

Short-lived radioactive (RaF) molecules: a sensitive laboratory for new physics

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Thanks to Ronald Garcia Ruiz (CERN, MIT)
for providing lot's of material for this presentation





CRIS Collaboration

J. Billowes, C. Binnersley, T.E. Cocolios, B. Cooper, K.T. Flanagan, S. Franchoo, V. Fedosseev, B.A. Marsh, M. Bissell, R.P. De Groote, R.F. Garcia Ruiz, A. Koszorus, G. Neyens, H. Perrett, F. Parnefjord Gustafsson, C. Ricketts, H.H. Stroke, A. Vernon, K. Wendt, S. Wilkins, X. Yang

ISOLTRAP (F. Wienholtz), RILIS (S. Wilkins, K. Chrysalidis)
Target group (S. Rothe), ISOLDE Technical group



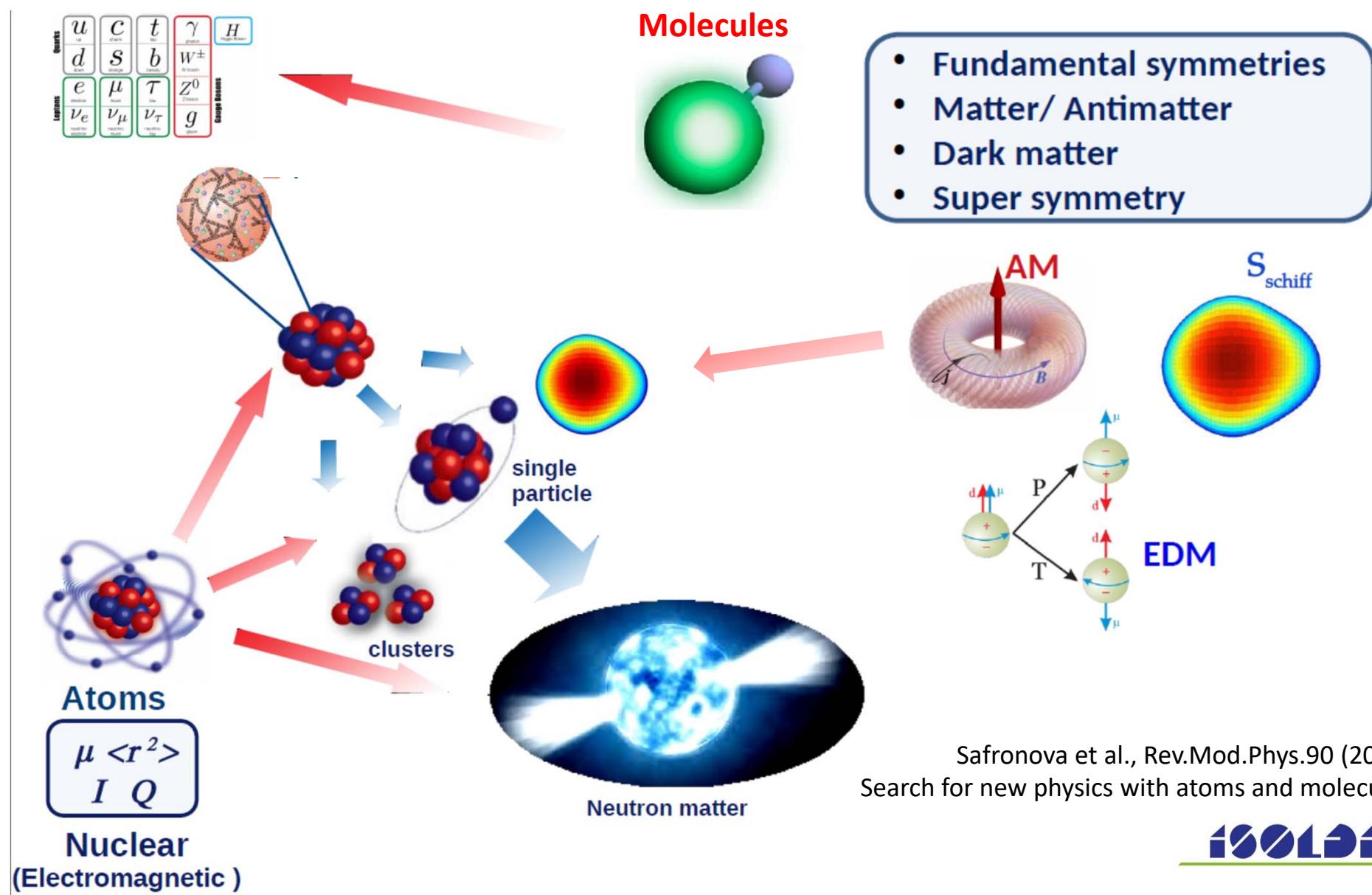
Massachusetts
Institute of
Technology



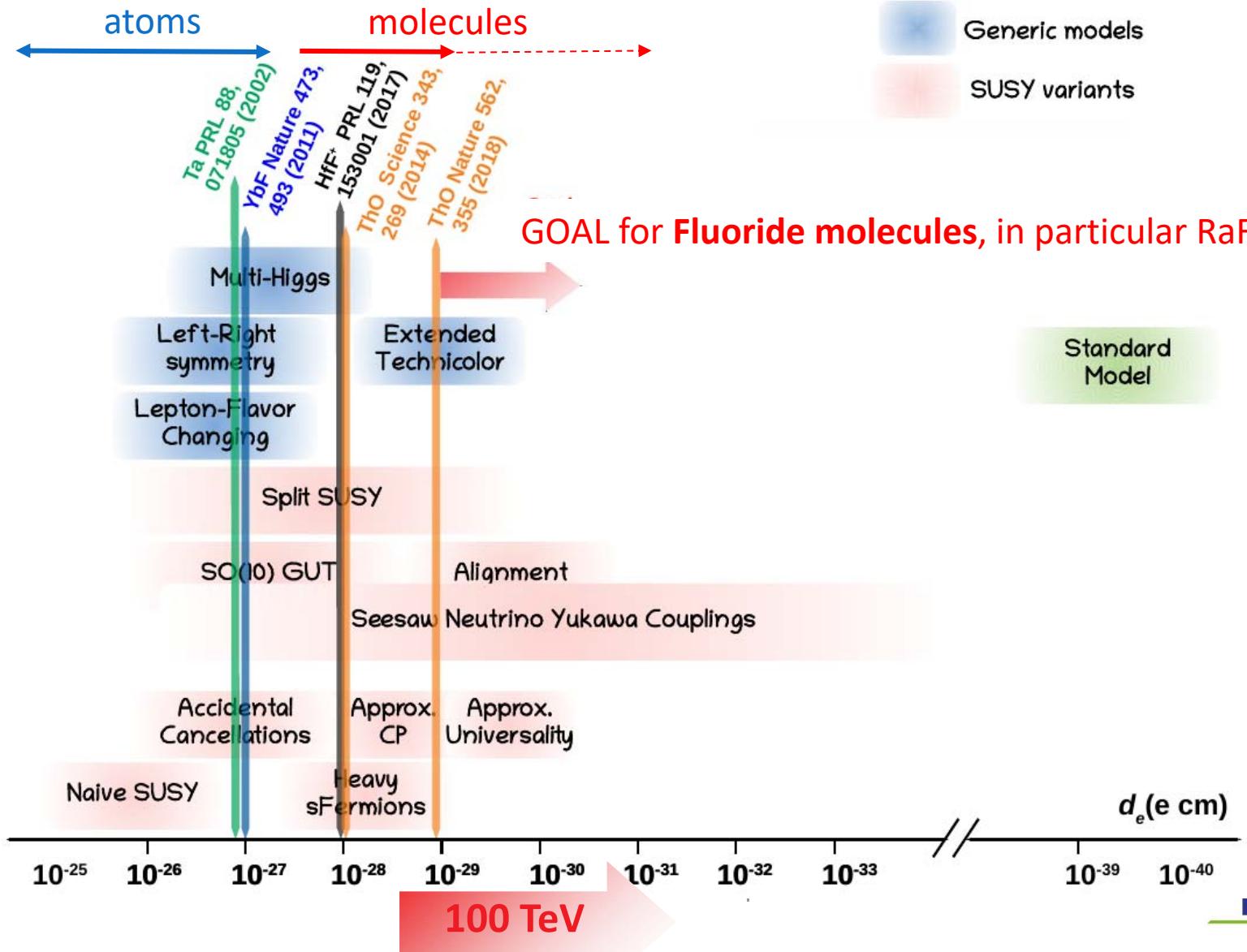
European Research Council
Established by the European Commission

Quantum chemistry: R. Berger (U. Marburg, Germany), T. Isaev (PNPI NRCKI, St. Petersburg)

Molecules: laboratories for nuclear and particle physics

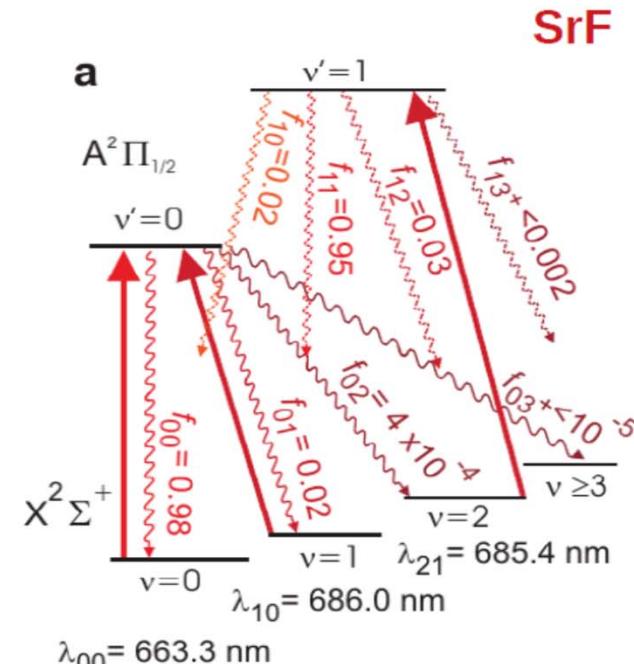


Best limit on electron EDM comes from molecules



Fluoride Molecules laser spectroscopy and cooling

- SrF → First evidence of laser cooling
