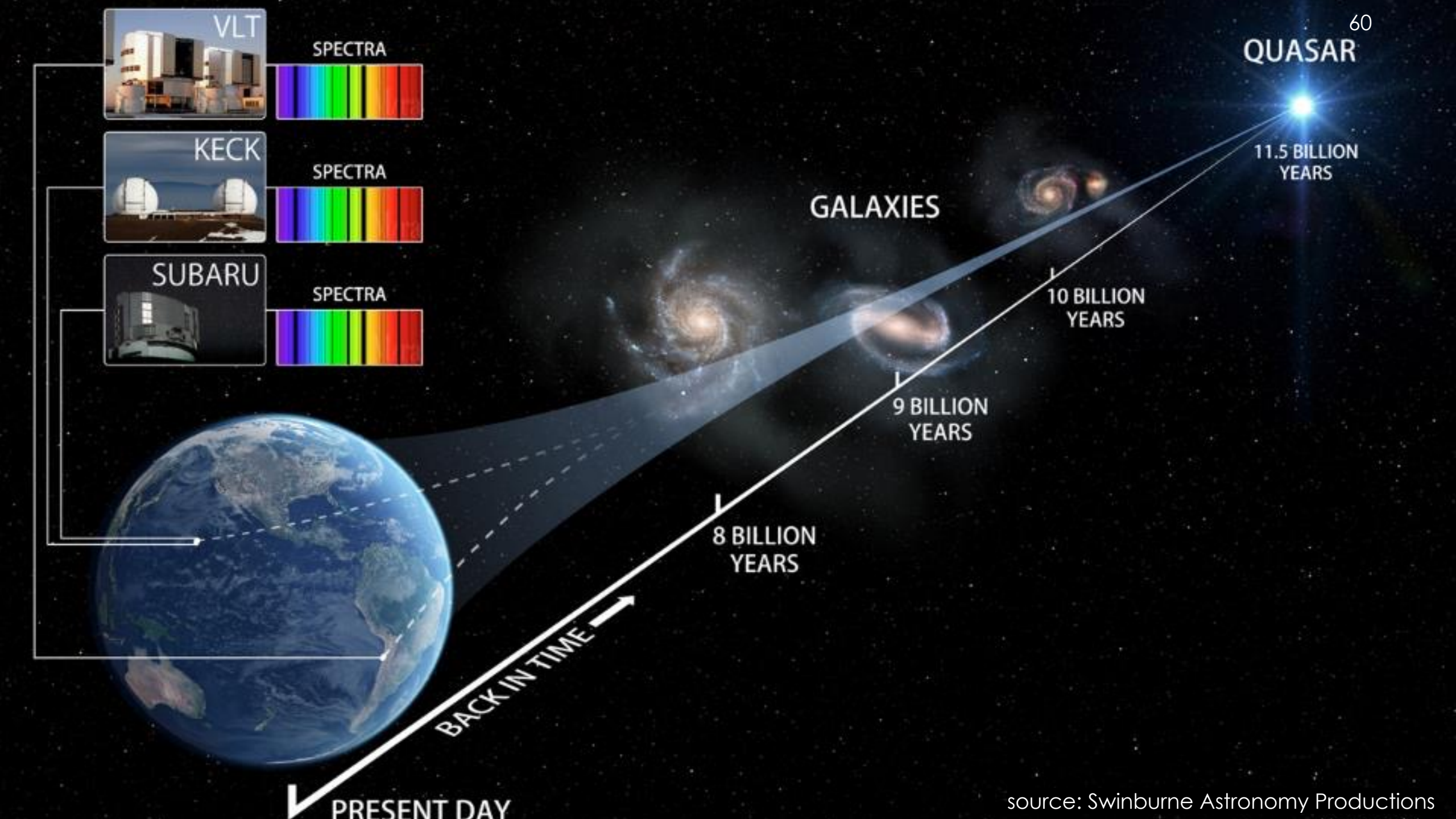
Quasar spectra

quasar



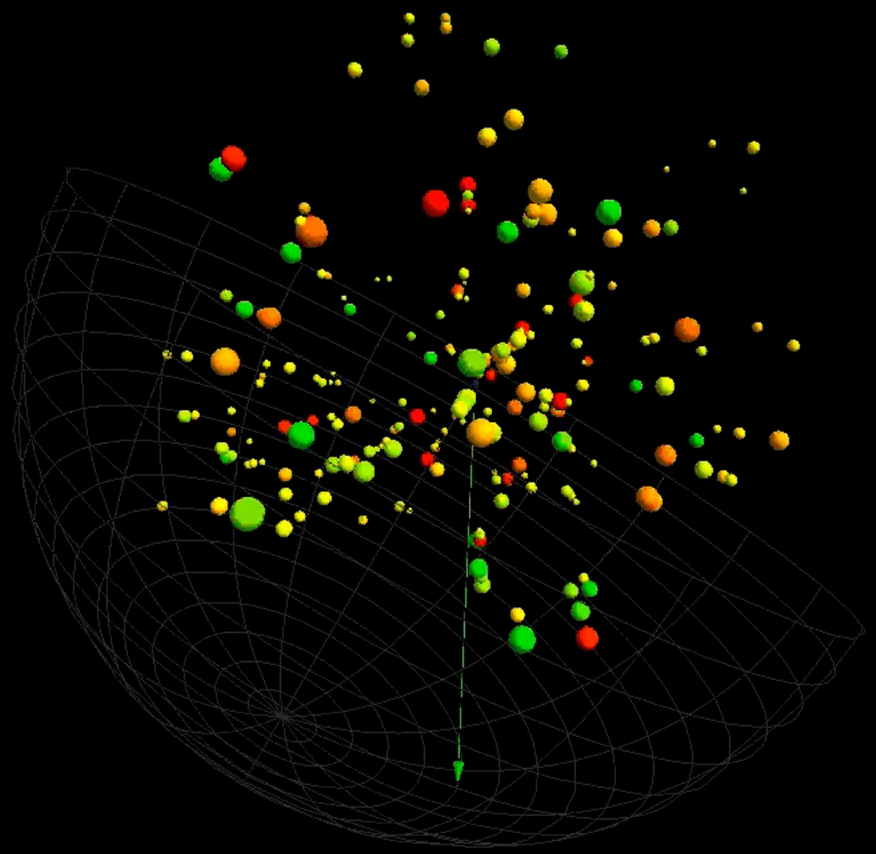
laboratory

α-meter

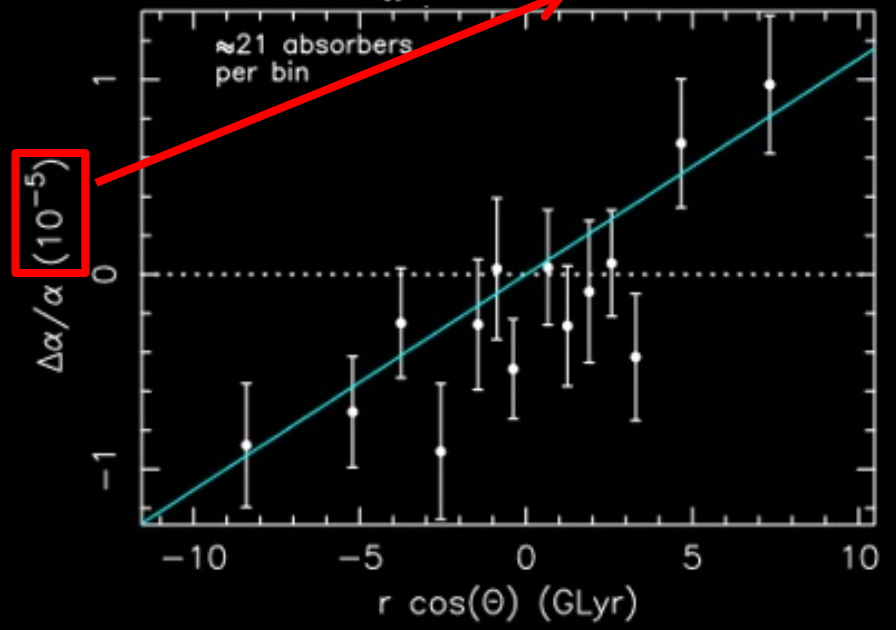


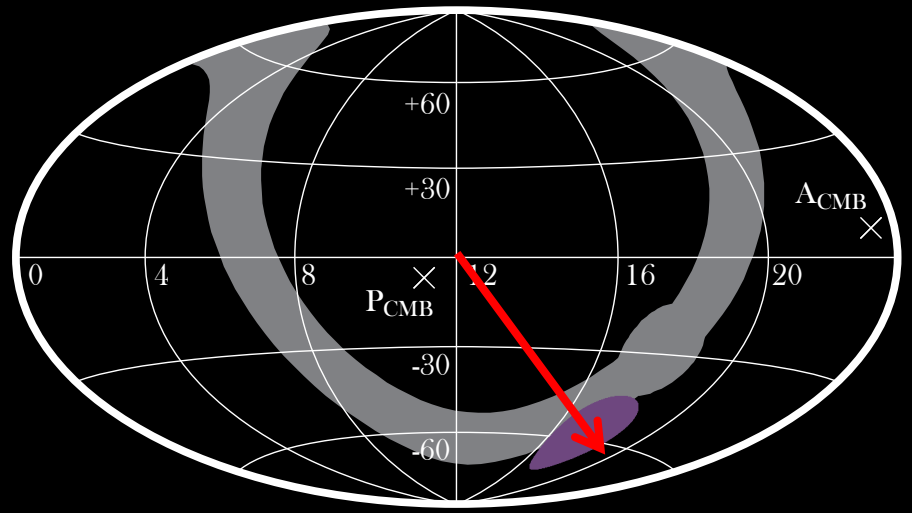
source: Swinburne Astronomy Productions

α-variation



Terrestrial: $\frac{\dot{\alpha}}{\alpha} = 1.35 \times 10^{-18} \cos\theta \; yr^{-1}$





Webb et al. ***PRL*** 107, 191101 (2011); King et al. ***MNRAS*** (2012); Berengut, Flambaum, ***EPL*** 97, 20006 (2012)

Lab vs astro

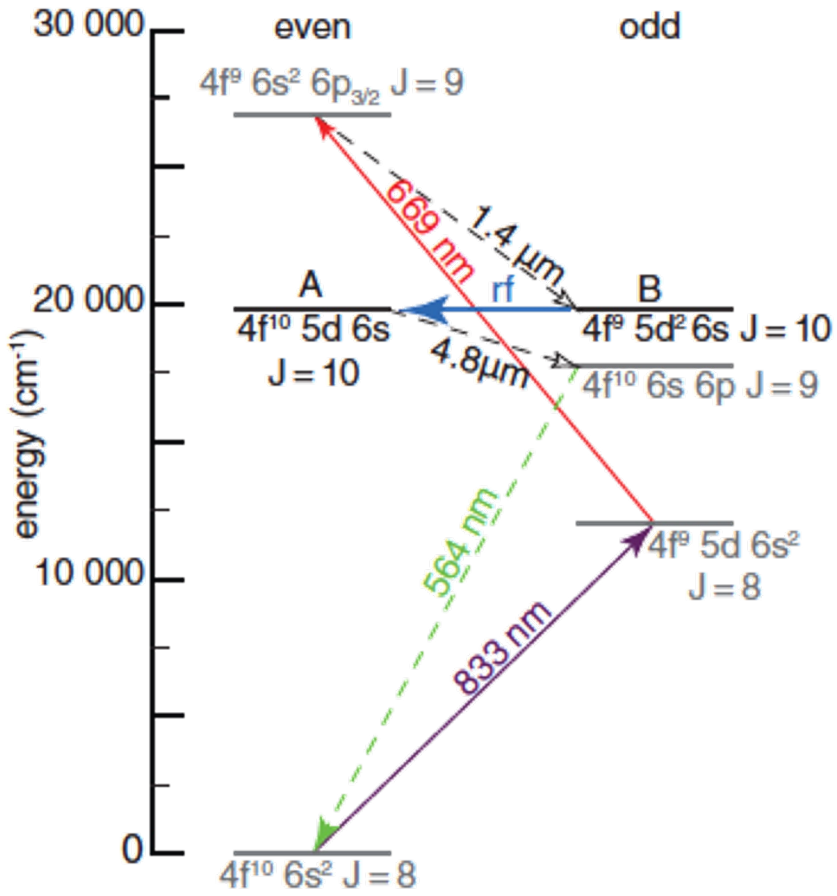
- astronomical experiments
  - large scales
  - low error control
- laboratory (terrestrial) experiments
  - local
  - high accuracy and error control
  - requires
    - very sensitive systems
    - extremely precise measurements

Search for VFC in atomic spectra

- $^{162/164}$Dy transitions
- 2 year-long experiment
- temporal variation

$$\left|\alpha/\alpha\right| = (-5.8 \pm 6.9) \times 10^{-17}\ \mathrm{yr}^{-1}$$

- serves as a constraint only



Leefer, Weber, Cingöz, Torgerson, Budker, PRL 111, 060801 (2013)

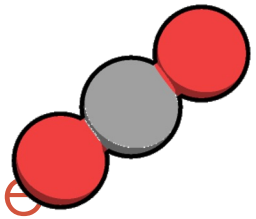
Search for VFC in atomic spectra

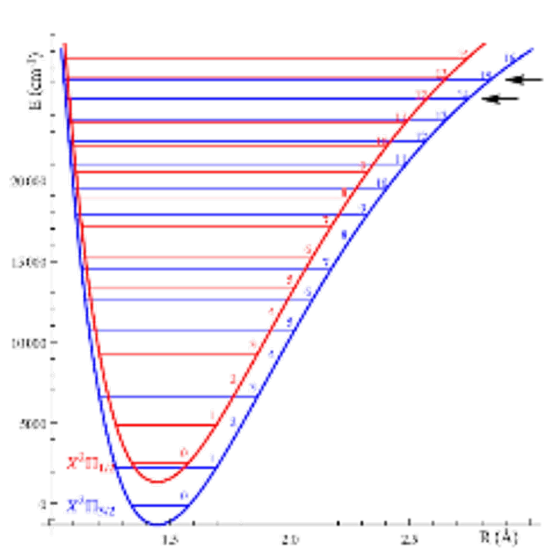
Clock 1	Clock 2 $\frac{\mathrm{d}}{\mathrm{d}t}\ln\left(\frac{\nu_{\text{clock 1}}}{\nu_{\text{clock 2}}}\right)$	Constraint (yr^{-1})
^{87}Rb	^{133}Cs	$(0.2 \pm 7.0) \times 10^{-16}$
^{87}Rb	^{133}Cs	$(-0.5 \pm 5.3) \times 10^{-16}$
^{1}H	^{133}Cs	$(-32 \pm 63) \times 10^{-16}$
^{199}Hg^{+}	^{133}Cs	$(0.2 \pm 7) \times 10^{-15}$
^{199}Hg^{+}	^{133}Cs	$(3.7 \pm 3.9) \times 10^{-16}$
^{171}Yb^{+}	^{133}Cs	$(-1.2 \pm 4.4) \times 10^{-15}$
^{171}Yb^{+}	^{133}Cs	$(-0.78 \pm 1.40) \times 10^{-15}$
^{87}Sr	^{133}Cs	$(-1.0 \pm 1.8) \times 10^{-15}$
^{87}Dy	^{87}Dy	$(-2.7 \pm 2.6) \times 10^{-15}$
^{27}Al^{+}	^{199}Hg^{+}	$(-5.3 \pm 7.9) \times 10^{-17}$

