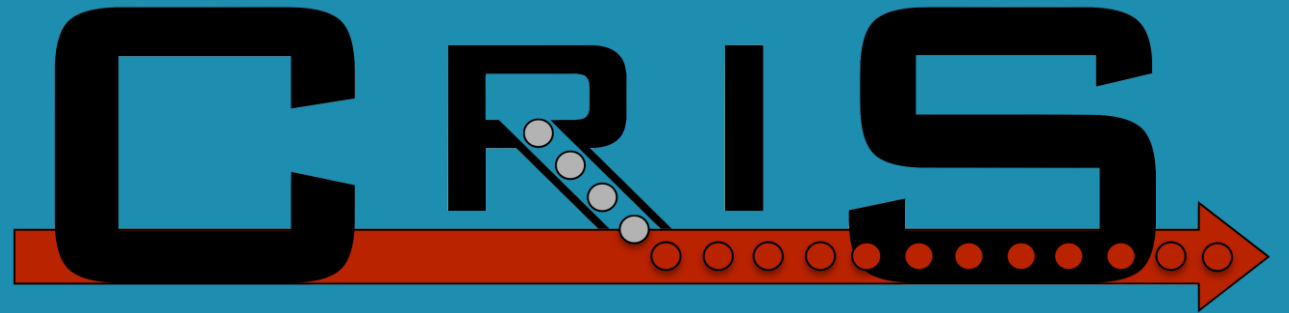


New results from the laser spectroscopy of RaF at CRIS towards searches for new physics



Michail Athanasakis-Kaklamanakis

December 2, 2022

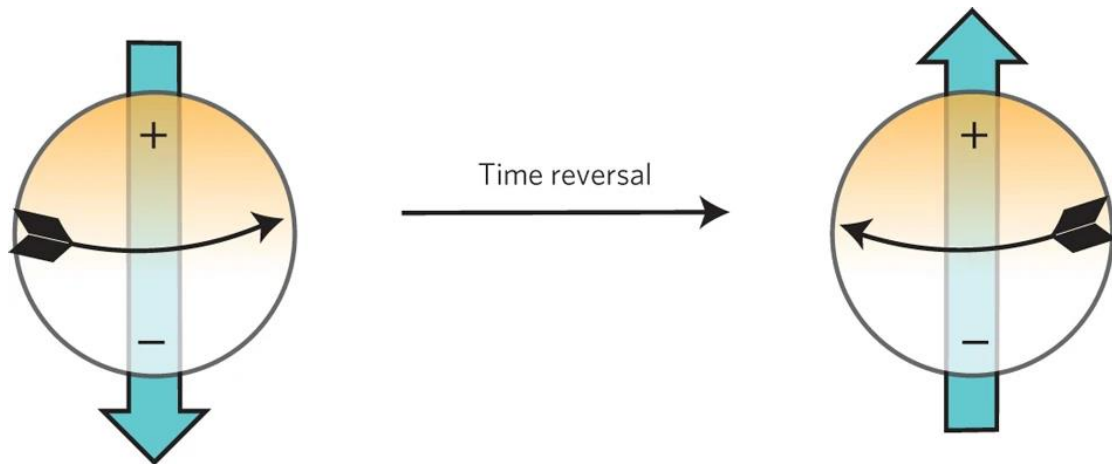
ISOLDE Workshop and Users Meeting 2022



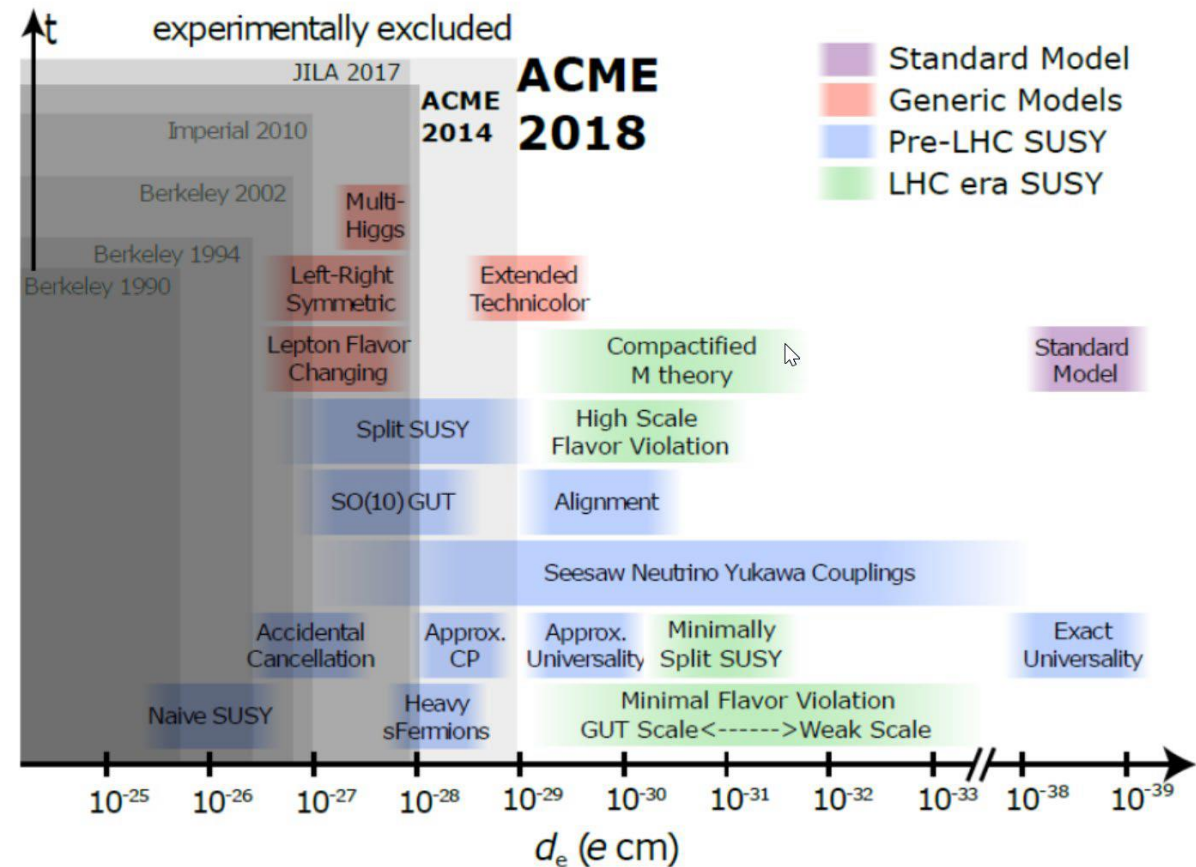
Symmetry-odd moments as a test of the Standard Model

The Standard Model is incomplete

- e.g. baryon asymmetry, strong CP problem
- Use magnitudes of symmetry-violating moments
 - Electric dipole moments (proton, neutron, electron)
 - Nuclear Schiff moment
 - Nuclear anapole moment
 - Nuclear magnetic quadrupole moment



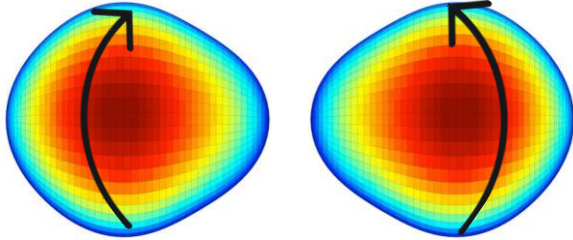
Benchmarks of Beyond-the-Standard-Model theories with the electron EDM



RaF is a highly promising system!