[Nature 467, 820-823 (2010)]
- YbF → Nature 473, 493 (2011)
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- SrF → Nature Physics 13, 1173(2017)
- YbF → Phys. Rev. Lett. 120, 123201 (2018)
- CaF → Nature Physics 14, 890 (2018)
Phys. Rev. Lett. 120, 163201 (2018)



[Nature 467, 820-823 (2010)]

RaF PRA A 82, 052521 (2010) Isaev, Hoekstra and Berger

Laser-cooled RaF as a promising candidate to measure molecular parity violation

Why Radium (radioactive, Z=88) Fluorides?

- ✓ Large A and Z of Ra isotopes → enhanced E_{eff} increases sensitivity to eEDM by factor 10^5
- ✓ “Large enhancement of P,T-odd effects in nuclei with Octopole Deformation
→ Sensitive to MQM, Schiff Moment, ...
Flambaum, PRC99, 035501 (2019)
Flambaum et al., PRL 113, 103003 (2014)
Auerbach et al., PRL 76, 4316 (1996)
- ✓ Access to different nuclear isotopes (spins)
→ Nuclear spin-dependent PV interactions
Aluntas et al., PRL 120, 142501 (2018)

Molecules: Electroweak structure

- Anapole moment: AM
- Magnetic Quadrupole Moment: MQM
- Schiff Moment: S_{schiff}
- eEDM, nEDM, ...

P- and P,T- odd effects

[Isaev & Berger Phys. Rev. A 82, 052521 (2010)]
[Kudashov Phys. Rev. A 90, 052513 (2014)]