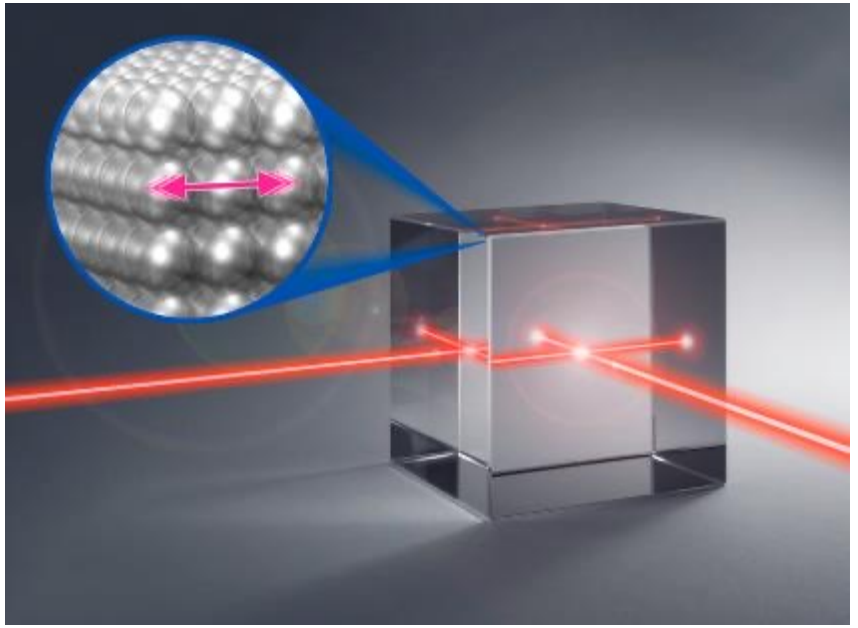
Uzan, Living Rev. Relativity, 14, 2 (2011)

A way out?

- higher sensitivity
  - highly charged or muonic atoms
  - molecular spectroscopy
  - up to 5 orders more sensitive







- higher precision
  - laser interferometry
  - up to 5 orders more precise

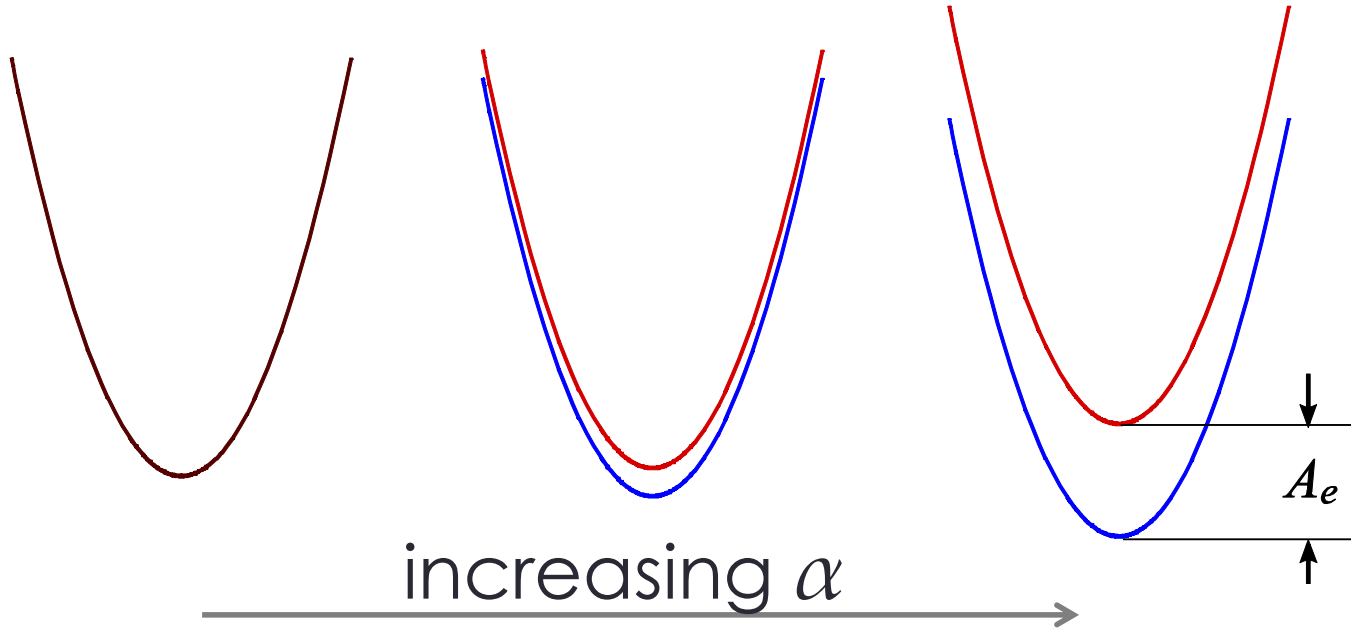
Searching for variation of fundamental constants

(with diatomic molecules)

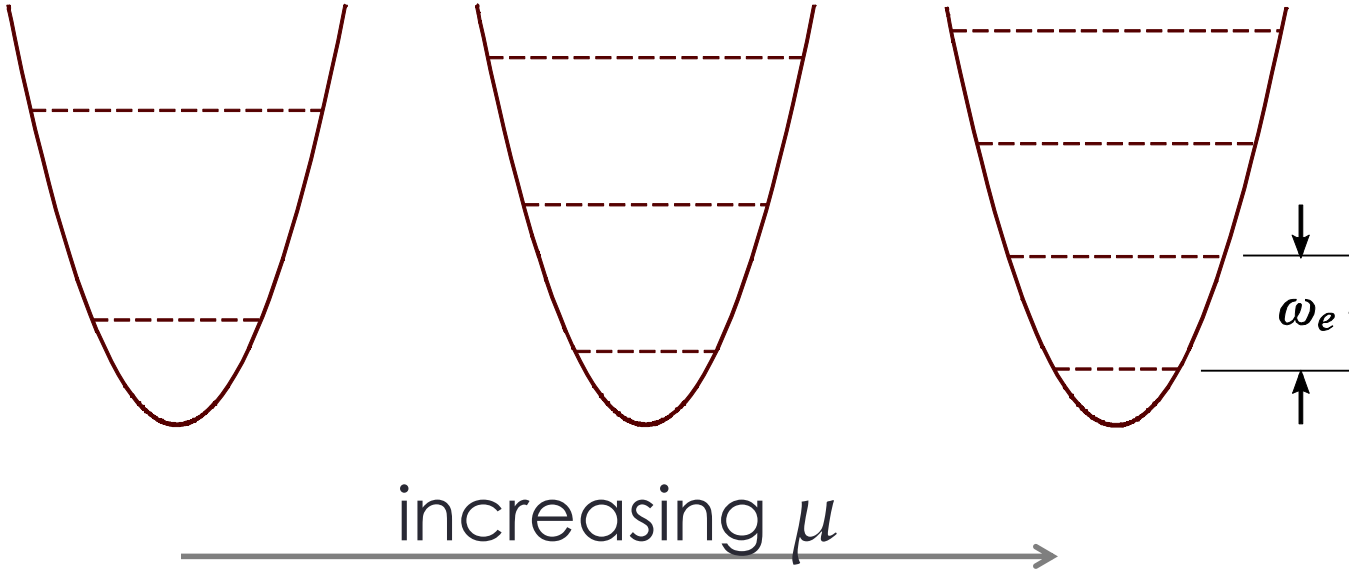
$^2\Pi$ cations

- $X\ ^2\Pi$ cations of dihalogens and hydrogen halides
- cations – trappable
- $^2\Pi$ states split into SO substates $^2\Pi_{1/2}$ and $^2\Pi_{3/2}$
  - strong α-dependence
  - forbidden electronic transitions ($\Delta\Sigma \neq 0$, Laporte) – narrow linewidths
- easily available

Pasteka, Borschevsky, Flambaum, Schwerdtfeger, PRA 92, 012103 (2015)