Heavy & deformed nucleus

Butler et al.,
PRL **124** (2020)



close-lying opposite-parity
rotational doublet

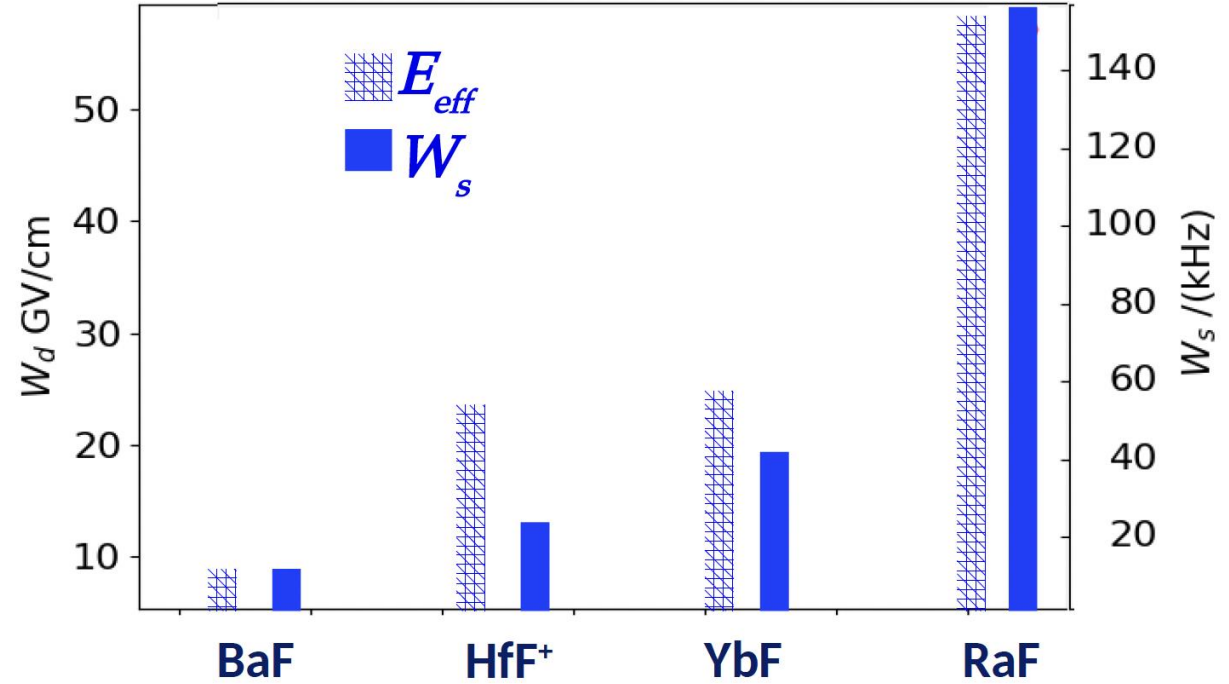
Gaffney et al.,
Nature **497** (2013)

$$|J^\pm\rangle = \frac{1}{\sqrt{2}} (|\Omega\rangle \pm |-\Omega\rangle)$$

stronger P, T -odd
interaction mixing $\alpha = \frac{\langle J^+ | \hat{W} | J^- \rangle}{E^+ - E^-}$

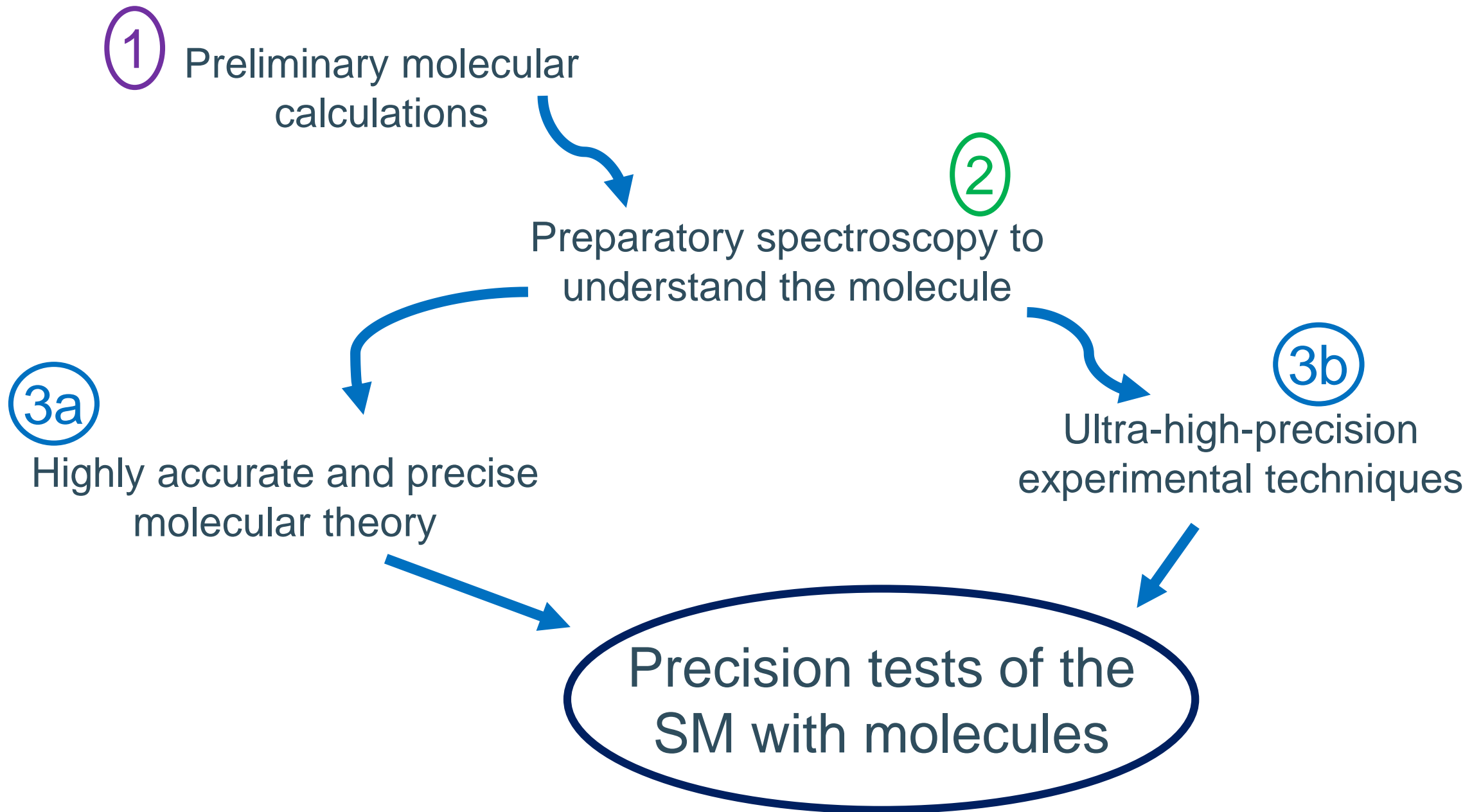
Enhanced symmetry-violating
nuclear moments in Ra