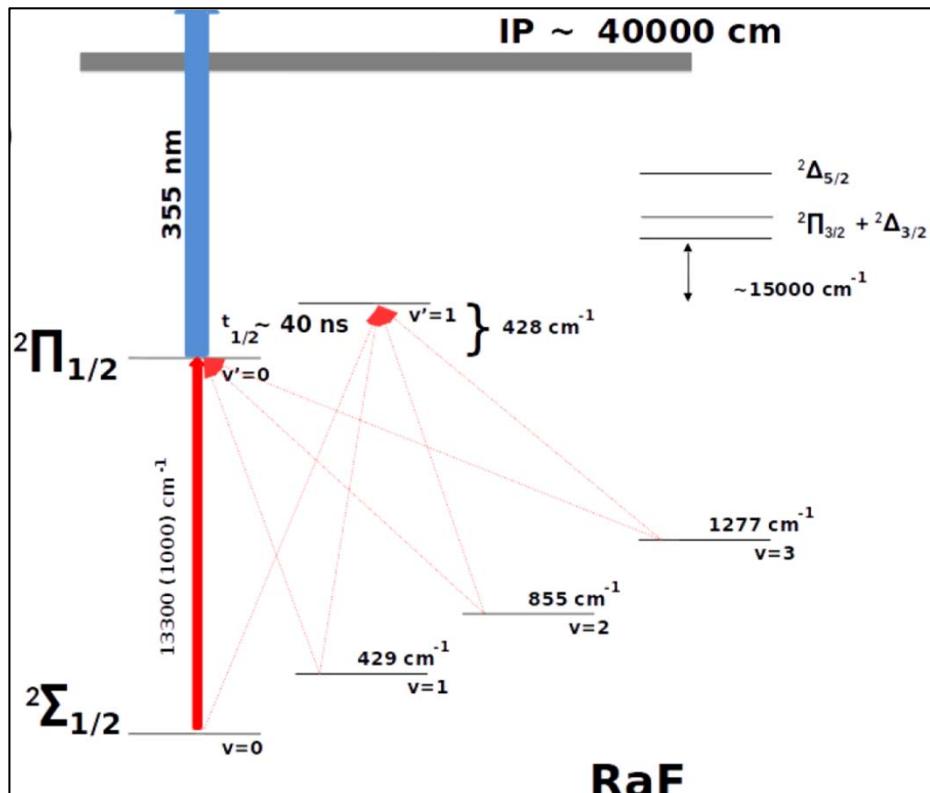


RaF → All-in-one probe

[Gaffney et al. Nature 497, 199 (2013)]

BUT....

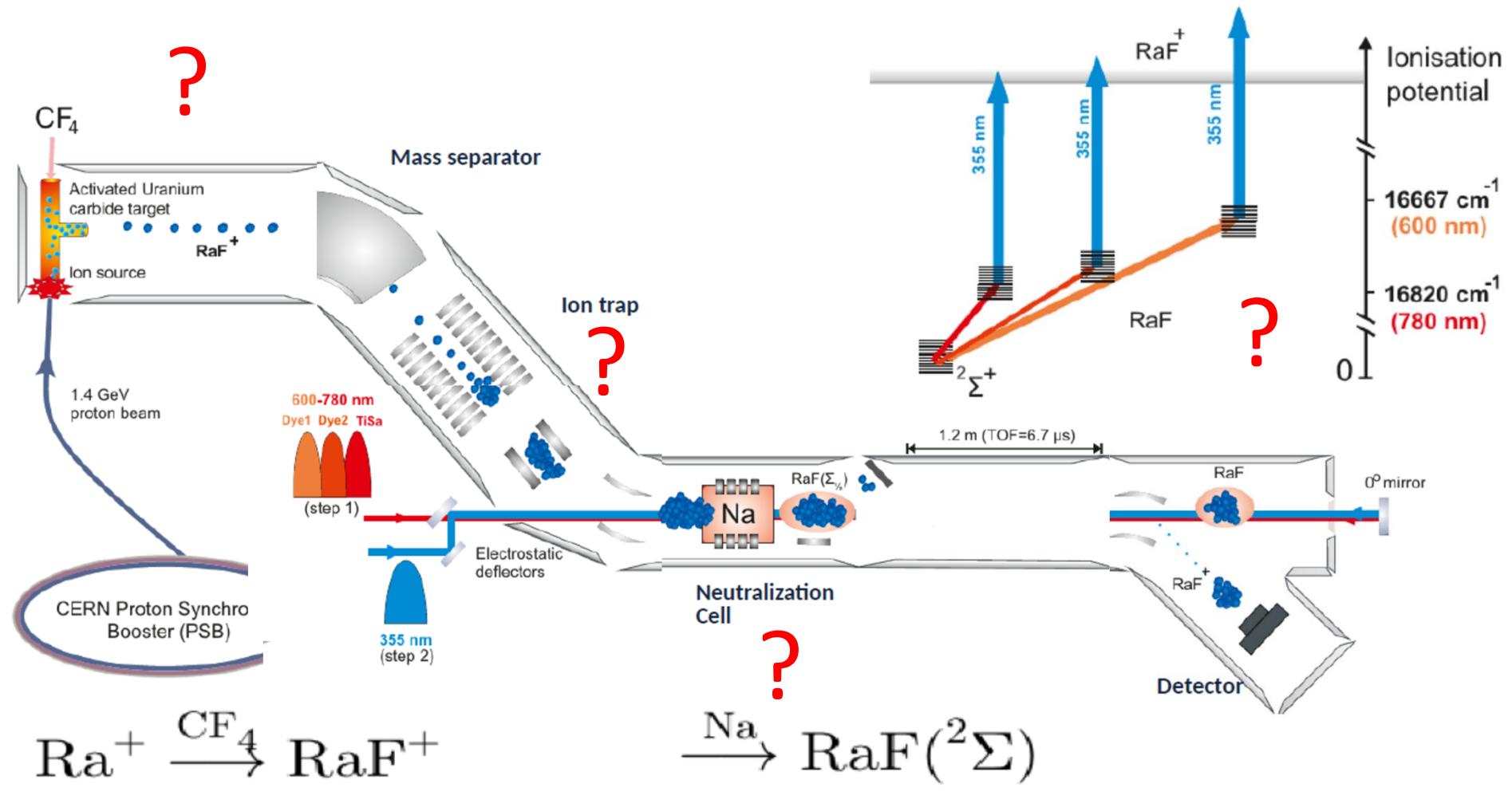
- No experimental spectroscopy on RaF known
- ✓ November 29, 2017: Robert Berger (Marburg) gives seminar to the ISOLDE Physics Group
"Molecules as versatile probes for Physics Beyond the Standard Model"



- ✓ January 10, 2018: Ronald Garcia Ruiz and Robert Berger submit a proposal to INTC
"Collinear resonance ionization spectroscopy of RaF molecules" CERN-INTC-2018-017 (2018)
Spokespersons:
R.F. Garcia Ruiz, S. Wilkins, R.P. de Groot
- ➔ approved February 2018, to run as 'winter physics' without protons (never done before)!