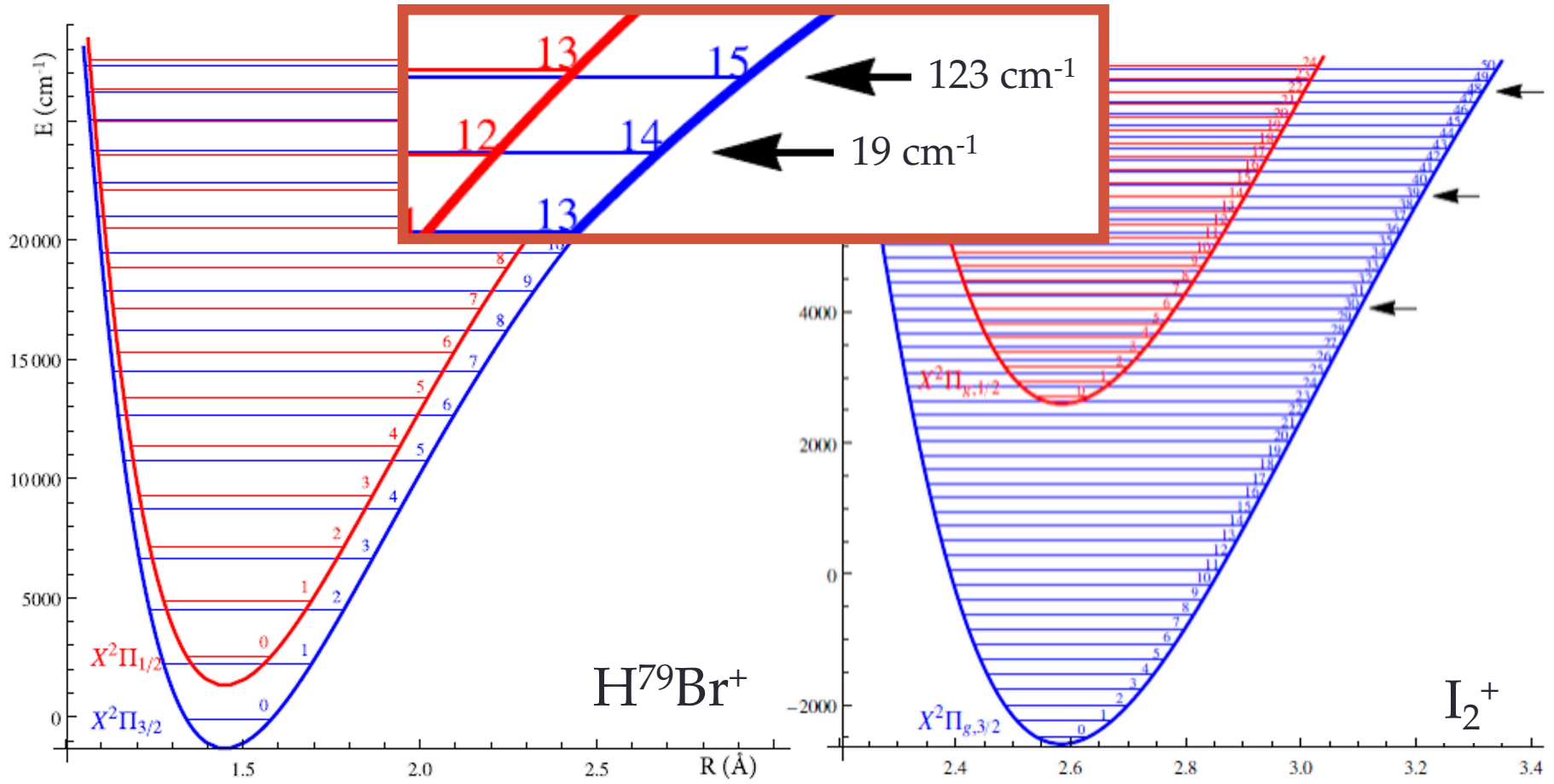


$A_e \sim \alpha^2$
but not
sensitive to μ



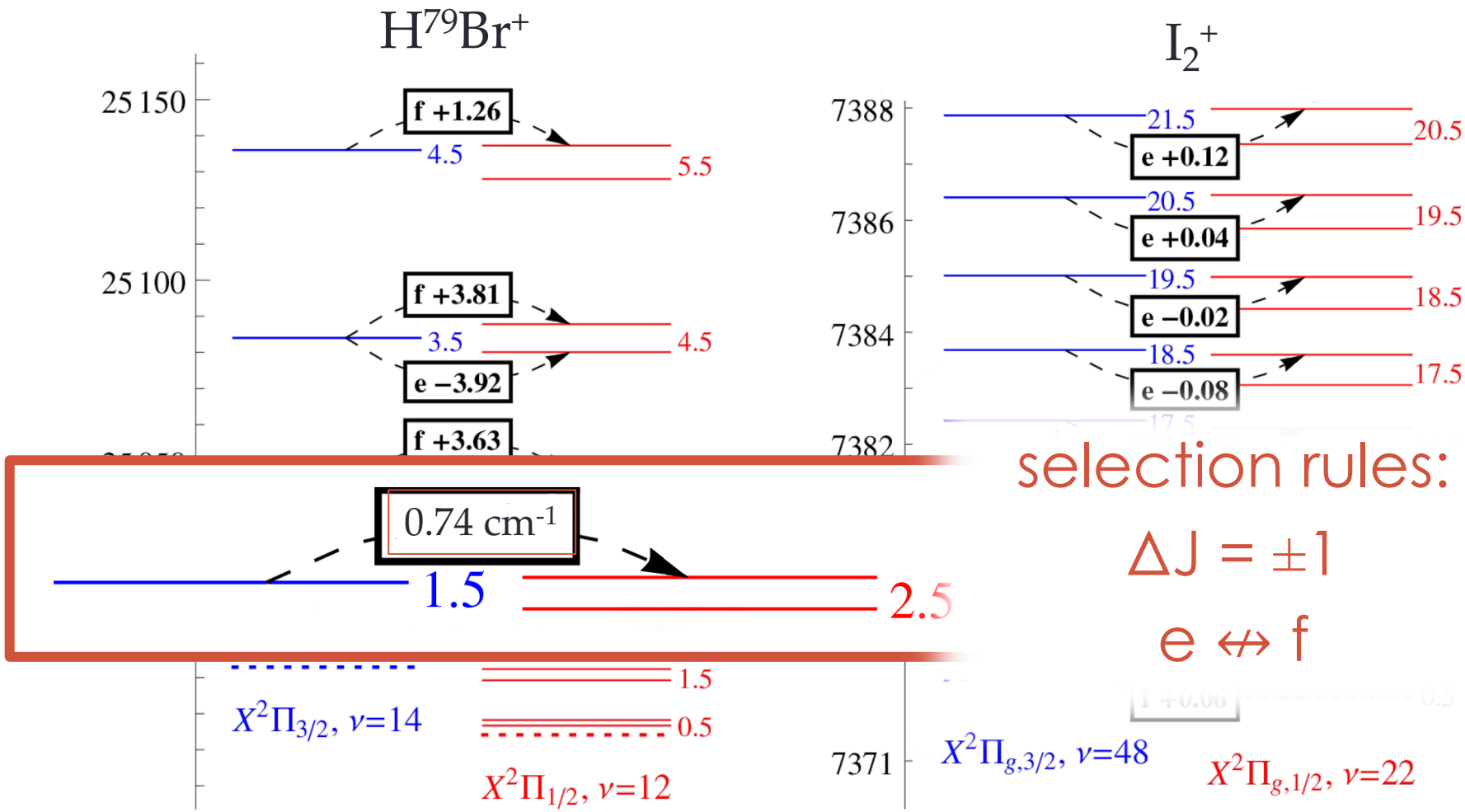
$\omega_e \sim \mu^{-1/2}$
but not
sensitive to α

$^2\Pi$ cations



Pasteka, Borschevsky, Flambaum, Schwerdtfeger, PRA 92, 012103 (2015)

$^2\Pi$ cations



selection rules:

$\Delta J = \pm 1$

e ↮ f

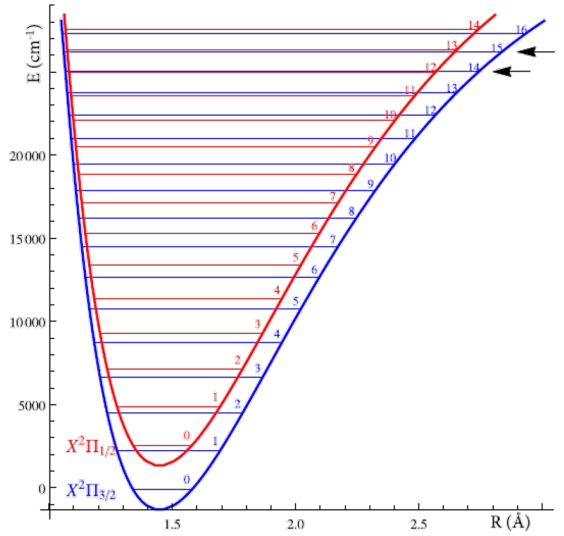
Pasteka, Borschevsky, Flambaum, Schwerdtfeger, PRA 92, 012103 (2015)

Enhancement factors

$$\frac{\delta\omega}{\omega} = K_\alpha \frac{\delta\alpha}{\alpha} + K_\mu \frac{\delta\mu}{\mu}$$

$$\begin{aligned} K_\mu =& [\frac{1}{2}\omega_e(\nu'' - \nu') - \omega_e x_e(\nu'' - \nu')(\nu'' + \nu' + 1) \\ &+ B_e(J'' - J')(J'' + J' + 1) \\ &+ \frac{1}{4}A^{(1)}(\nu'' + \nu' + 1)]\omega^{-1} = \bar{K}_\mu\omega^{-1} \end{aligned}$$

$$K_\alpha = [-2A_e - A^{(1)}(\nu'' + \nu' + 1)]\omega^{-1} = \bar{K}_\alpha\omega^{-1}$$



Pasteka, Borschevsky, Flambaum, Schwerdtfeger, PRA 92, 012103 (2015)

cation	ν''	ν'	J''	J'	s	ω	$\bar{K}_\mu$	K_μ	$\bar{K}_\alpha$	K_α
$H^{79}Br^+$	14	12	1.5	2.5	f	0.74	–80.8	–110	5250	7120
	15	13	11.5	12.5	f	0.14	–426	–3030	5250	37200
$H^{81}Br^+$	14	12	5.5	6.5	f	–0.27	–145	543		–19700
	15	13	6.5	5.5	f	0.52	–119	–228		10100
$D^{79}Br^+$	9	7	7.5	8.5	f	2.20	881	400	5270	2390
	10	8	1.5	0.5	e	1.99	871	437	5270	2650

	ν''	ν'	J''	J'	ω	$\bar{K}_\mu$	K_μ	$\bar{K}_\alpha$	K_α
I_2^+	30	6	30.5	31.5	-0.00	2270	-682000	9990	-3010000
$I^{81}Br^+$	36	19	5.5	4.5	0.01	1170	216000	9320	1720000
DI^+	7	3	1.5	2.5	0.27	2230	8220	10700	39300
$^{79,81}Br_2^+$	30	21	3.5	4.5	-0.09	1160	-12900	5450	-60400

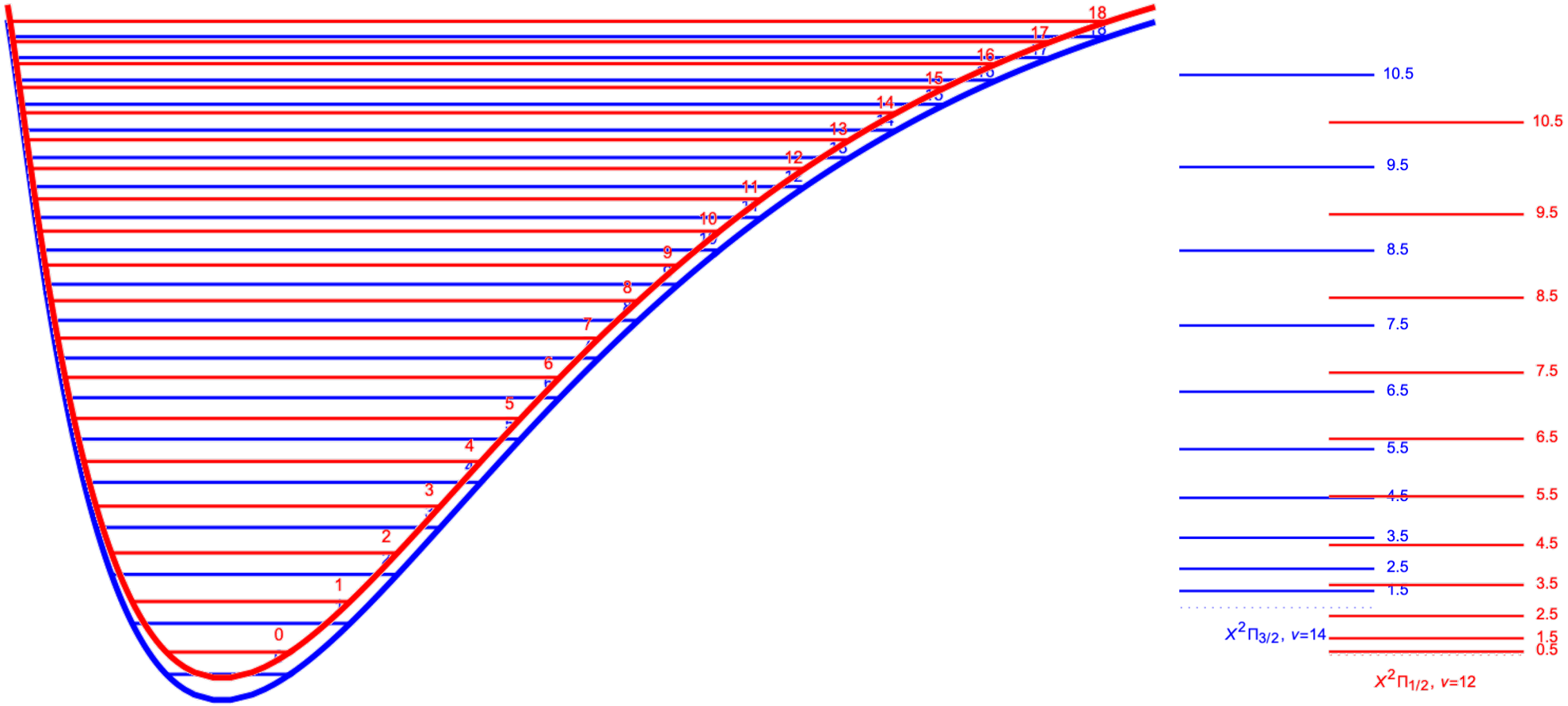
	48	22	19.5	18.5	e	–0.02	1900	–79100	–401000
$^{79}Br2^+$	11	3	24.5	25.5	f	–0.10	1350	–13700	–56600
	31	22	21.5	22.5	f	0.04	1190	33200	150000
$^{79,81}Br_2^+$	9	1	20.5	21.5	e	0.09	1360	14500	5600	59700

Promising systems; dedicated measurements are needed

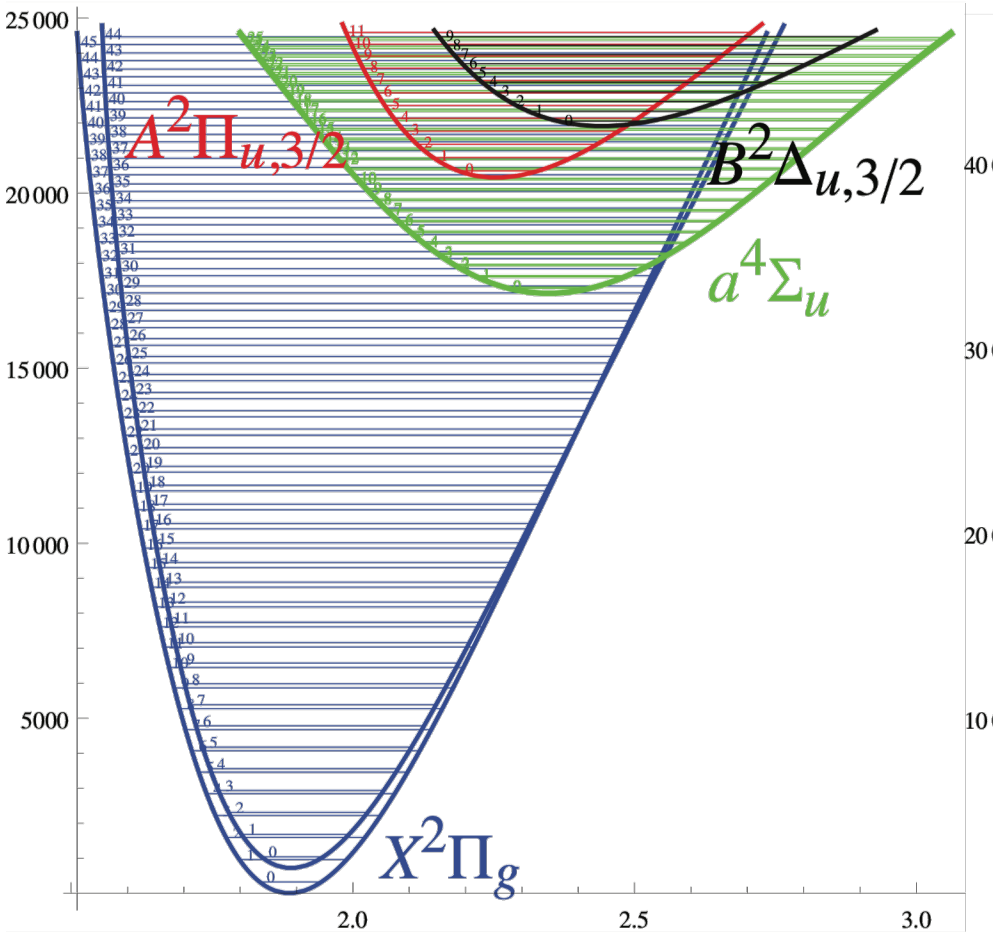
	28	19	36.5	37.5	e	0.05	1190	25700	5450	118000
$I^{79}Br^+$	25	8	33.5	34.5	f	0.11	1720	16300		87700
	39	22	33.5	34.5	f	–0.04	1020	–27900		–249000
$I^{81}Br^+$	24	7	37.5	38.5	f	0.04	1760	45200		240000
	36	19	5.5	4.5	f	0.01	1170	216000	9320	1720000
	37	20	40.5	41.5	e	0.07	1120	15600	9320	131000