The spectra of RaF are highly sensitive to symmetry-violating nuclear and electronic moments

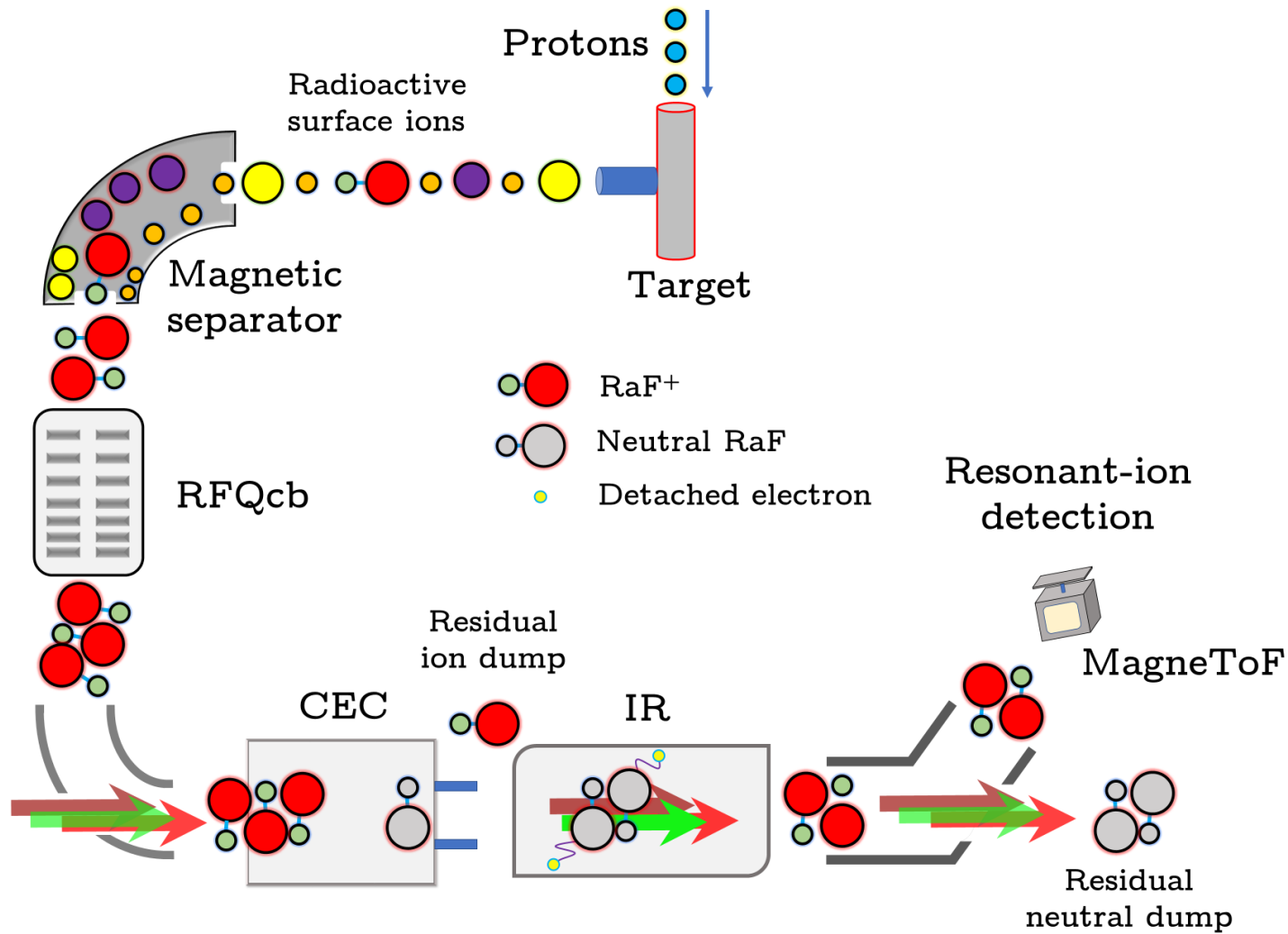


Plot courtesy of R. F. Garcia Ruiz and S. G. Wilkins (MIT)

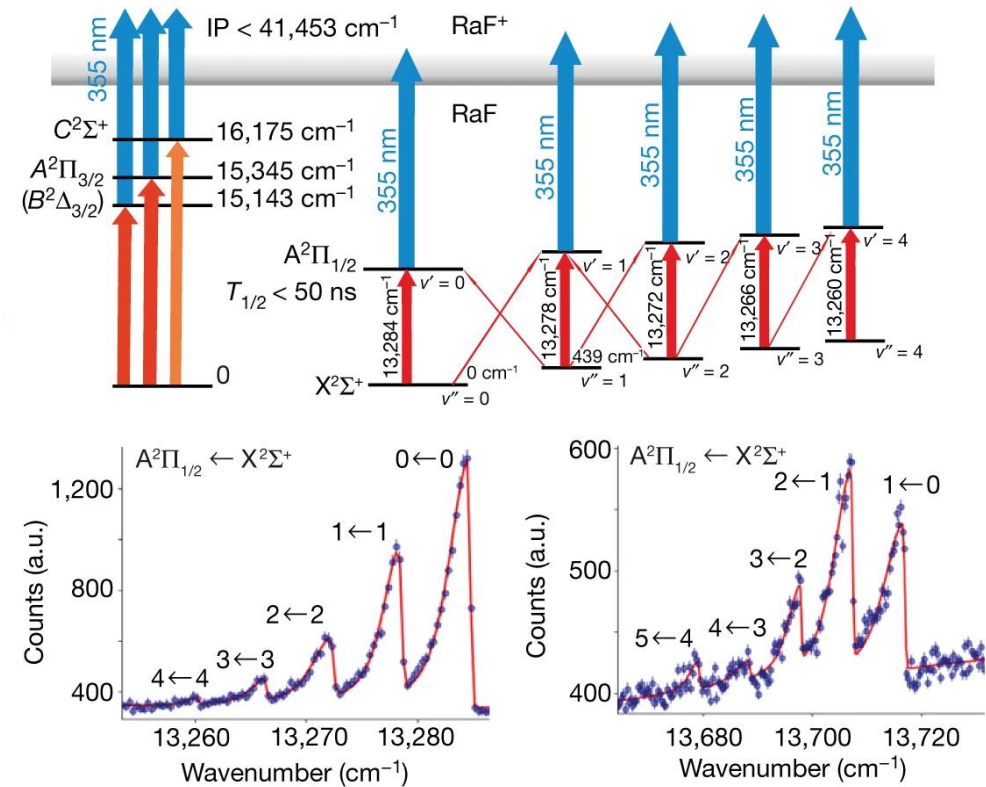
Signatures of P, T -violating moments are
 $\sim 10^3$ times stronger than in atoms!