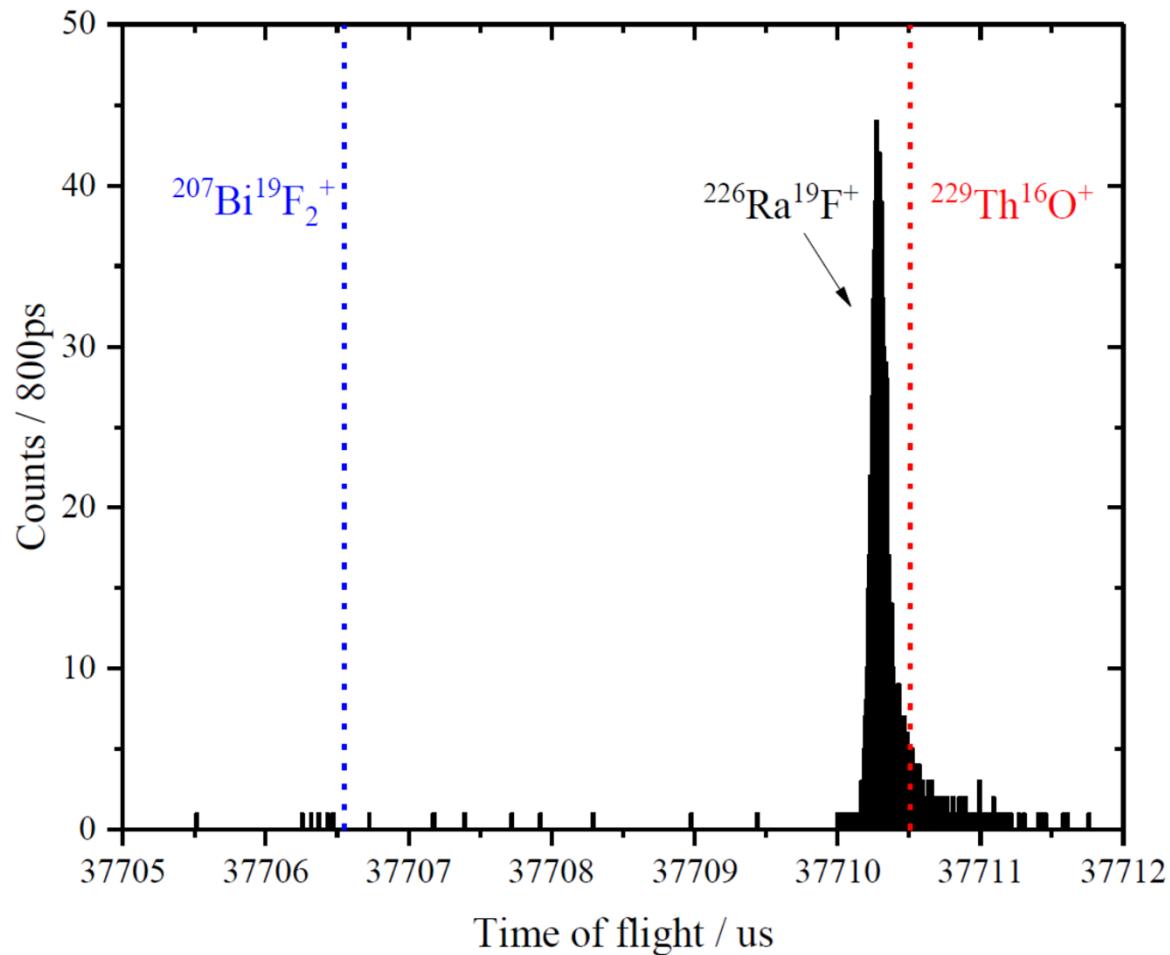
- ✓ December 2018: EXPERIMENT planned for 5 days, continued 12 days !

Unknowns in the experiment



Production of RaF confirmed by MR-TOF

(thanks to F. Wienholtz)



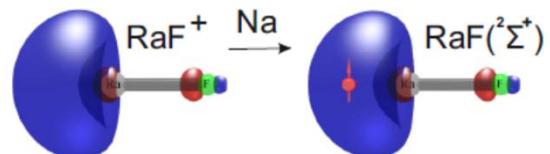
Other possible complications

Molecules have complex structures

→ More than 10⁴ states can be populated

Vibrational / rotational / hyperfine

Impossible with a hot (> 300 K) molecule?



Theory: 13300(1000)cm⁻¹

Scanning 1000 cm⁻¹ at 10 MHz/min (1 cm⁻¹ = 30 GHz)

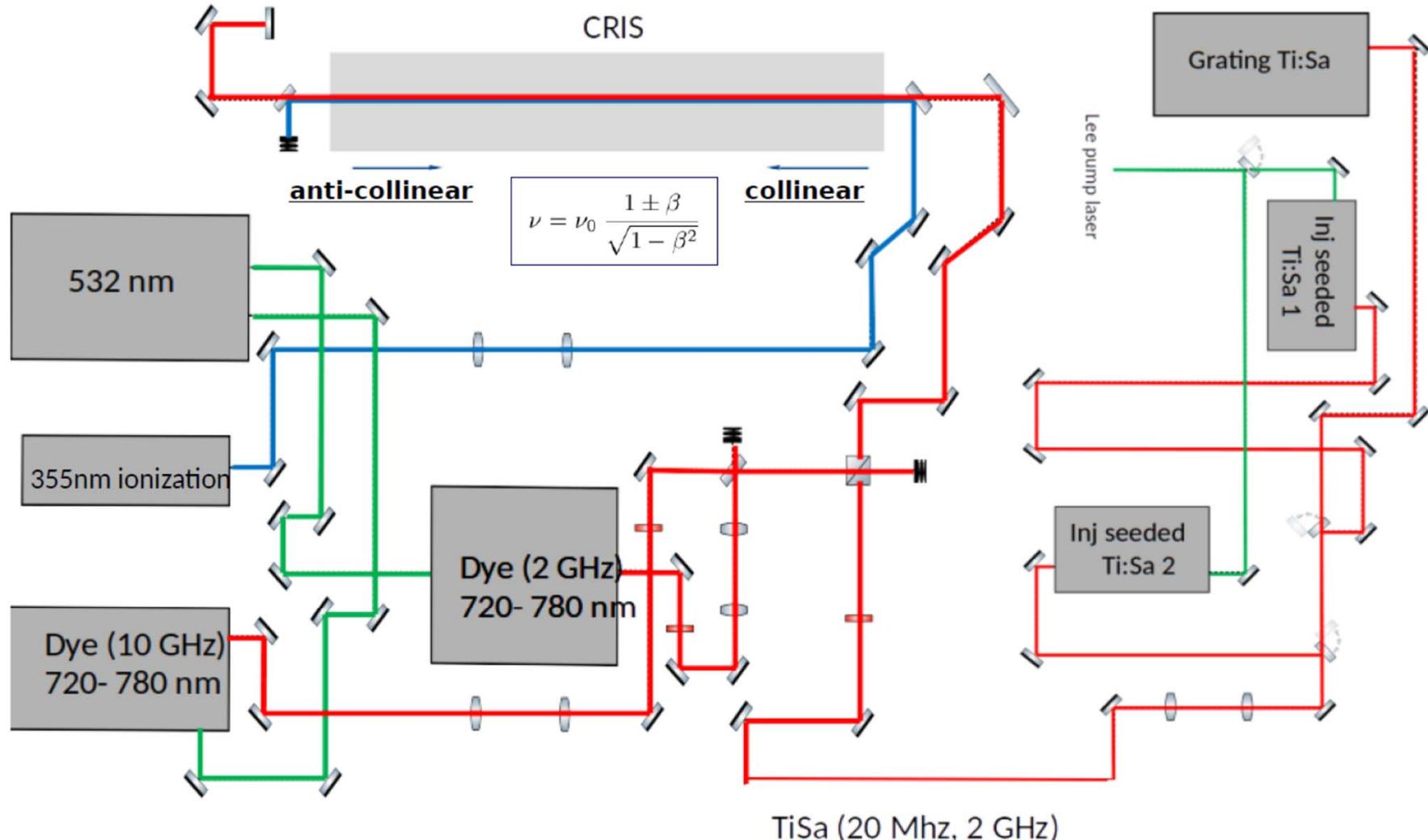
→ 2080 days!!