Precision

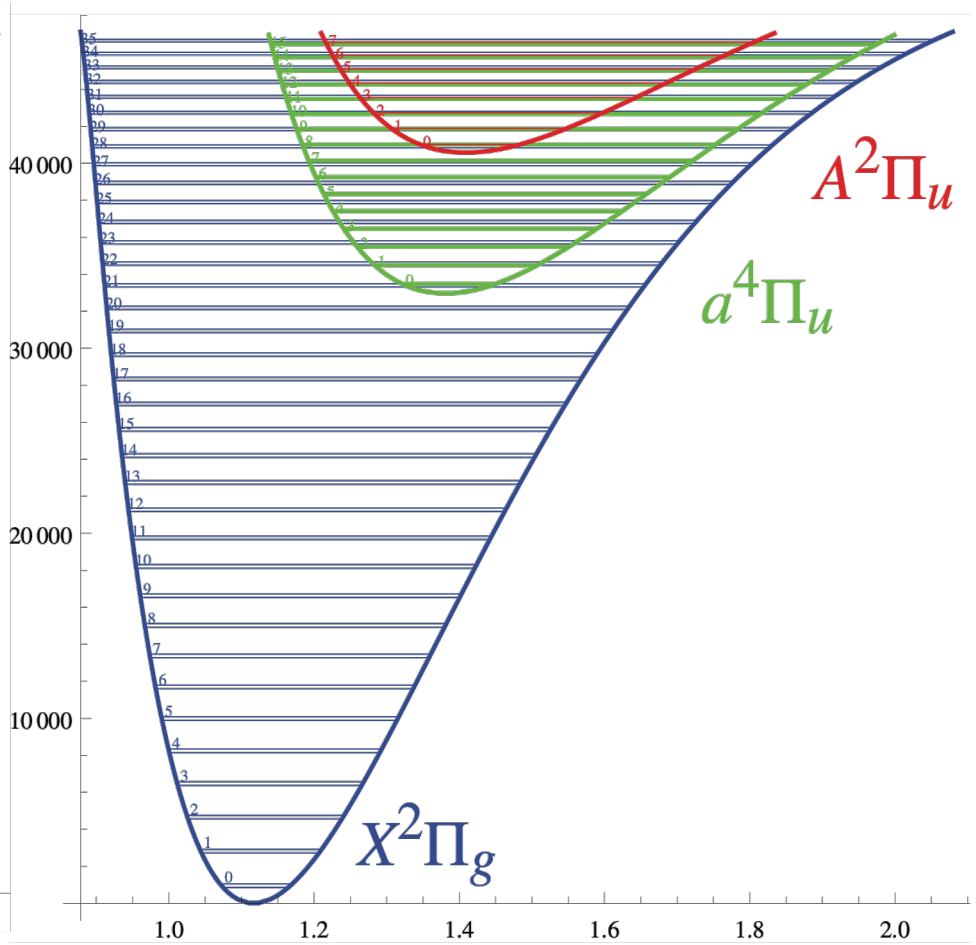
- Are we good enough?



Excited electronic states

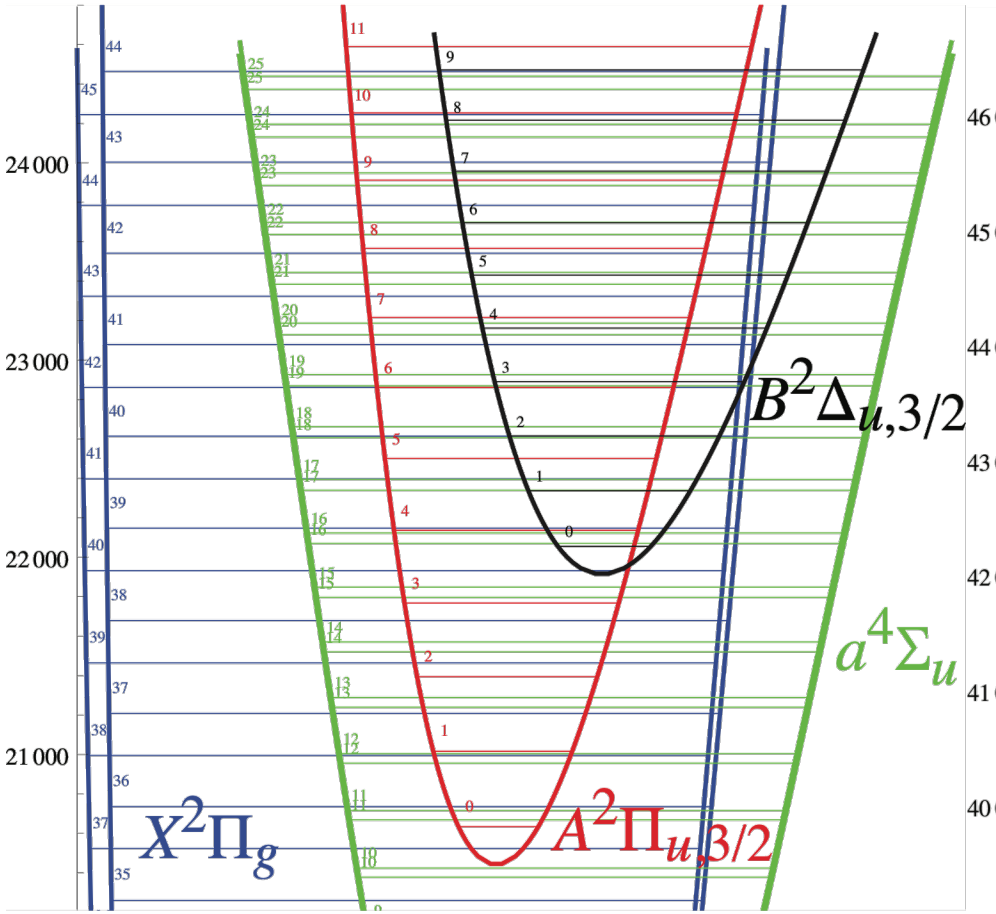


Cl_2^+

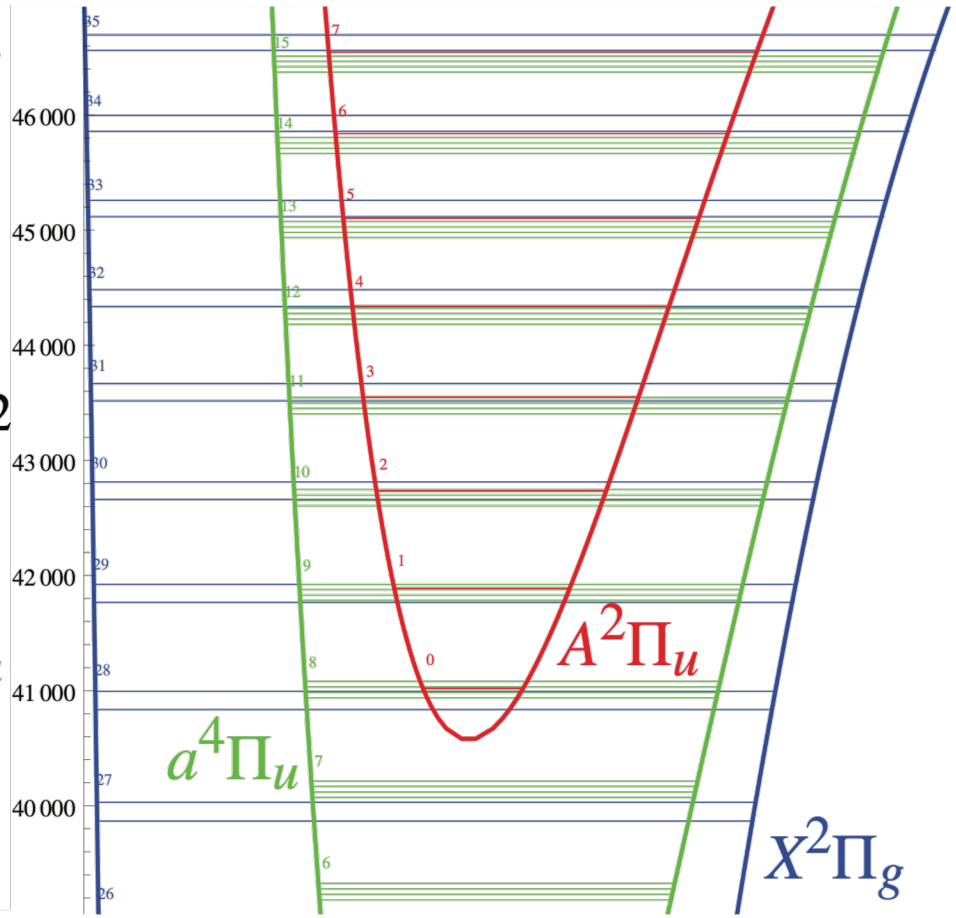


O_2^+

Excited electronic states



Cl_2^+



O_2^+

Quasidegeneracies

Near cancellation between

- vibrational and SO splitting
- hyper-fine and rotational splitting
- hyper-fine and Λ-doubling

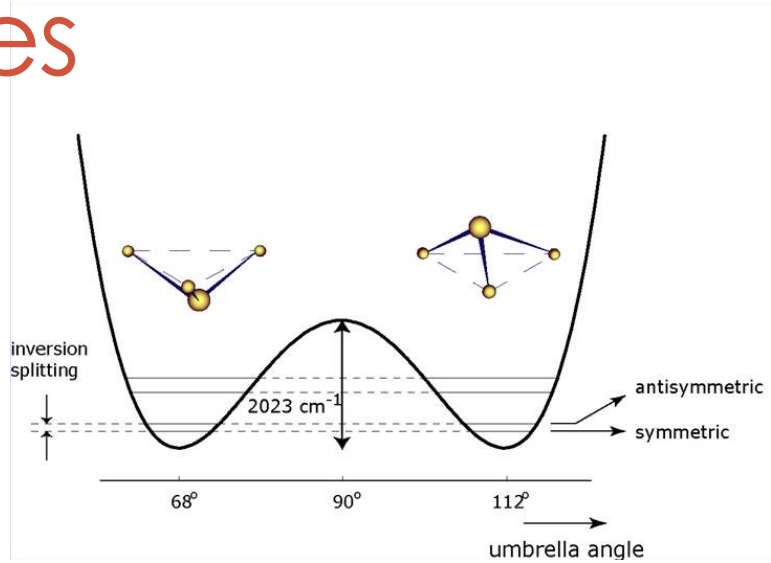
$$E_{\mathrm{HFS}} \sim \alpha^2 g_p \mu^{-1}$$

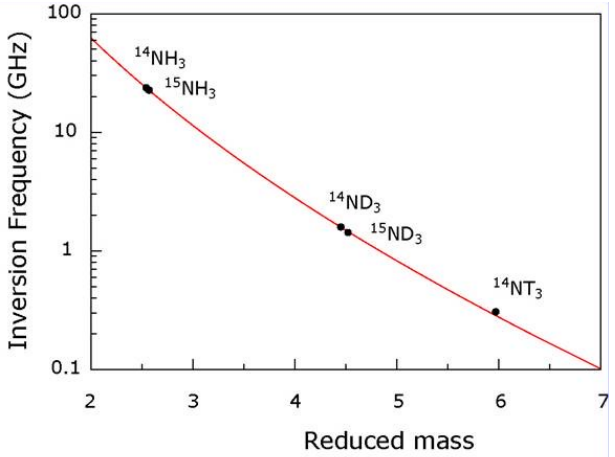
$$\frac{\delta(\omega_1/\omega_2)}{(\omega_1/\omega_2)} = (K_\mu^1 - K_\mu^2)\frac{\delta\mu}{\mu} + (K_\alpha^1 - K_\alpha^2)\frac{\delta\alpha}{\alpha}$$

Flambaum, Kozlov in Cold Molecules (Eds. Krems, Friedrich, Stwalley), CRC, p 597 (2009)

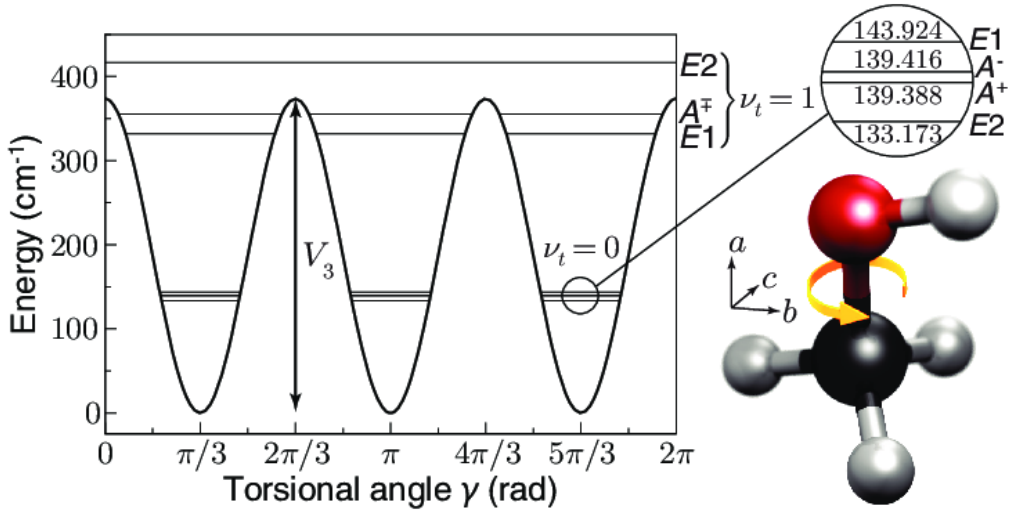
Polyatomic molecules

- Inversion tunneling in NH_3
  - lab and astro $\frac{\delta\mu}{\mu} = (-0.6 \pm 1.9) \times 10^{-6}$





- Hindered rotation of methanol
  - K = 40



Flambaum, Kozlov, PRL 98, 240801 (2007); Murphy et al. Science 320, 1611 (2008)
Jansen et al., PRL 106, 100801 (2011)