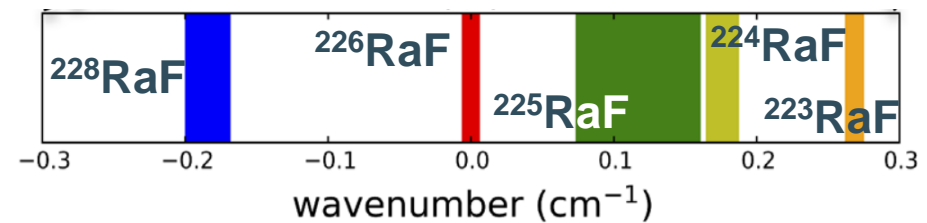
RaF at CRIS



RaF @ CRIS (2018)



Garcia Ruiz *et al.*, *Nature* **581**, 396-400 (2020)

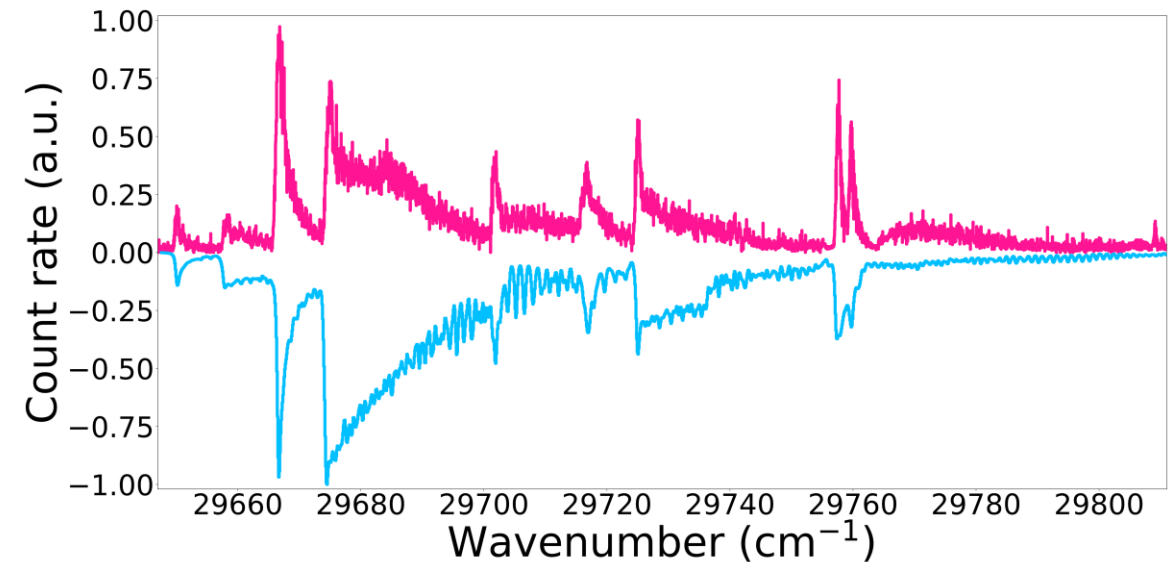
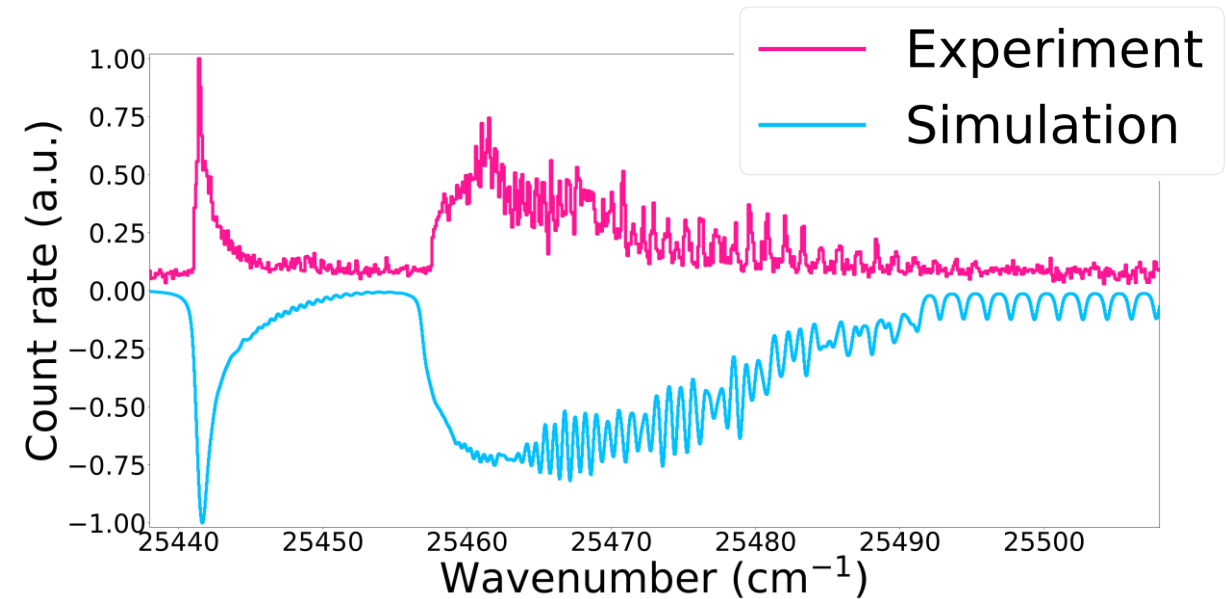


Udrescu *et al.*, *PRL* **127**(3), 033001 (2021)

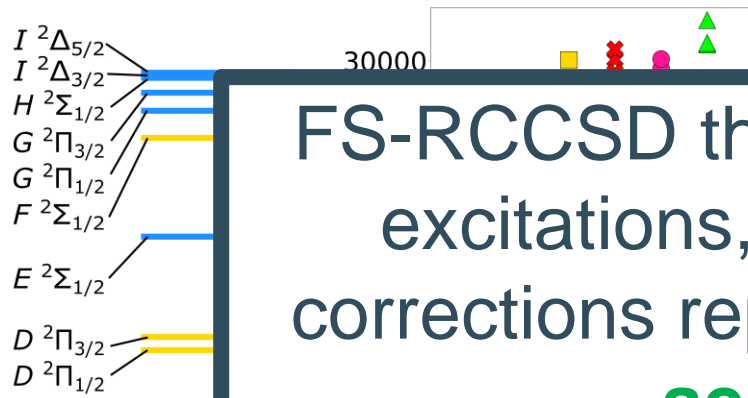
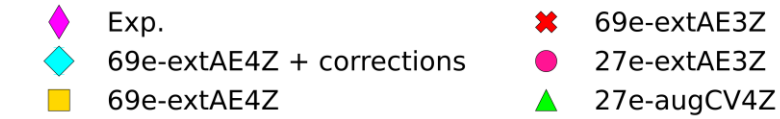
Excited electronic states