→ How to make the impossible a little more possible:

- set-up 3 different lasers to scan 3 regions simultaneously
- set-up collinear / anti-collinear laser beams: scan 6 regions simultaneously !
- take advantage of all possible disadvantages for laser spectroscopy
(laser bandwidth, power broadening, energy spread, ...)

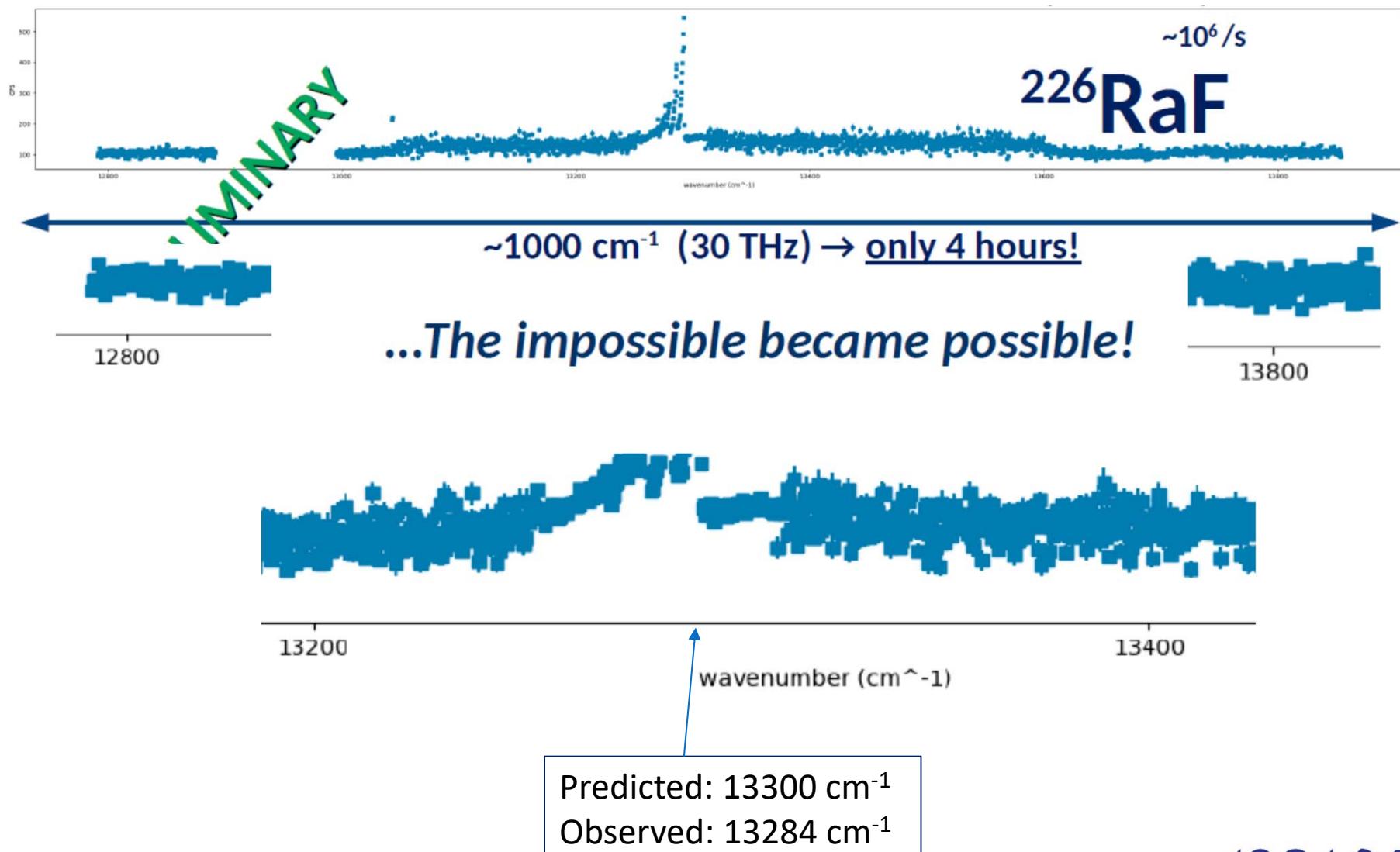
Broad-band and narrow-band lasers

(about 20 lasers from CRIS and RILIS)