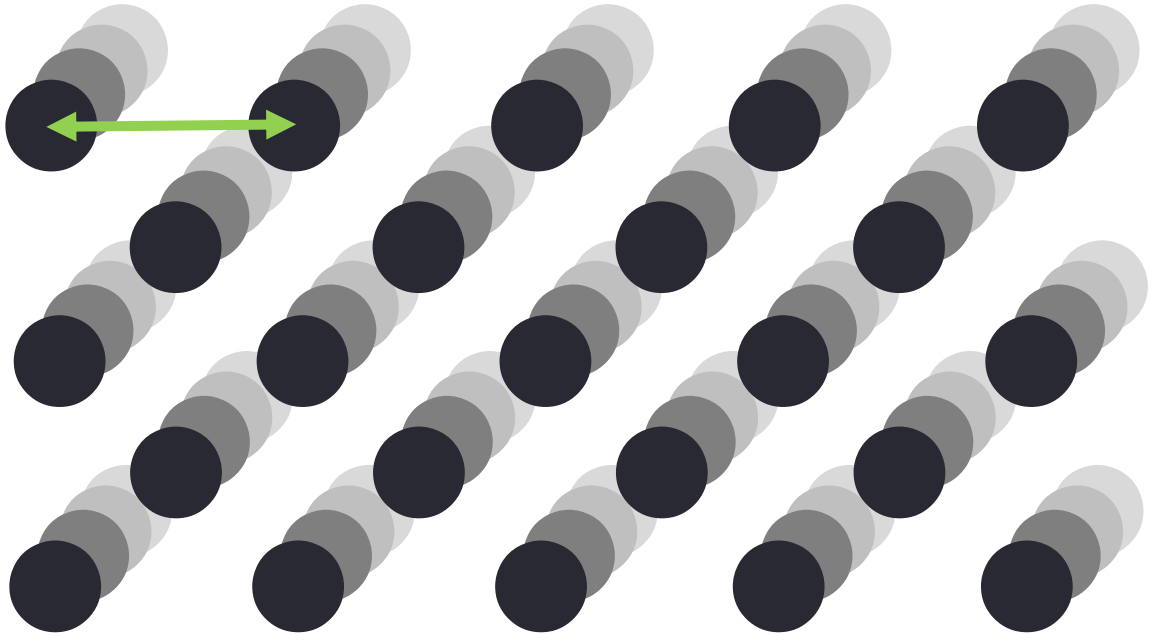
Searching for variation of fundamental constants

(with solids)

Laser interferometry

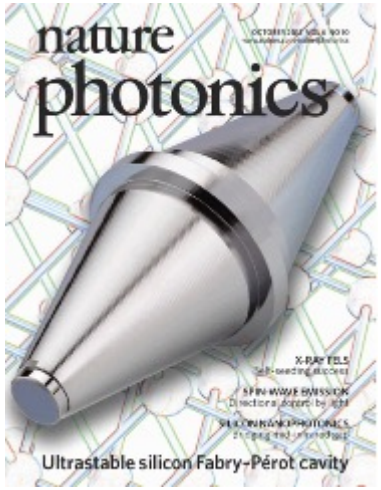
- highest instrumental precision
- matter structure may depend on fundamental constants

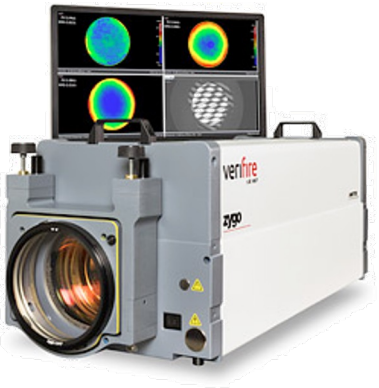
α-meter

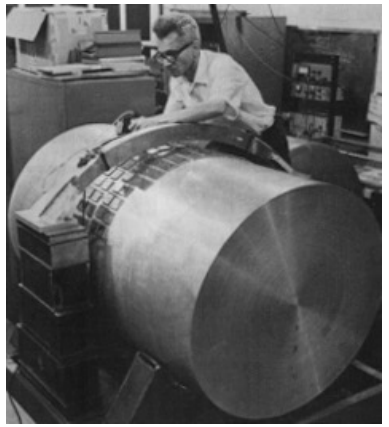


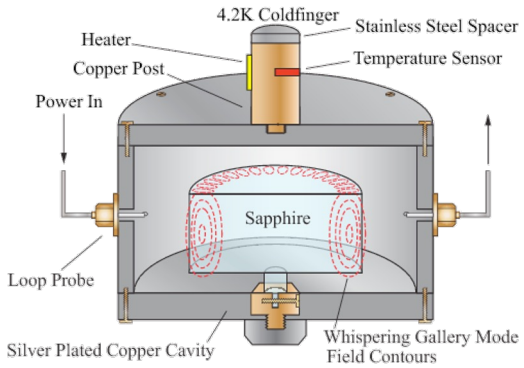
Matter structure

- tabletop optical cavity laser interferometers
- resonant-mass detectors (Al, Cu, Nb)
- cryogenic sapphire/silicon oscillators



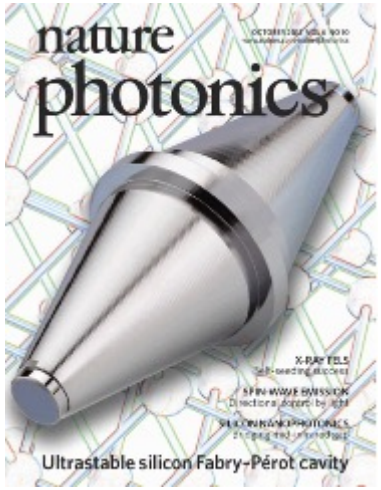


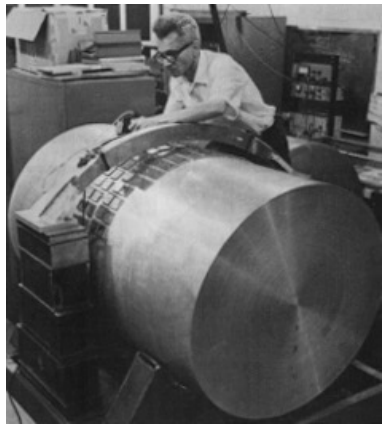


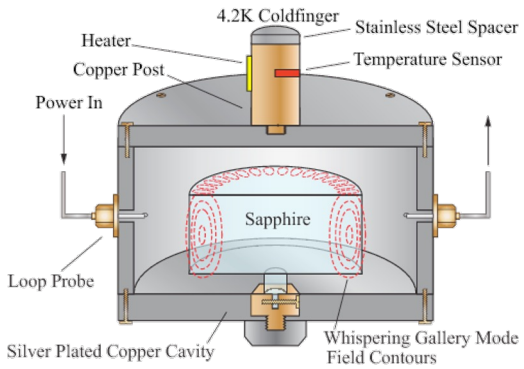


Matter structure

- Cu, Ag, Au
- Al
- Nb
- WC
- Si, Si, Ge, Sn, Pb
- Al_2O_3
- SiC
- Ti







Overview

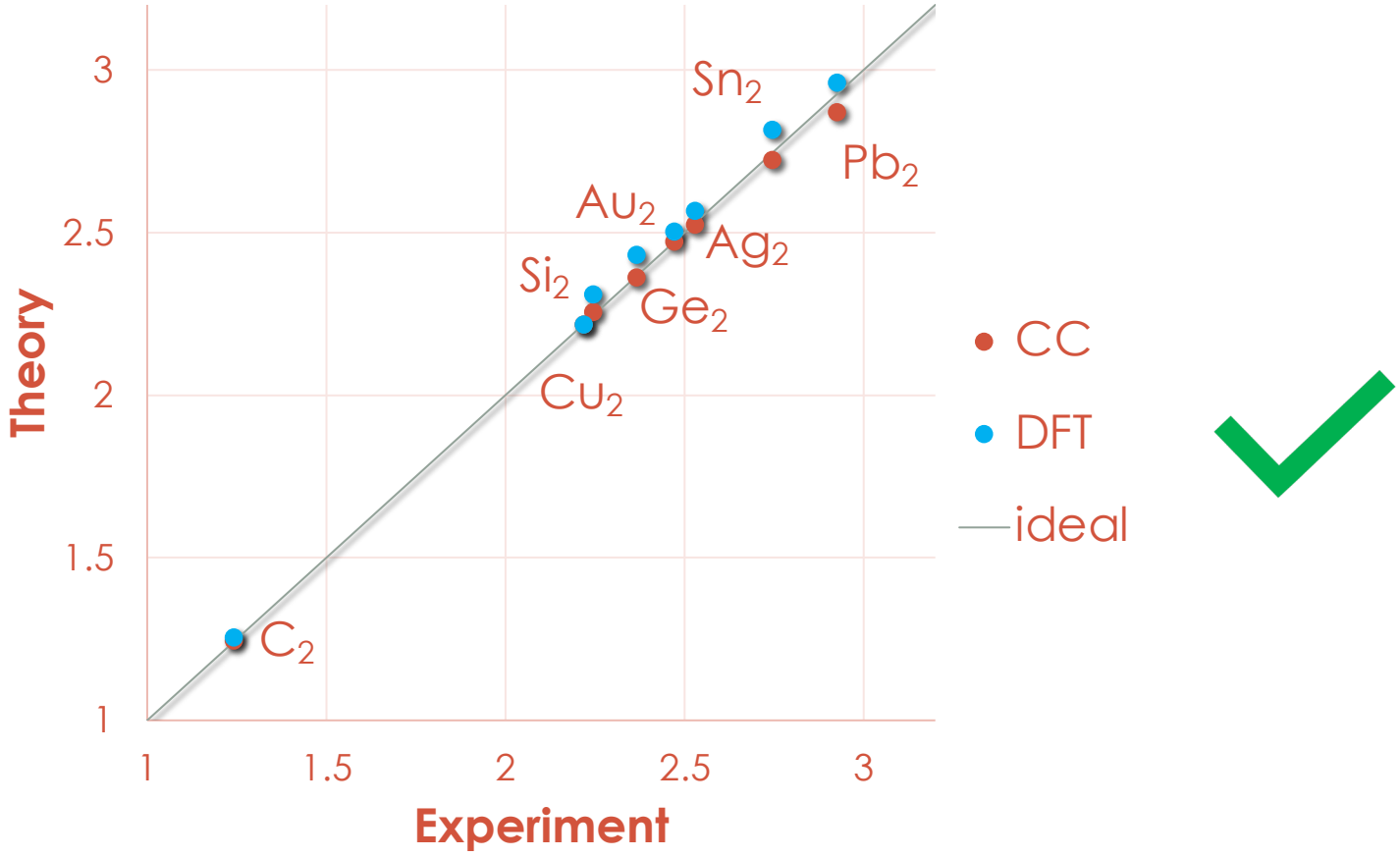
- Diatomics – bond lengths
- Solids – lattice constants
- α-dependence
- μ-dependence

Diatomics

(the test case)