- Search for excited electronic states following theoretical predictions
- Measure spectra and extract molecular parameters
- Compare with predictions

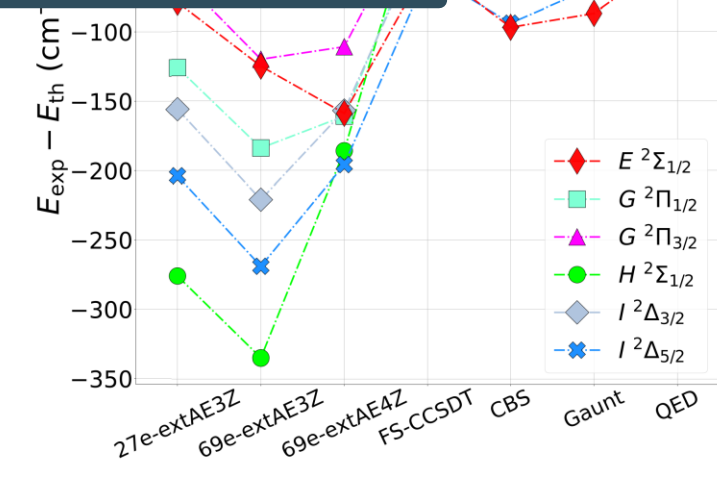
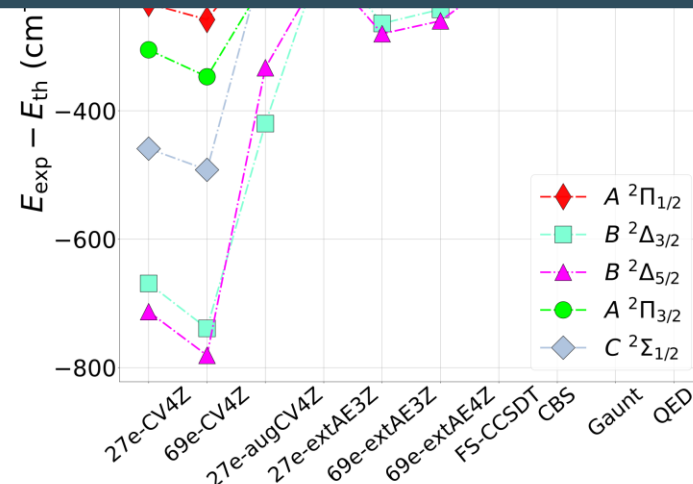
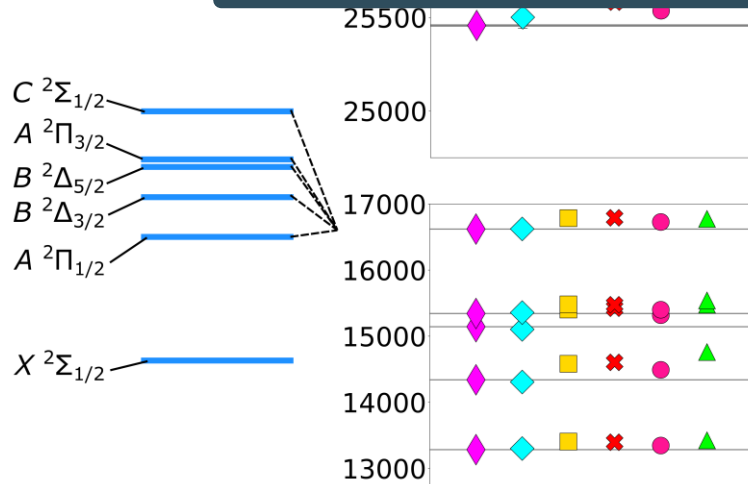
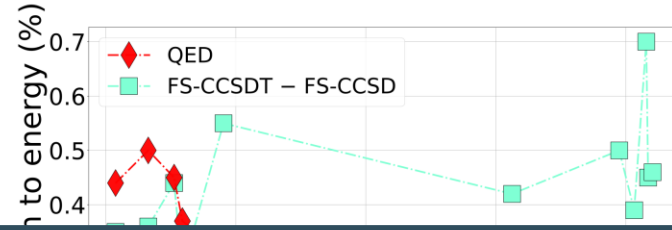
Powerful benchmark of precision molecular theory at high electronic energies



Compare excitation energies with Fock-space relativistic coupled cluster theory FS-RCCSD