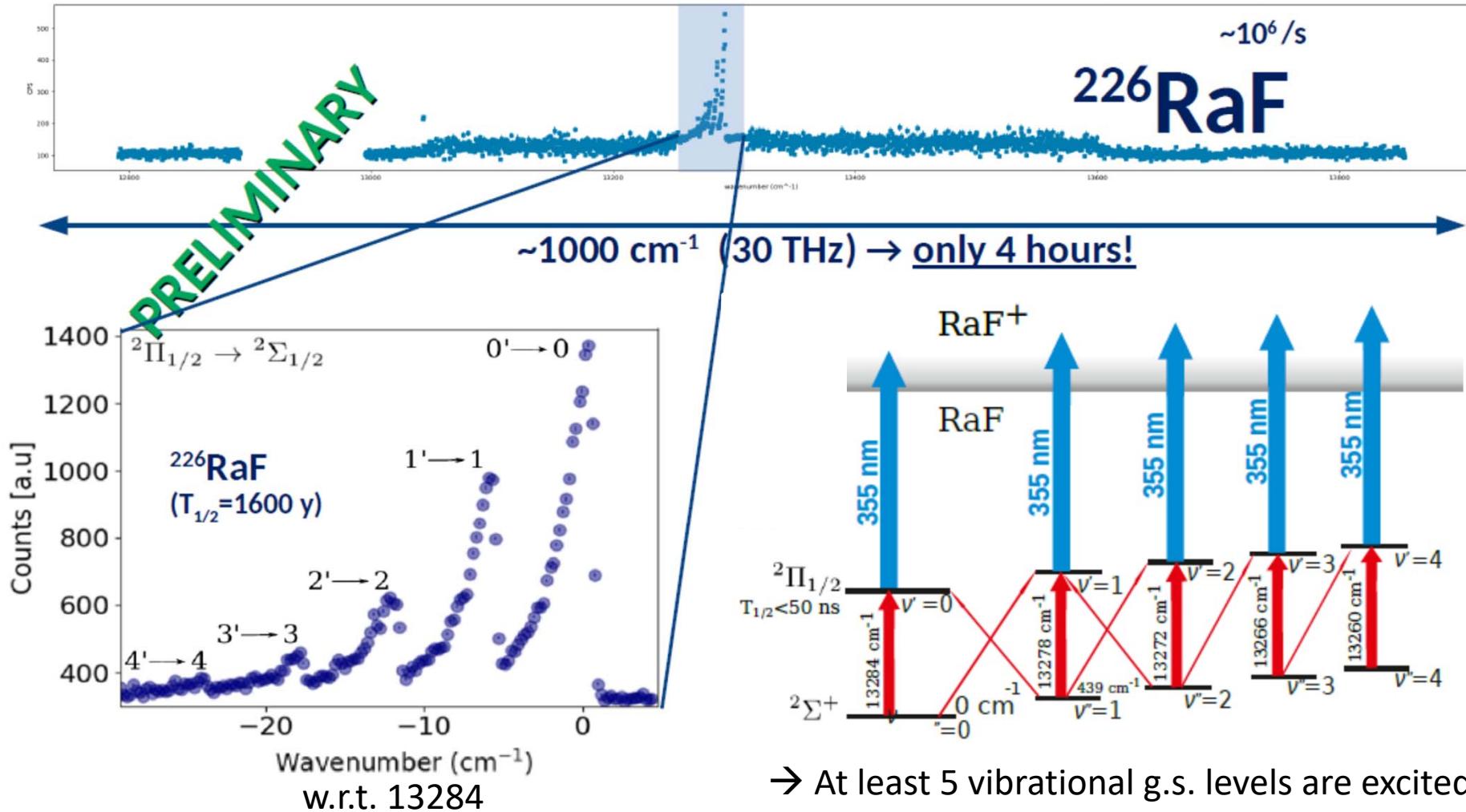


About 20 laser systems
(simplified scheme)

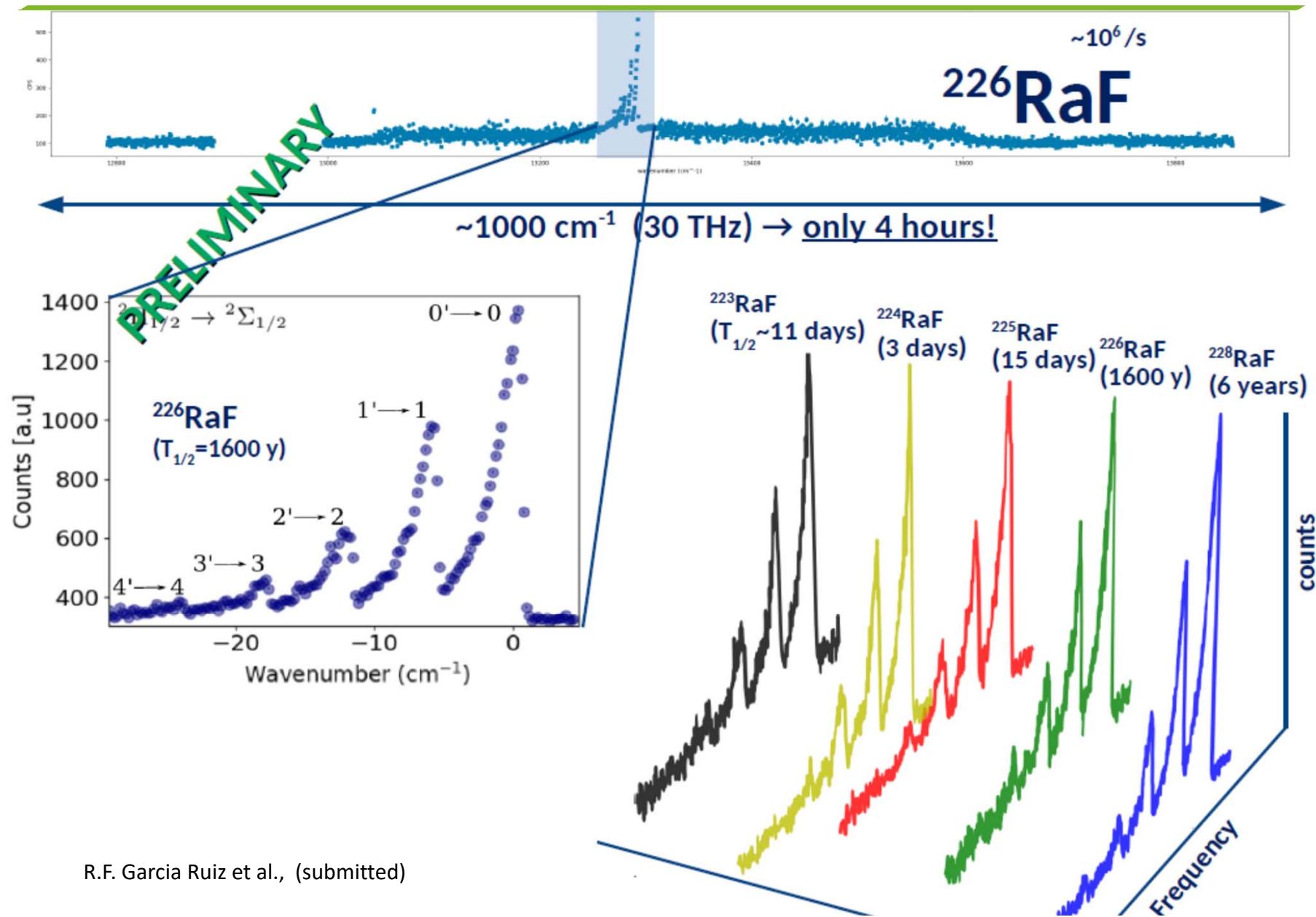
RaF Results with ^{226}Ra ($I=0$)