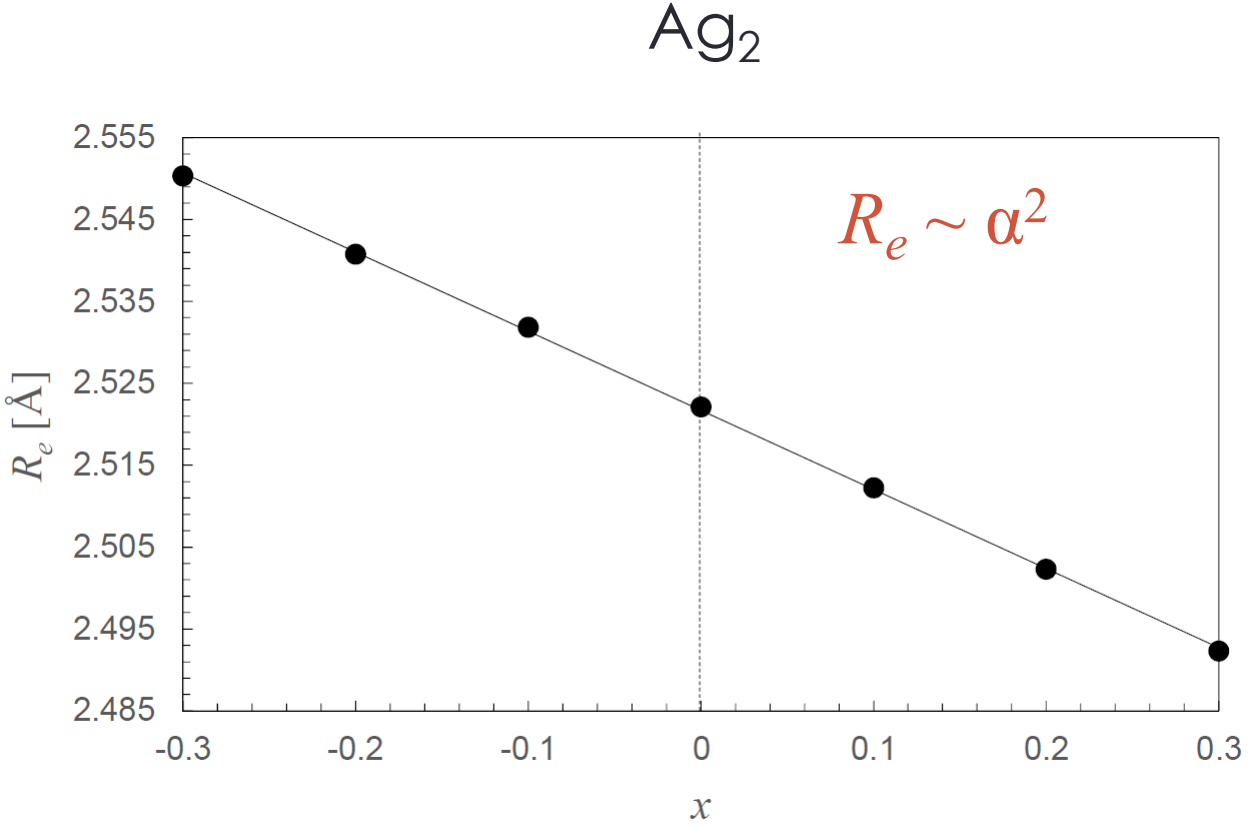
Diatomics: Bond lengths

- Average errors
  - CC: 0.5%
  - DFT: 1.6%



Diatomics: α-dependence

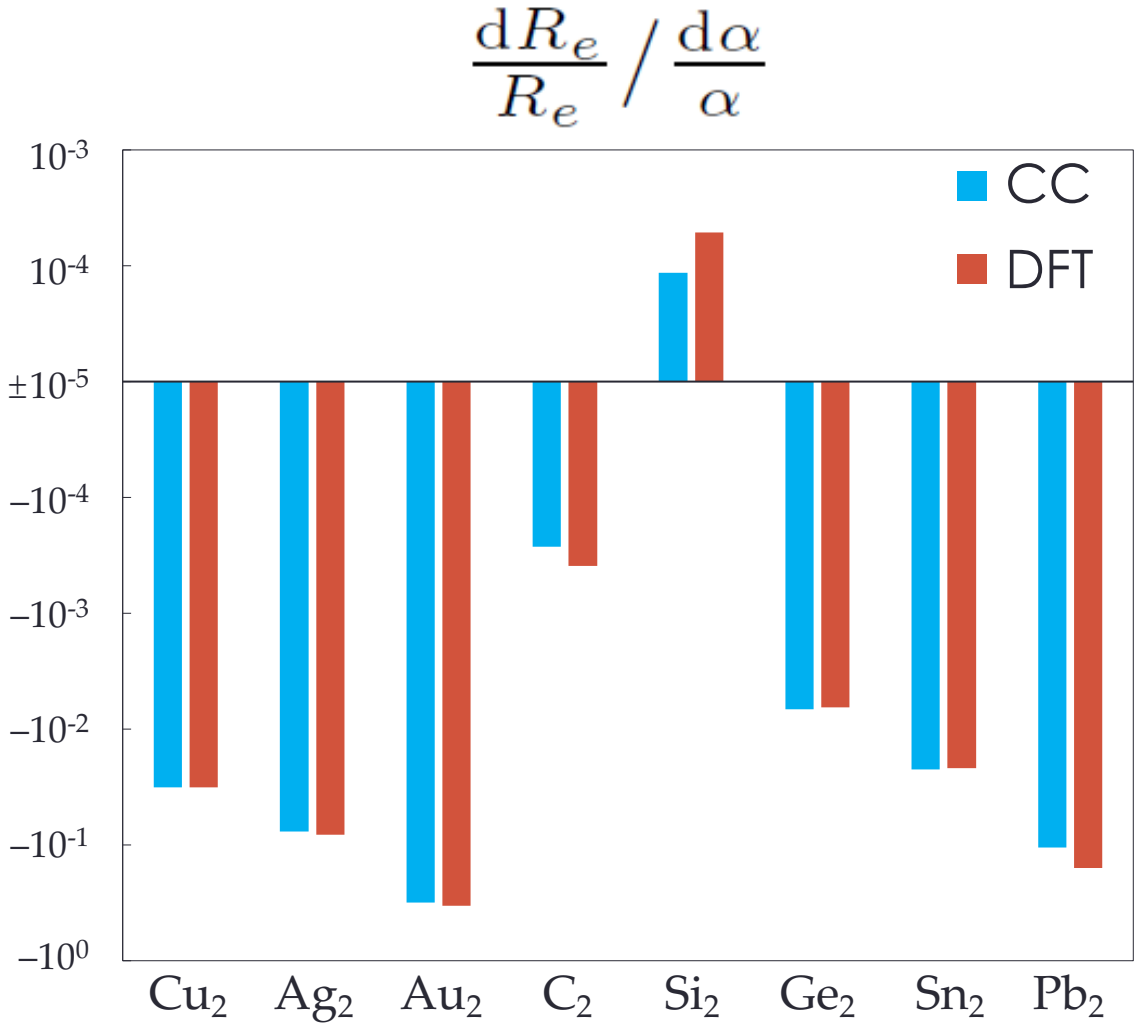
- varying α = varying c (because a.u.)
- optimizing R_e w.r.t. $x = \left(\frac{\alpha}{\alpha_0}\right)^2 - 1$



Diatomics: α-dependence

mol.	state	$\frac{dR_e}{R_e} / \frac{d\alpha}{\alpha}$ CC	DFT
Cu_2	$^1\Sigma_g^+$	-3.19×10^{-2}	-3.18×10^{-2}
Ag_2	$^1\Sigma_g^+$	-7.66×10^{-2}	-8.21×10^{-2}
Au_2	$^1\Sigma_g^+$	-3.15×10^{-1}	-3.37×10^{-1}
C_2	$^1\Sigma_g^+$	-2.65×10^{-4}	-3.88×10^{-4}
Si_2	$^3\Sigma_g^-$	8.66×10^{-5}	1.94×10^{-4}
Ge_2	$^3\Sigma_g^-$	-6.74×10^{-3}	-6.48×10^{-3}
Sn_2	0_g^+	-2.24×10^{-2}	-2.17×10^{-2}
Pb_2	0_g^+	-1.05×10^{-1}	-1.58×10^{-1}

Diatomics: α-dependence



Diatomics: μ-dependence

- vibrational $B_0 = B_e - \frac{\alpha_e}{2}$ $B \sim \frac{1}{R^2}$ $B_e \sim \mu^{-1}$ $\alpha_e \sim \mu^{-\frac{3}{2}}$

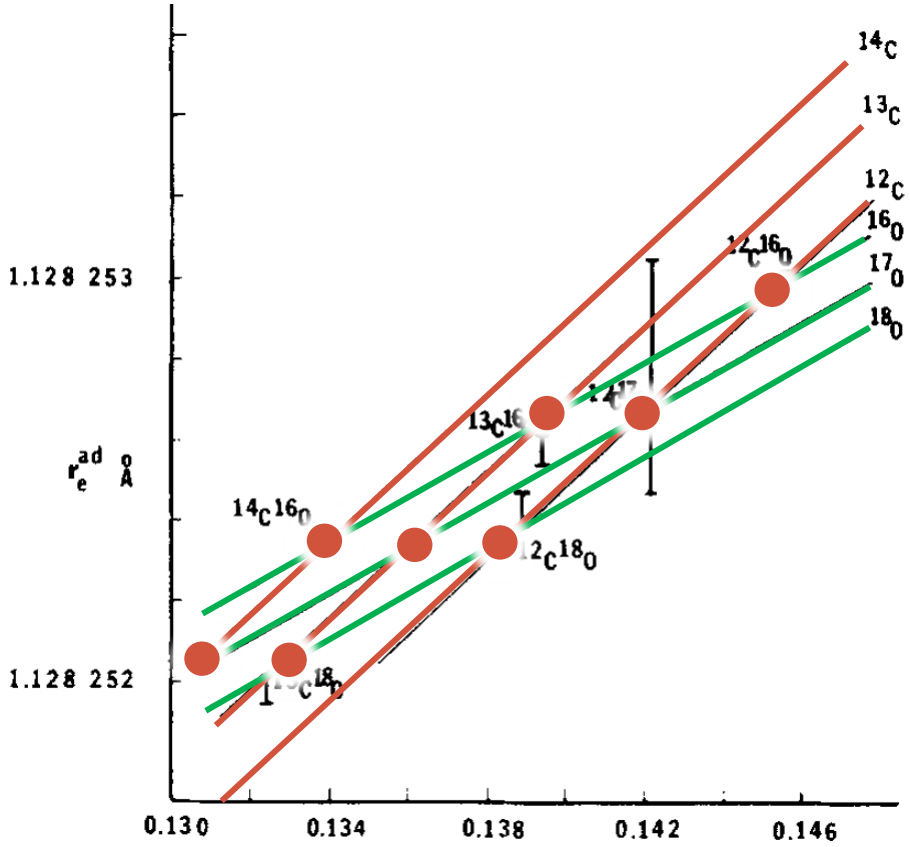
$$\frac{dR_0}{R_0} \Big/ \frac{d\mu}{\mu} = -\frac{\alpha_e}{4(2B_e - \alpha_e)}$$

- non-BO effects
  - within BOA

    R_e is isotope mass-invariant (independent on μ)
  - outside BOA

    nuclear kinetic terms contribute to weak μ-dependence $R_e \sim \mu^{-1}$

Diatomics: μ-dependence



Isotope	Γ_{01}/MHz[b]	r_e/Å[b,c]
$^{12}C^{16}O$	57 898.3675 (±25)	1.128 336 346 (±25)
$^{12}C^{17}O$	56 432.4817 (±300)	1.128 333 997 (±300)
$^{13}C^{16}O$	55 346.2594 (±40)	1.128 332 196 (±40)
$^{12}C^{18}O$	55 135.2616 (±40)	1.128 331 825 (±40)
$^{14}C^{16}O$	53 166.7589 (±20)	1.128 328 817 (±22)
$^{13}C^{18}O$	52 583.1129 (±40)	1.128 327 673 (±40)

$$R_e \sim \mu^{-1}$$

Watson, J. Mol. Spec. (1973) 45, 99

Diatomics: μ-dependence

- non-BOA effects are negligible

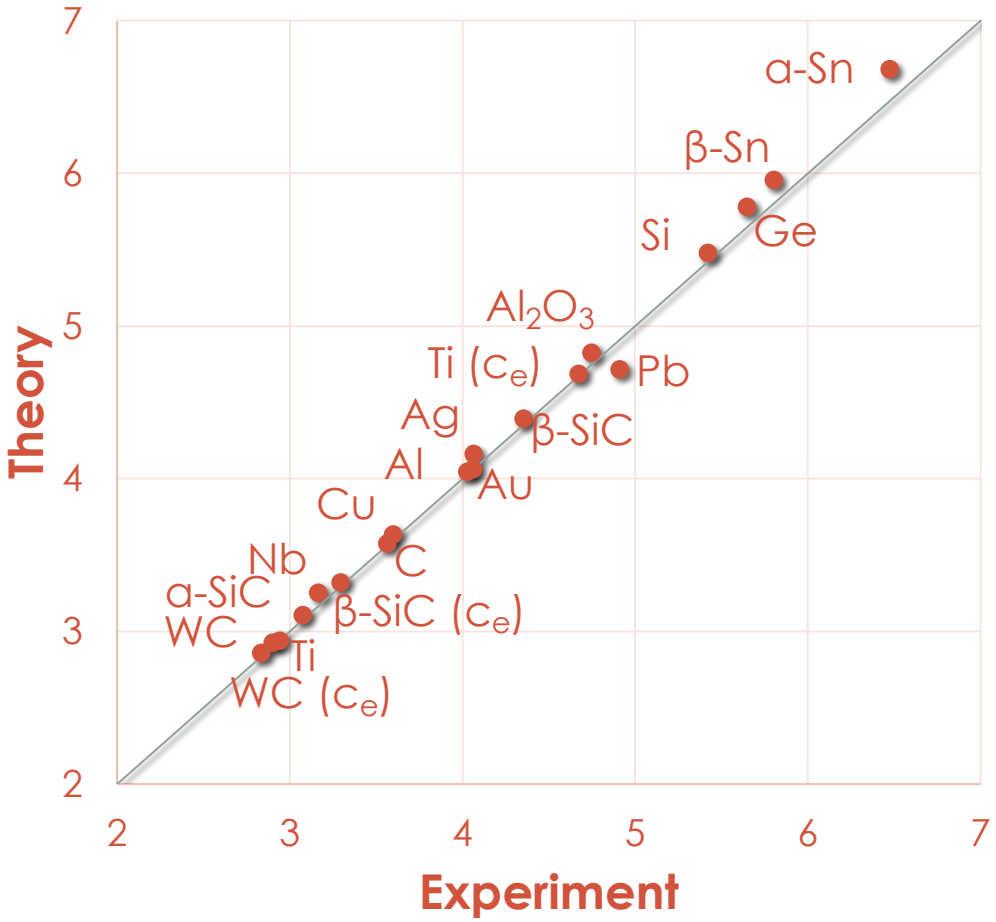
		vibrational	non-BOA
mol.	state	$\frac{dR_0}{R_0} / \frac{d\mu}{\mu}$	$\frac{dR_e}{R_e} / \frac{d\mu}{\mu}$
Cu_2	$^1\Sigma_g^+$	-7.15×10^{-4}	-7.31×10^{-6}
Ag_2	$^1\Sigma_g^+$	-4.98×10^{-4}	-3.38×10^{-6}
Au_2	$^1\Sigma_g^+$	-2.95×10^{-4}	9.16×10^{-7}
C_2	$^1\Sigma_g^+$	-1.17×10^{-3}	-6.94×10^{-6}
Si_2	$^3\Sigma_g^-$	-7.08×10^{-4}	-6.63×10^{-6}
Ge_2	$^3\Sigma_g^-$	-2.34×10^{-3}	-4.46×10^{-6}
Sn_2	0_g^+	-3.25×10^{-4}	-3.82×10^{-6}
Pb_2	0_g^+	-3.76×10^{-4}	3.32×10^{-7}

Solids

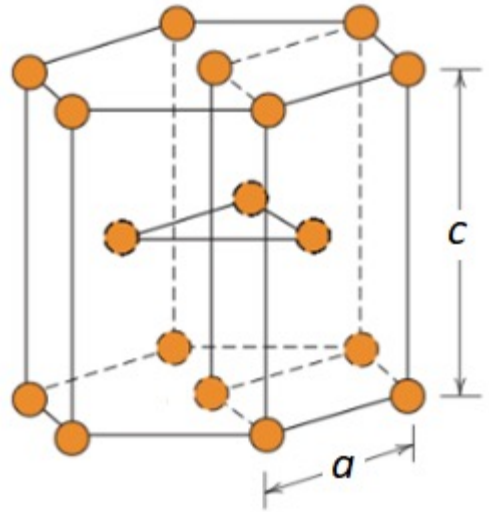
(the real deal)