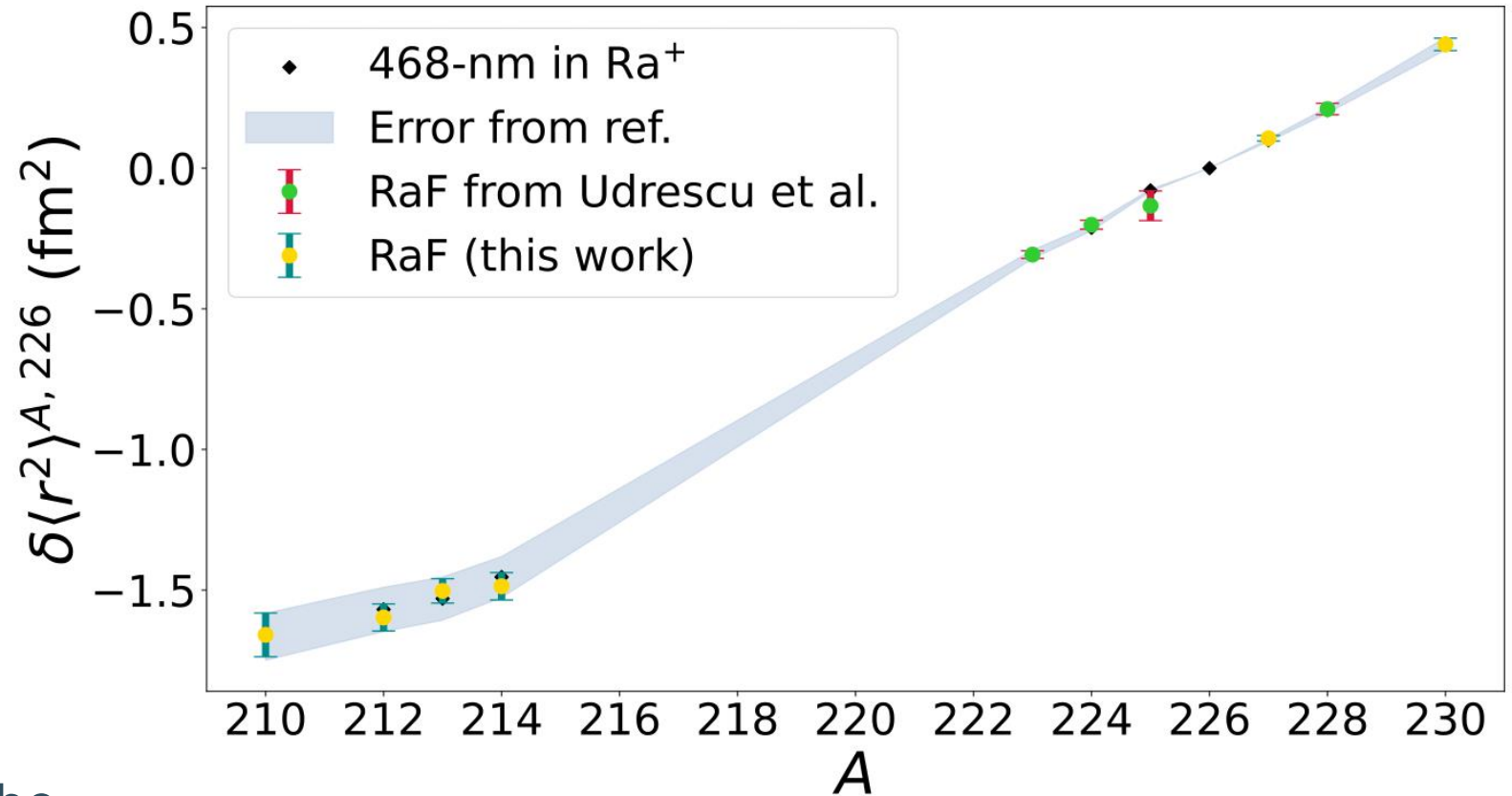


FS-RCCSD theory with 69 correlated electrons, triple excitations, basis-set extension, and Breit+QED corrections reproduces all excitation energies with an **accuracy of 99.7% or higher!**



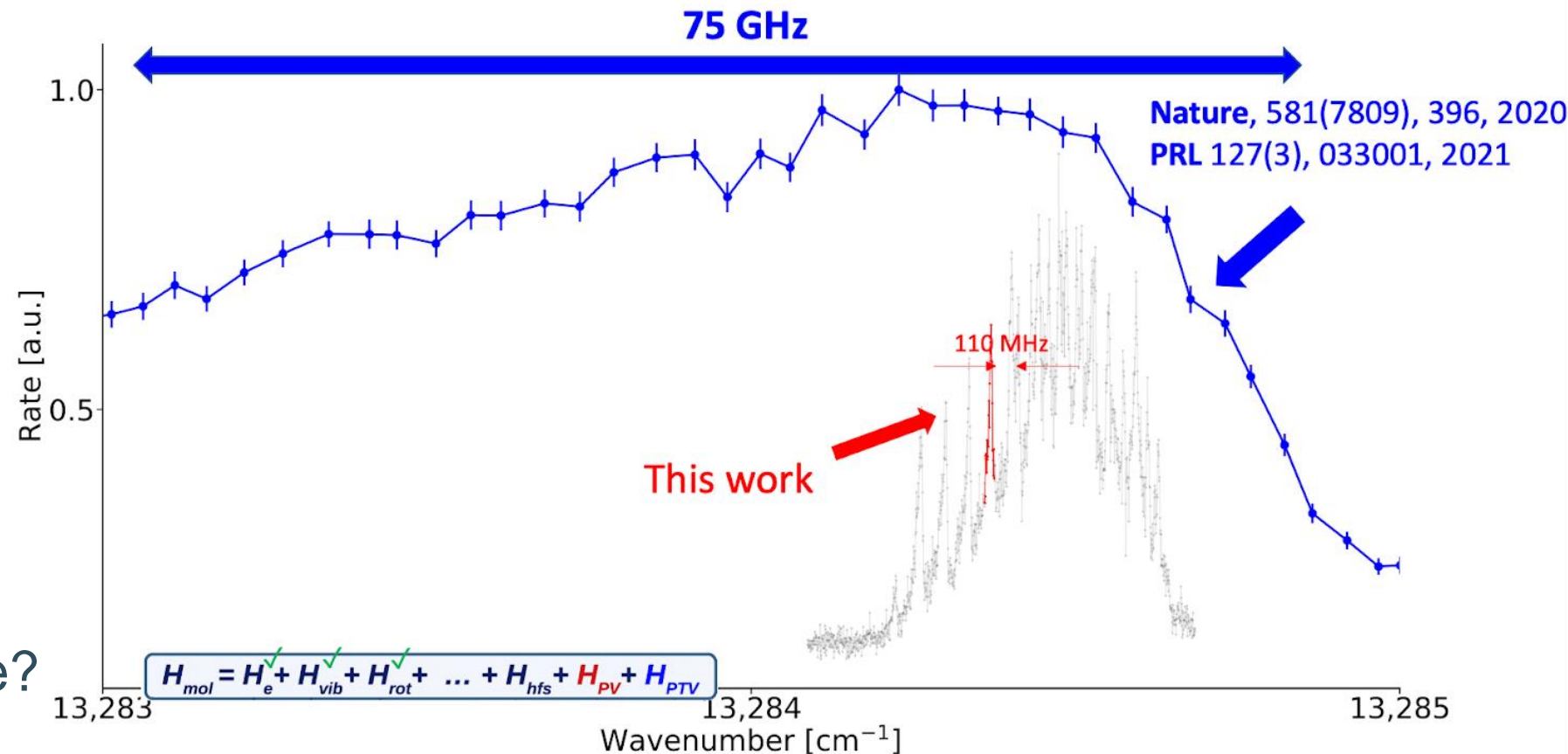
Isotope shifts

- Window to electron-nucleus overlap
- Quantum chemistry towards searches for new physics
- Explore nuclear effects in molecules
- Recent theoretical work on the topic from CRIS accepted at PRX