RaF Results: vibrational structures



RaF Results: $^{223,225}\text{RaF}$ and $^{224,226,228}\text{RaF}$



RaF Results: suited for laser cooling

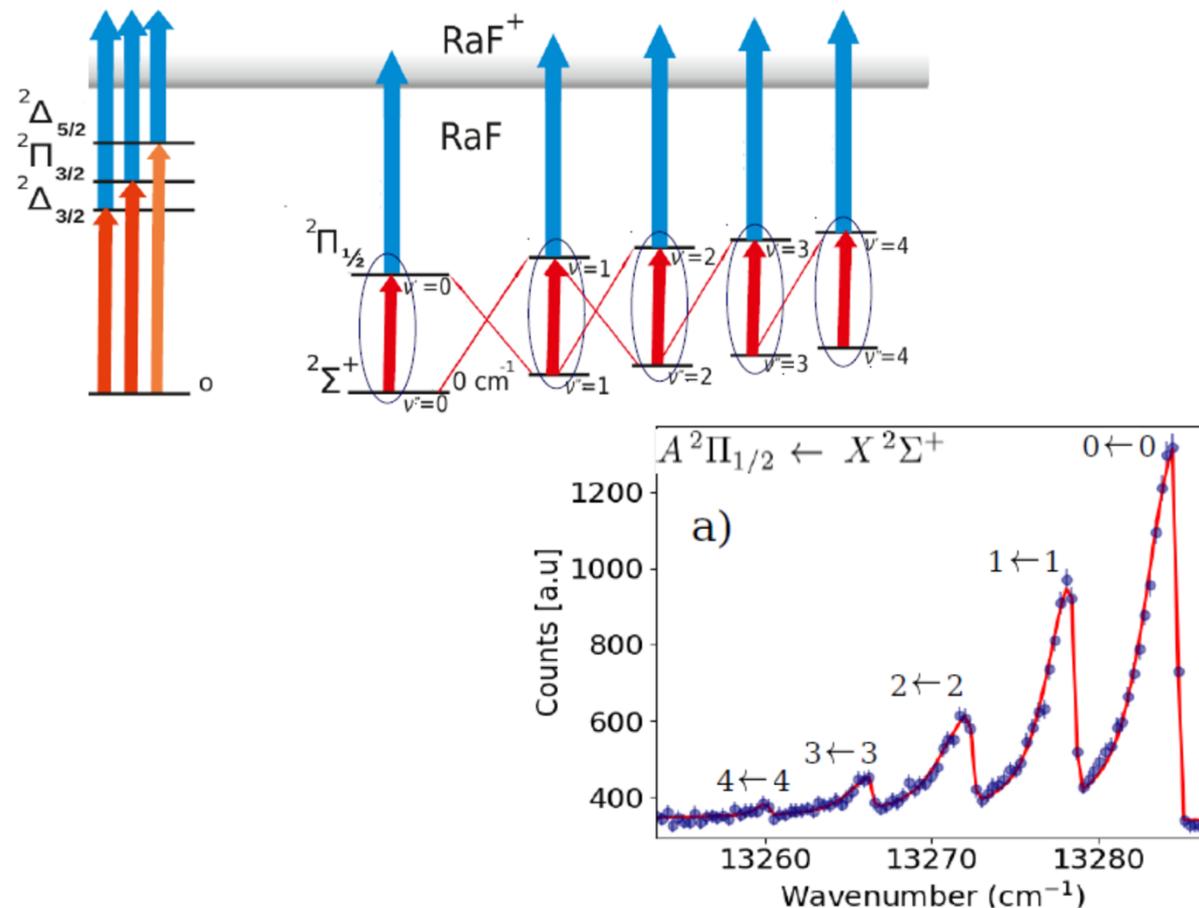
I. Low-lying structure

II. Feasibility of laser cooling?

1. Dominant f_{00} ?

2. Short-lived excited state ($T_{1/2}$)?

3. Electronic states of lower energy (E)?



RaF Results: suited for laser cooling

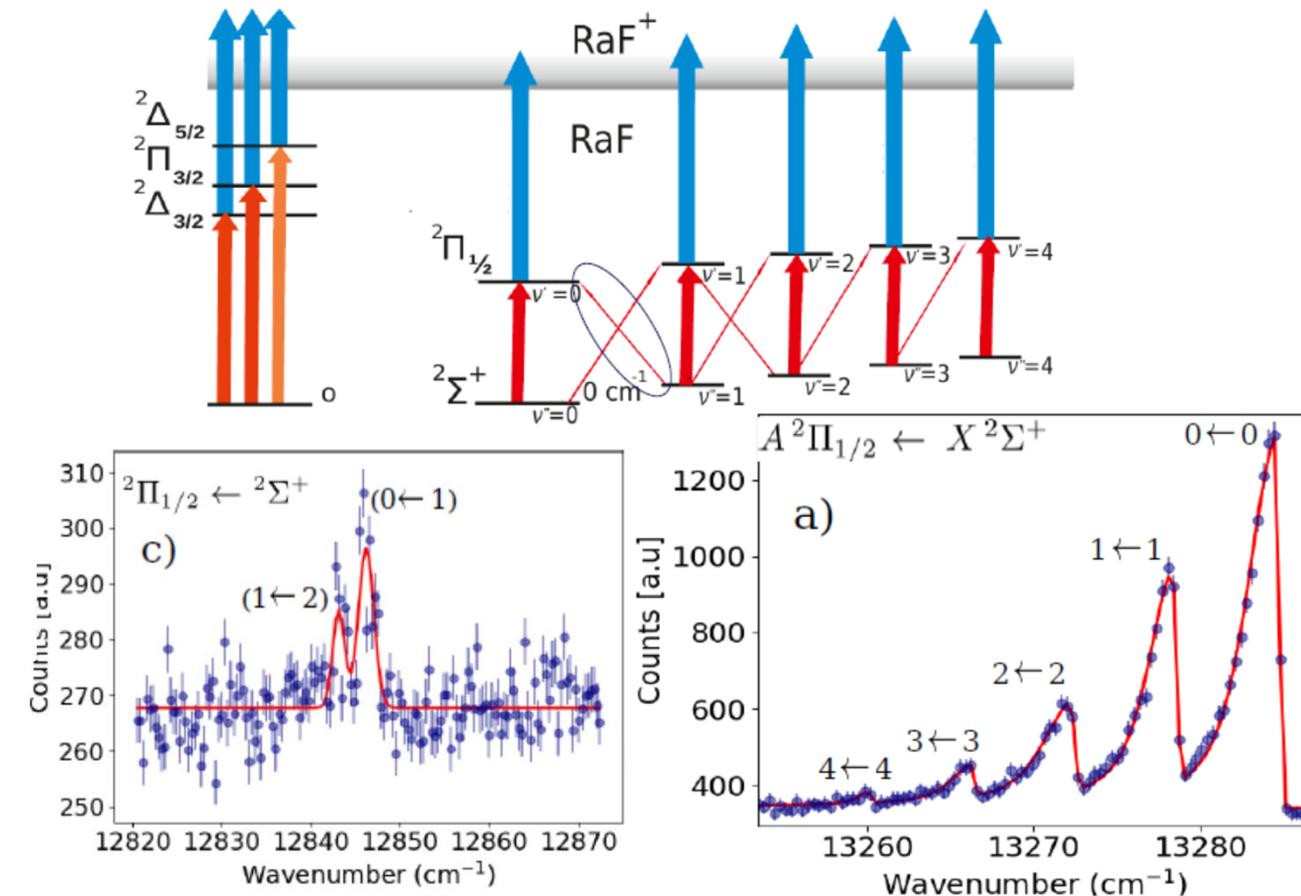
I. Low-lying structure

II. Feasibility of laser cooling?

1. Dominant f_{00} ? $\rightarrow f_{00}/f_{ij} > 0.97$