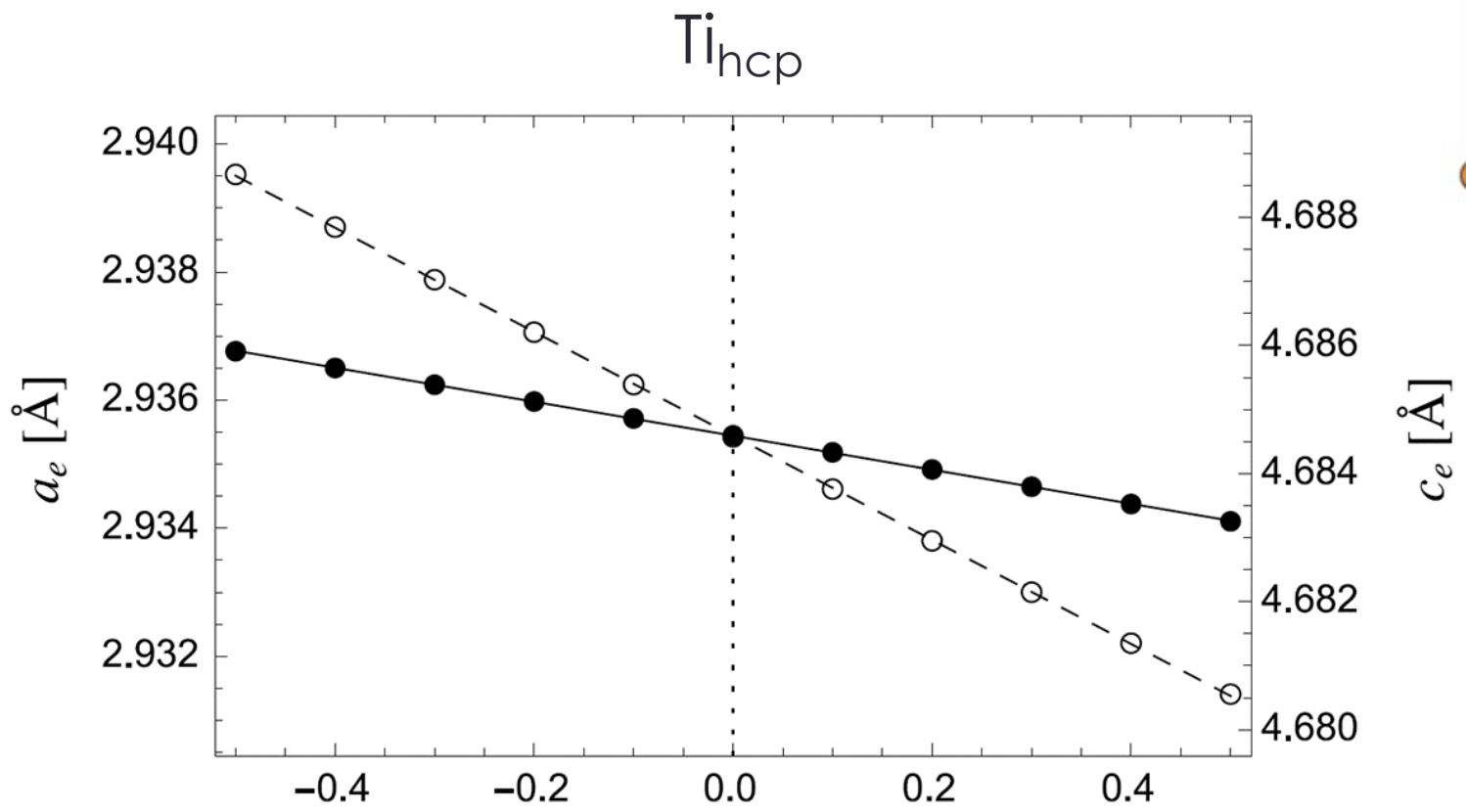
Solids: Lattice parameters

- Average error
  - 1.3%



Solids: α-dependence

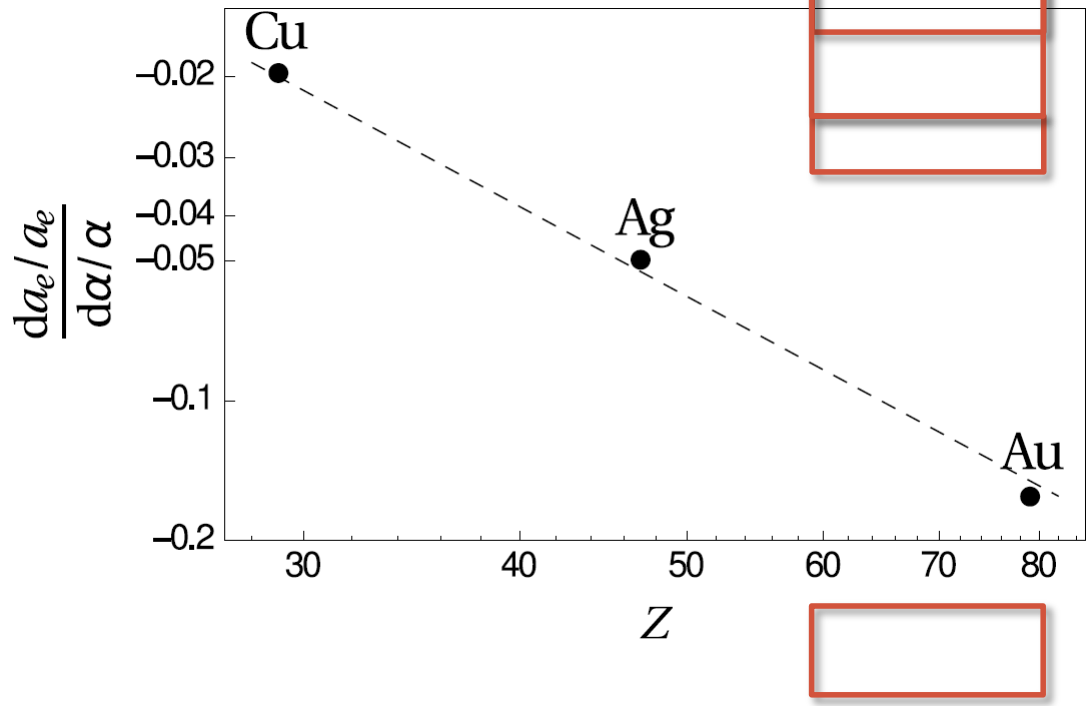




$$x = \left(\frac{\alpha}{\alpha_0}\right)^2 - 1$$

Solids: α-dependence

solid	structure	spc. group	$\frac{da_e}{a_e} / \frac{d\alpha}{\alpha}$
Cu	fcc	$Fm\bar{3}m$	-1.97×10^{-2}
Ag	fcc	$Fm\bar{3}m$	-4.97×10^{-2}
Au	fcc	$Fm\bar{3}m$	-1.61×10^{-1}

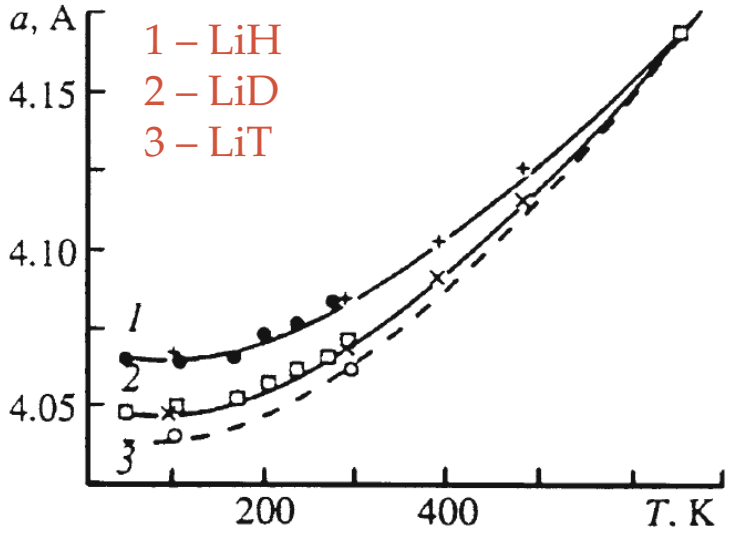


Solids: μ-dependence

- lattice parameter is mass-dependent
- vibrational effect
- isotope substitution studies

$$\frac{M dV}{V dM} = -\frac{9}{16}\frac{\gamma\kappa}{V} R\Theta_D$$

$$\frac{da_0}{a_0} \Big/ \frac{d\mu}{\mu} = -\frac{3}{16}\frac{\gamma}{BV} k_B\Theta_D$$



London, Z. Phys Chem. (1958) 16, 302

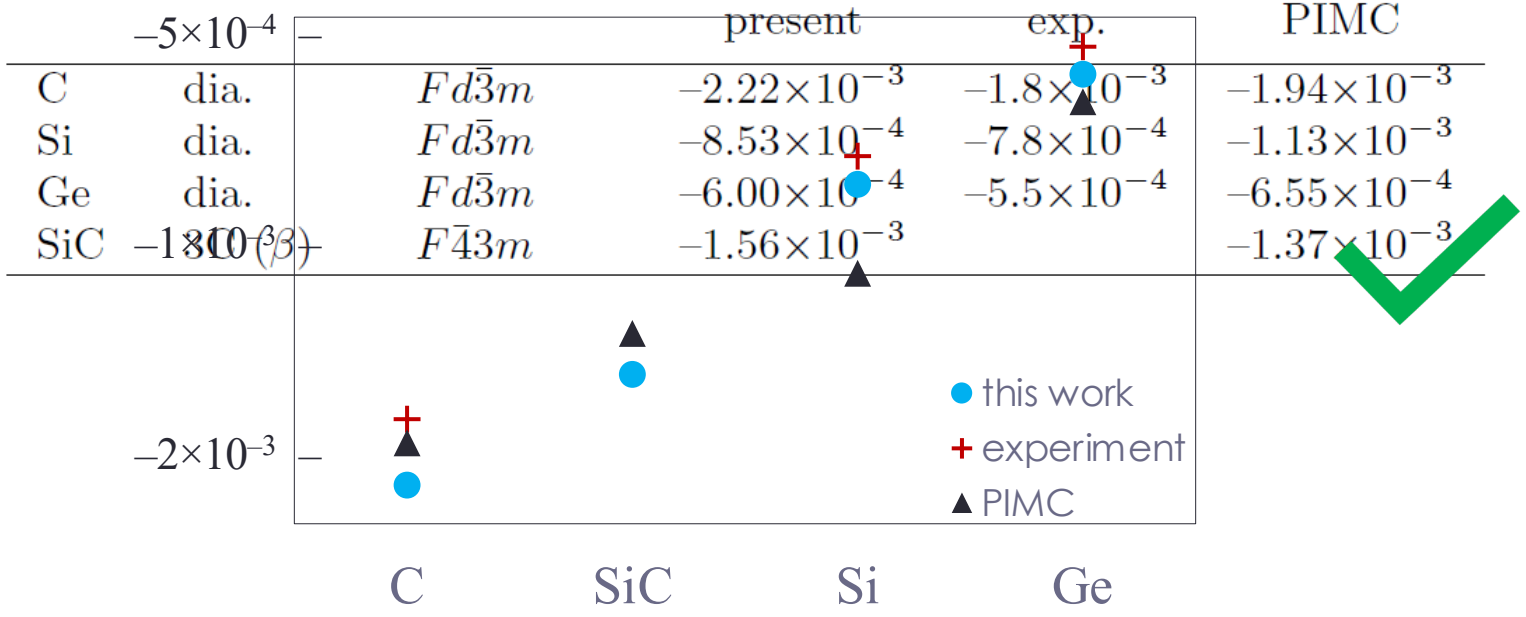
Solids: μ-dependence

solid	structure	spc. group	$\frac{da_0}{a_0}/\frac{d\mu}{\mu}$
Cu	fcc	$Fm\bar{3}m$	-1.11×10^{-3}
Ag	fcc	$Fm\bar{3}m$	-8.21×10^{-4}
Au	fcc	$Fm\bar{3}m$	-4.29×10^{-4}
C	dia.	$Fd\bar{3}m$	-2.22×10^{-3}
Si	dia.	$Fd\bar{3}m$	-8.53×10^{-4}
Ge	dia.	$Fd\bar{3}m$	-6.00×10^{-4}
Sn	dia. (α)	$Fd\bar{3}m$	-4.96×10^{-4}
	tet. (β)	$I4_1/amd$	-6.18×10^{-4}
Pb	fcc	$Fm\bar{3}m$	-5.52×10^{-4}
		$Fm\bar{3}m$	-2.08×10^{-3}
		$Im\bar{3}m$	-3.72×10^{-4}
		$P6_3/mmc$	-7.03×10^{-4}
Al_2O_3	hex.	$R\bar{3}c$	-2.05×10^{-3}
SiC	3C (β)	$F\bar{4}3m$	-1.56×10^{-3}
	6H (α)	$P6_3mc$	-1.47×10^{-3}
WC	hex.	$P\bar{6}m2$	-1.26×10^{-3}

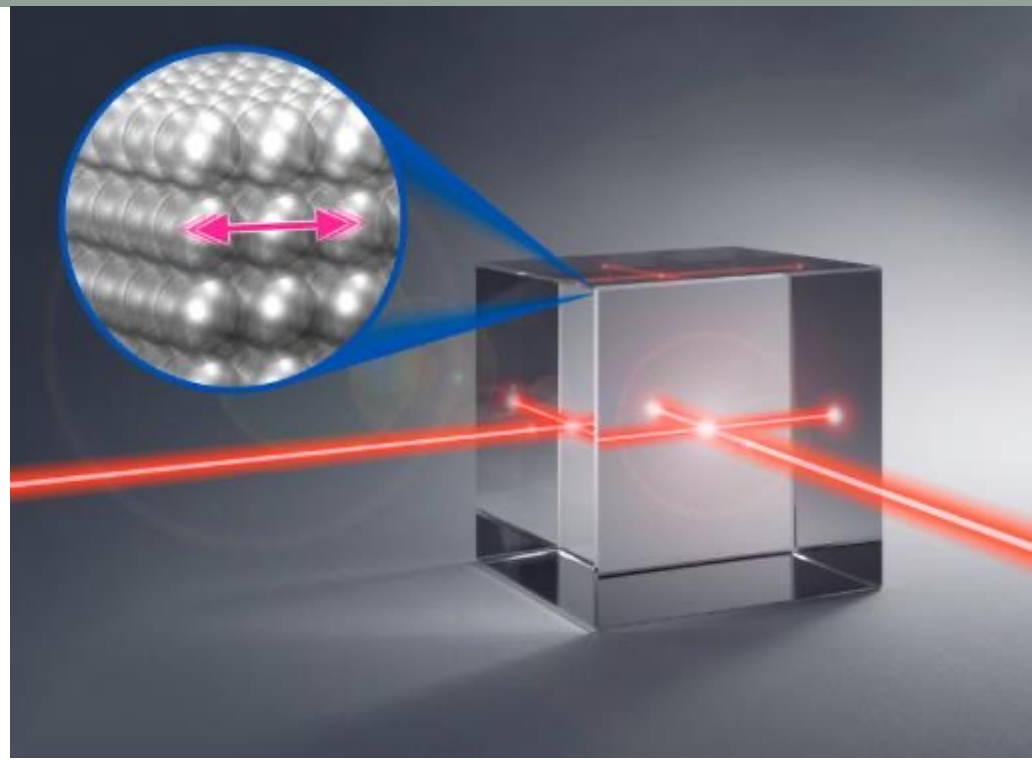
$$\frac{da_0}{a_0}/\frac{d\mu}{\mu} = -\frac{3}{16}\frac{\gamma}{BV}k_B\Theta_D$$