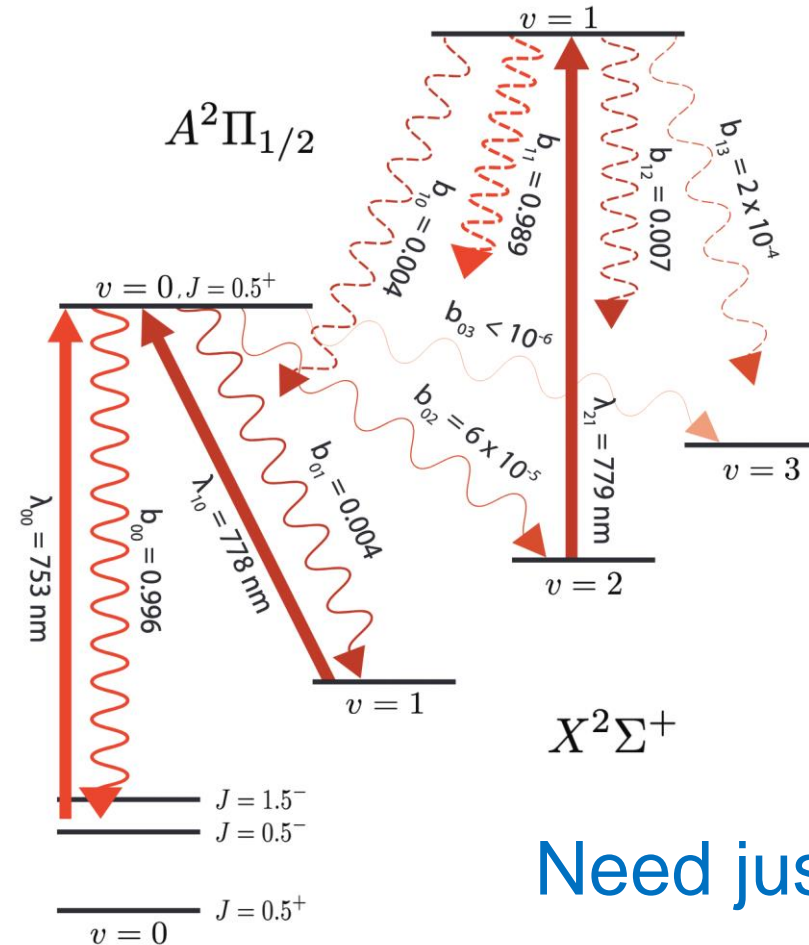
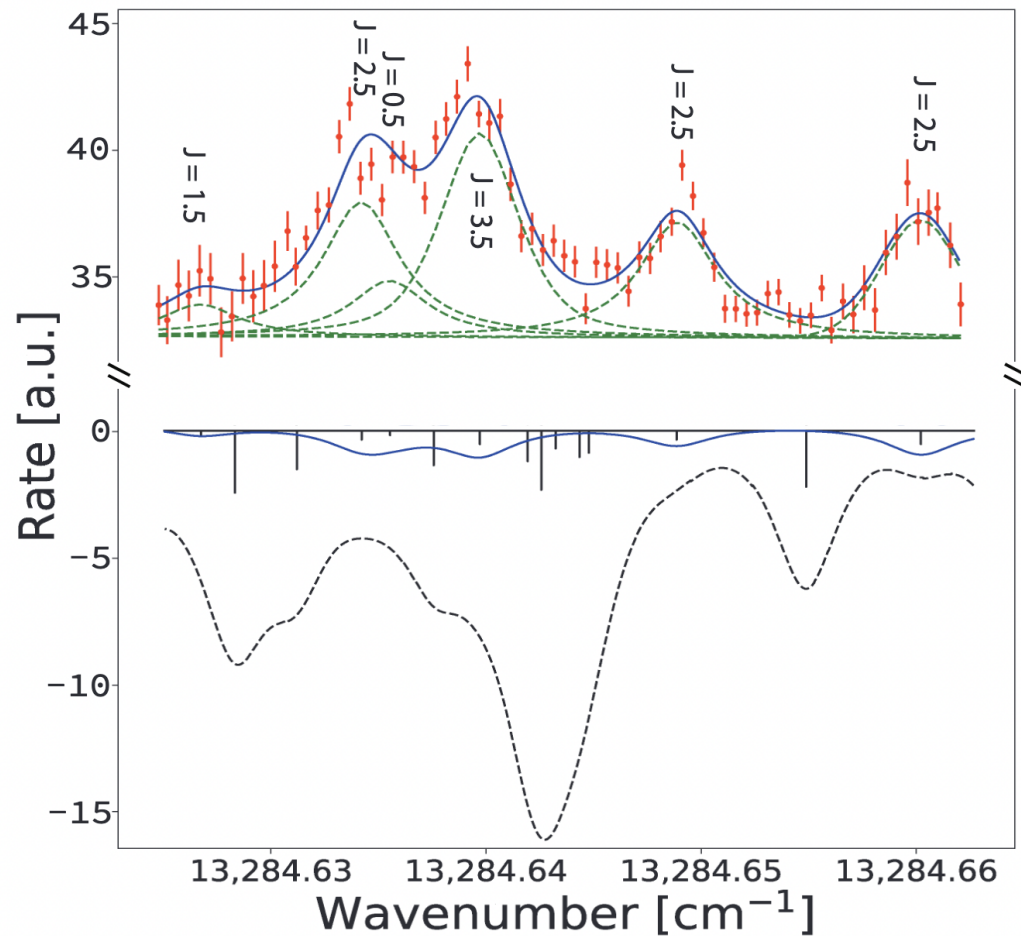
High-resolution spectroscopy: laser cooling

- Rotational structure
- High resolution
- ^{226}RaF , no Ra spin!
- Can we devise a laser-cooling scheme?



Laser-cooling scheme

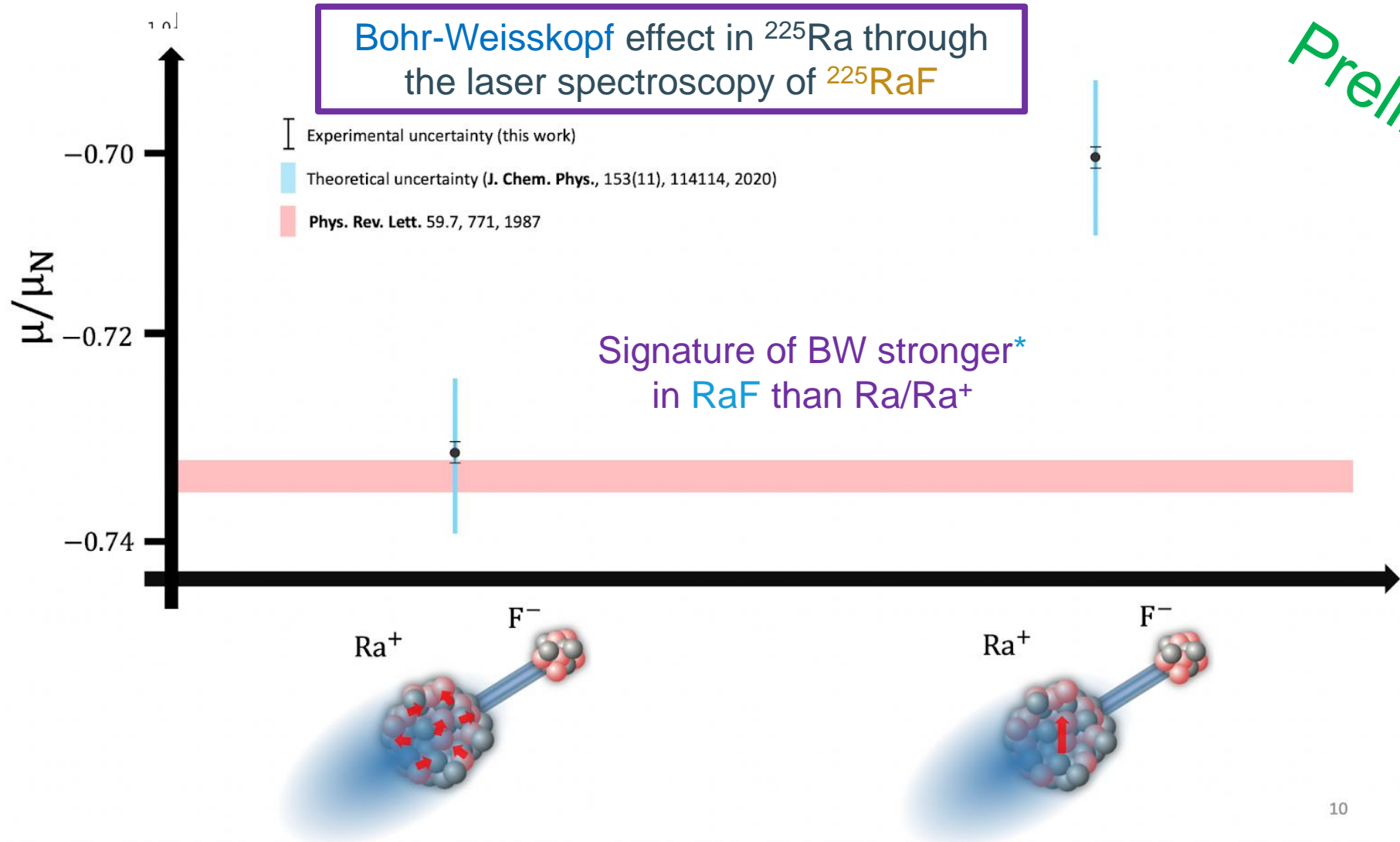
S.M. Udrescu, S.G. Wilkins, *et al.*, In preparation (2022)



Need just 3 lasers!

Hyperfine structure of ^{225}RaF

Wilkins, Udrescu, Athanasakis-Kaklamanakis *et al.*, in preparation (2022)

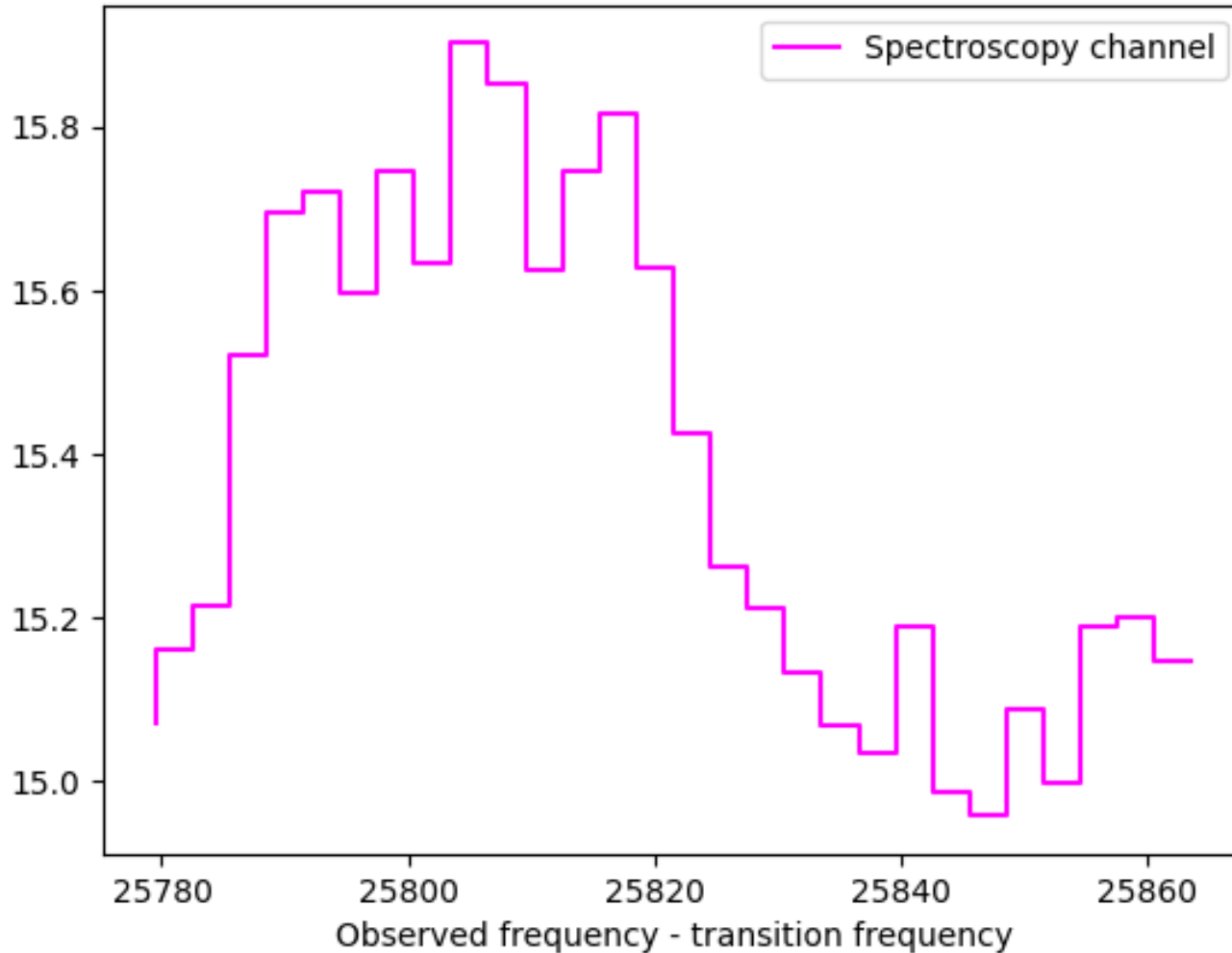


Preliminary!

Summary and next steps

- Molecules are promising for searches for new physics!
- Preparatory spectroscopy needed for all molecules
- CRIS can provide that! First experiments on RaF
- Excited electronic states → impressively accurate theory
- Isotope shifts to benchmark theory of nucleus-electron overlap
- Laser-cooling scheme
- Benchmark of calculated hyperfine factors and Bohr-Weisskopf effect

Test hfs model: AcF-22719, scan 4919



First spectra in AcF

Gathered as we speak

- First discovered electronic transition in AcF
- Within less than 30 /cm from prediction
- AcF sensitive to the nuclear Schiff moment

Special thanks

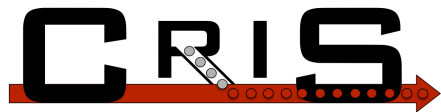


G. Neyens, S. G. Wilkins, R. F. Garcia Ruiz,
and the CRIS collaboration

<https://isolde-cris.web.cern.ch/>

and our molecules collaborators

L. V. Skripnikov, R. Berger, T. Isaev, K. Gaul, C. Zülch,
A. Borschevsky, A. Kiuberis, A. Breier, T. Giesen



UNIVERSITY OF
GOTHENBURG