Solids: μ-dependence

solid	structure	spc. group	$\frac{da_0}{a_0} / \frac{d\mu}{\mu}$ present	exp.	PIMC
C	dia.	$Fd\bar{3}m$	-2.22×10^{-3}	-1.8×10^{-3}	-1.94×10^{-3}
Si	dia.	$Fd\bar{3}m$	-8.53×10^{-4}	-7.8×10^{-4}	-1.13×10^{-3}
Ge	dia.	$Fd\bar{3}m$	-6.00×10^{-4}	-5.5×10^{-4}	-6.55×10^{-4}
SiC	zinc-blende	$F\bar{4}3m$	-1.56×10^{-3}		-1.37×10^{-3}



In practice



- new possibility to look for drifting constants
- interferometer with 2 different arms
- 2 optical cavities
- expected effect ~ 10^{-19} – 10^{-18} within current precision limits
- optical cavity/atomic clock – α-dependence suppressed

$$\omega_c \sim \frac{c}{\lambda} \sim \frac{c}{L} \sim \frac{c}{a_\mathrm{B}} \qquad \omega_a \sim \frac{e^2}{\hbar a_\mathrm{B}} \quad \Rightarrow \quad \frac{\omega_a}{\omega_c} \sim \frac{e^2}{\hbar c} = \alpha \quad \Rightarrow \quad K = 1$$

Pasteka et al., PRL 122, 160801; Kozlov, Budker, Ann. Phys. 531, 1800254

Detecting dark matter

Dark matter candidates

- scalar/axionlike oscillating DM field

$$\phi = \phi_0 cos(\omega t) \quad \omega \approx \frac{m_\phi c^2}{\hbar}$$
$$10^{-22} eV < m_\phi < 10^{-4} eV$$

- quadratic coupling to SM fields

$$\mathcal{L}_{\rm int} = \mp \sum_f \frac{\phi^2}{(\Lambda'_f)^2} m_f \bar{f} f \pm \frac{\phi^2}{(\Lambda'_\gamma)^2} \frac{F_{\mu\nu} F^{\mu\nu}}{4} \pm \sum_V \frac{\phi^2}{(\Lambda'_V)^2} \frac{M_V^2}{2} V_\nu V^\nu,$$

- induces effective changes in the SM
  - photons

$$\mathcal{L}_\gamma = \frac{\phi^2}{(\Lambda'_\gamma)^2} \frac{F_{\mu\nu} F^{\mu\nu}}{4} \Rightarrow \alpha \to \frac{\alpha}{1 - \phi^2/(\Lambda'_\gamma)^2} \simeq \alpha \left[1 + \frac{\phi^2}{(\Lambda'_\gamma)^2} \right]$$

  - fermions

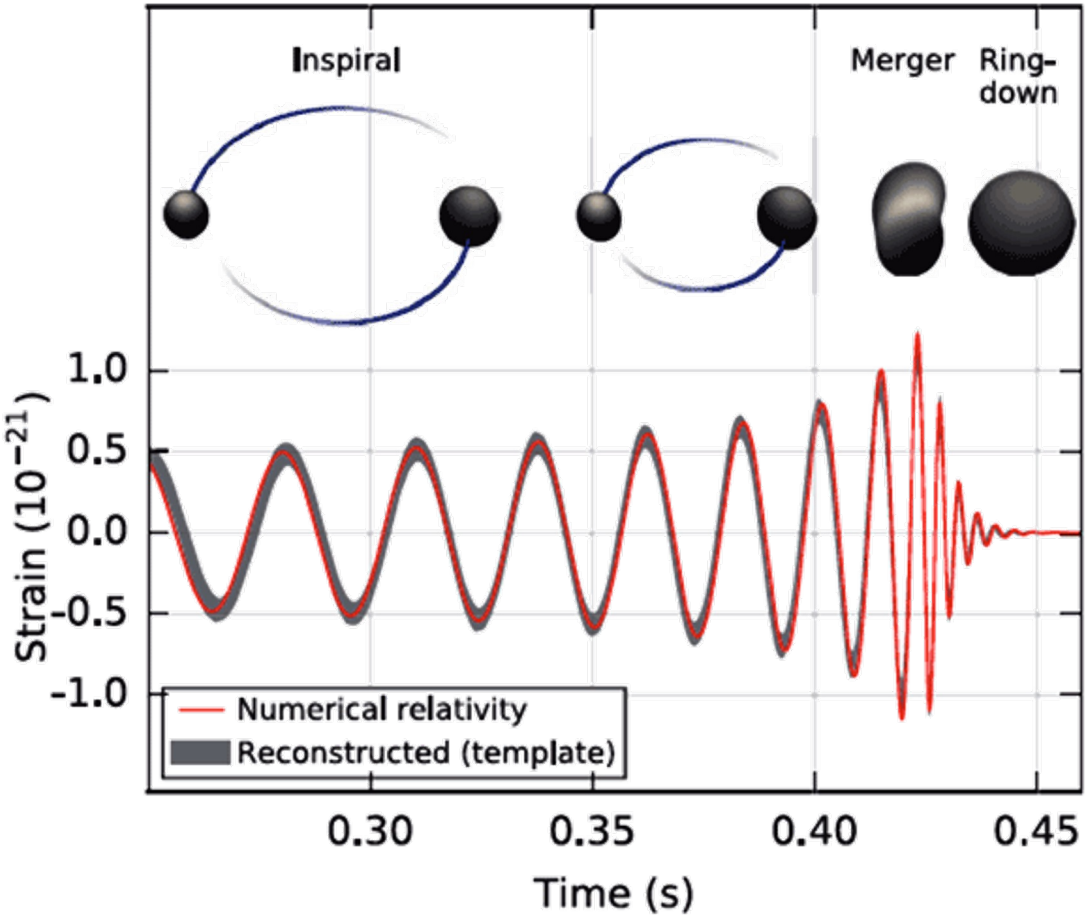
$$\mathcal{L}_f = -\frac{\phi^2}{(\Lambda'_f)^2} m_f \bar{f} f \Rightarrow m_f \to m_f \left[1 + \frac{\phi^2}{(\Lambda'_f)^2} \right]$$

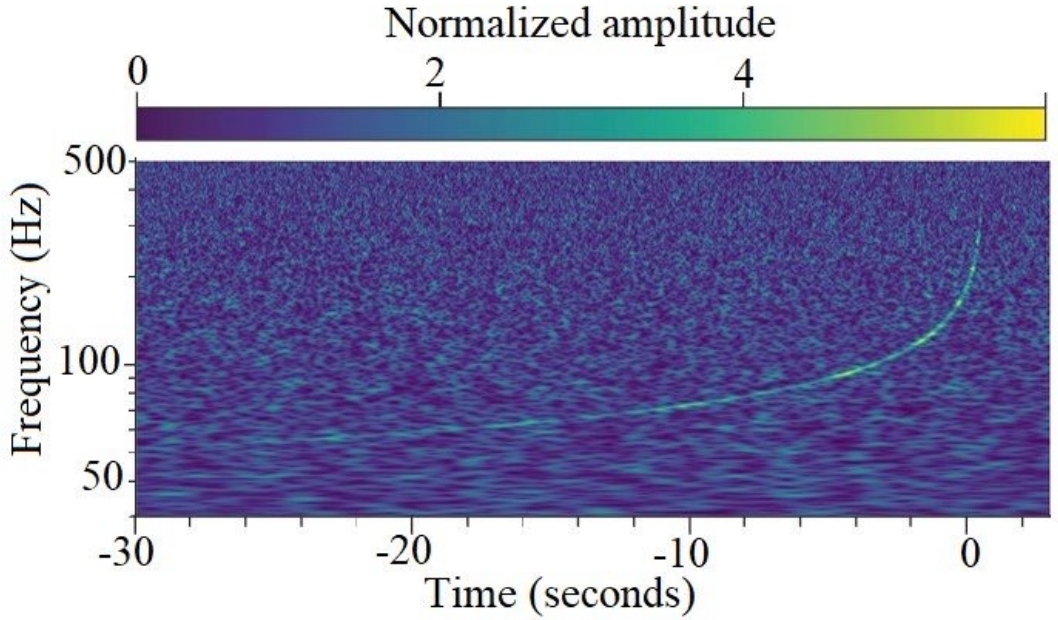
  - bosons

$$\mathcal{L}_V = \frac{\phi^2}{(\Lambda'_V)^2} \frac{M_V^2}{2} V_\nu V^\nu \Rightarrow M_V^2 \to M_V^2 \left[1 + \frac{\phi^2}{(\Lambda'_V)^2} \right]$$

Stadnik, Flambaum, PRL 115, 201301

Laser interferometry





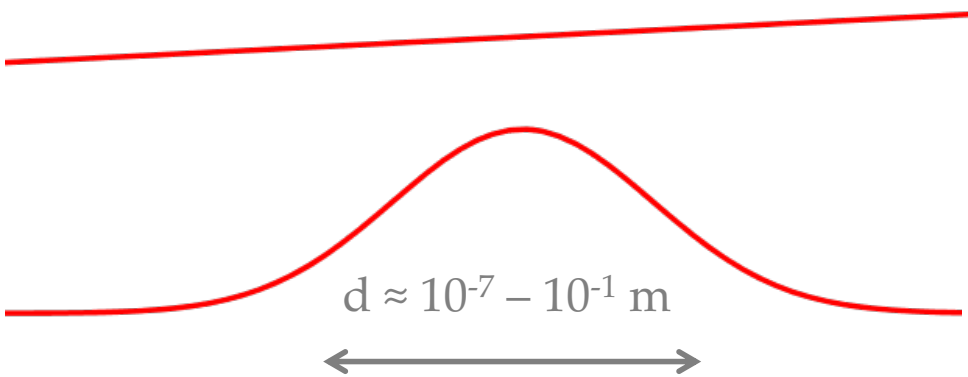
Expected signals

- DM field

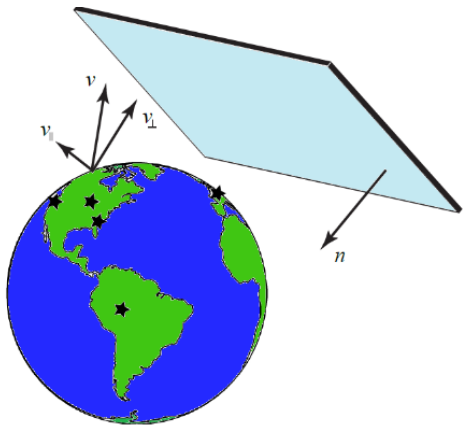
$$\frac{\delta m_f}{m_f} = \frac{\phi_0^2}{(\Lambda'_f)^2}\cos^2(m_\phi t) = \boxed{\frac{\phi_0^2}{2(\Lambda'_f)^2}} + \boxed{\frac{\phi_0^2}{2(\Lambda'_f)^2}\cos(2m_\phi t)}$$

- oscillating signal

- slow drift



- topological defect



Stadnik, Flambaum, PRL 115, 201301

Time variation of a fundamental dimensionless constant

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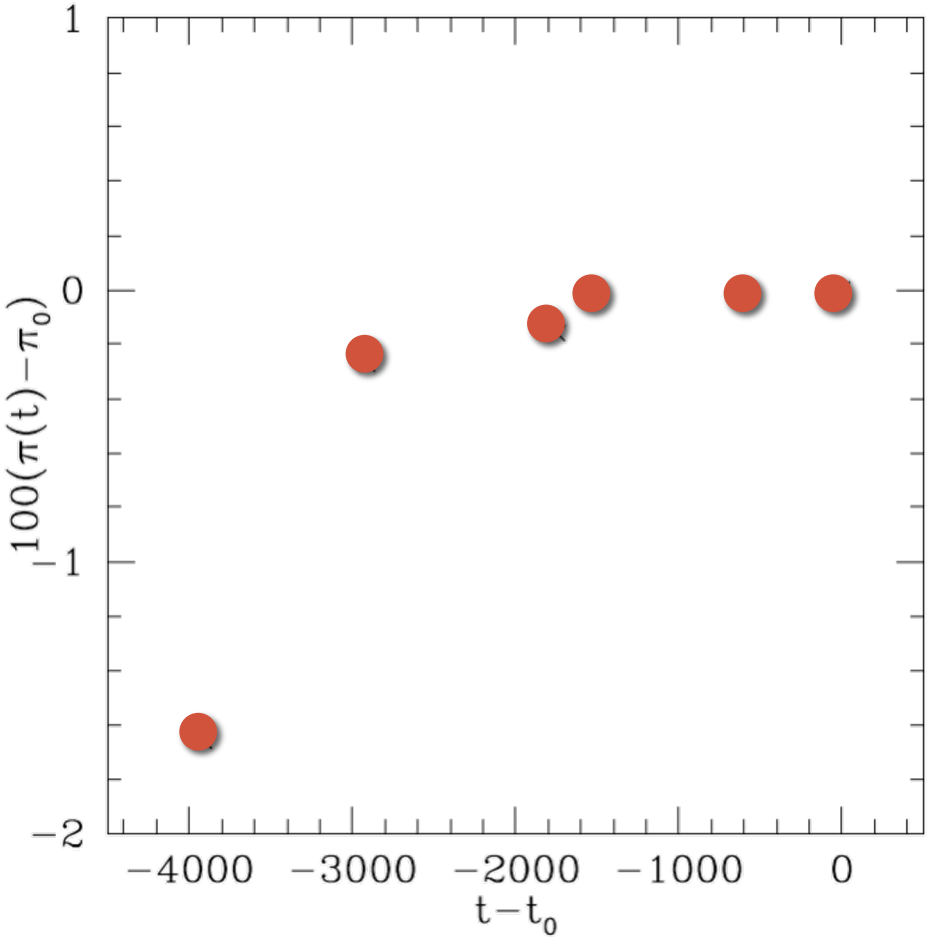
We examine the time variation of a previously-uninvestigated fundamental dimensionless constant. Constraints are placed on this time variation using historical measurements. A model is presented for the time variation, and it is shown to lead to an accelerated expansion for the universe. Directions for future research are discussed.

PACS numbers: 98.80.Cq

Location	Time	$\pi(t)$
Babylon	1900 BC	3.125
India	900 BC	3.139
China	263 AD	3.14
China	500 AD	3.1415926
India	1400 AD	3.14159265359



Thank you

- Experiment

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