2. Short-lived excited state ($T_{1/2}$)?

3. Electronic states of lower energy (E)?



RaF Results: suited for laser cooling

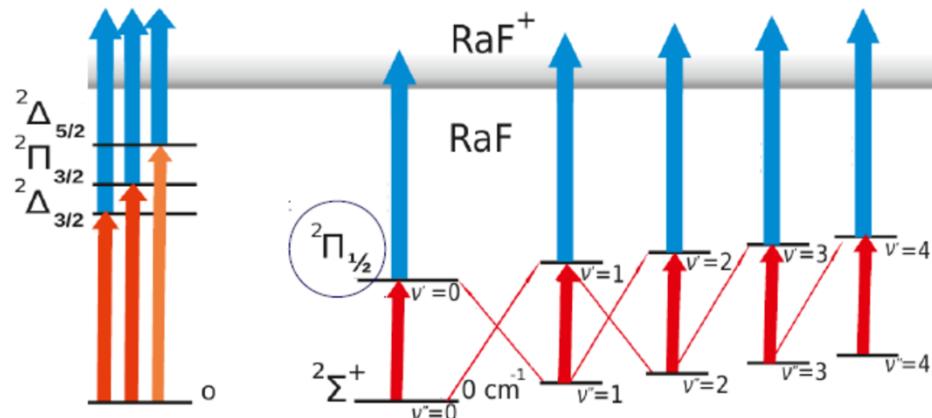
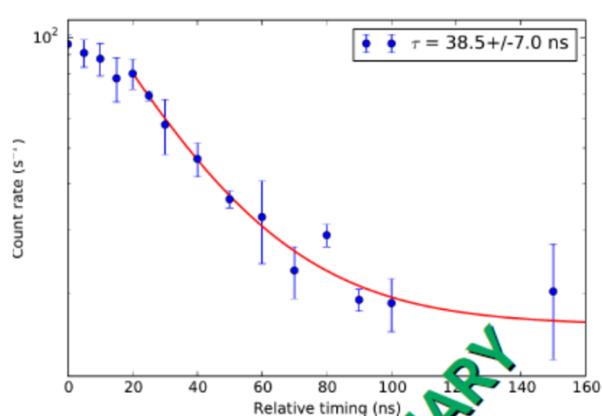
I. Low-lying structure ✓

II. Feasibility of laser cooling?

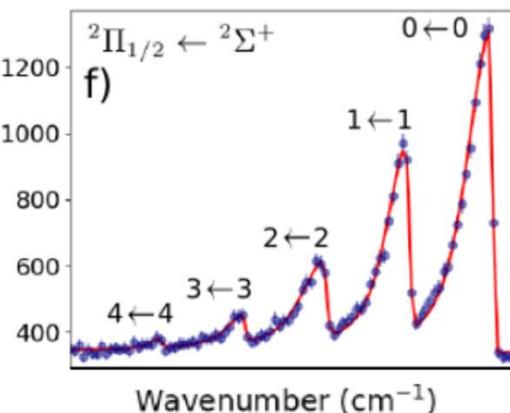
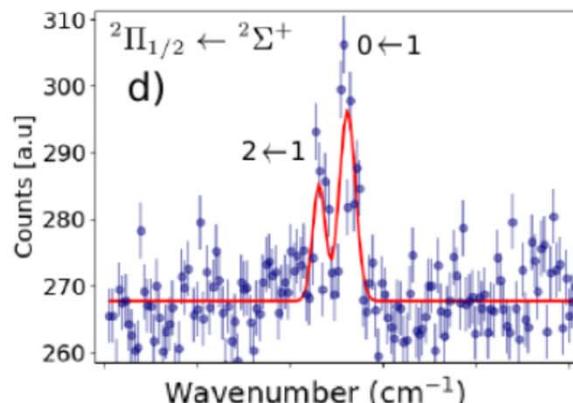
1. Dominant f_{00} ? $\rightarrow f_{00}/f_{ij} > 0.97$ ✓

2. Short-lived excited state ($T_{1/2}$)? $\rightarrow T_{1/2} < 50$ ns ✓

3. Electronic states of lower energy (E)?

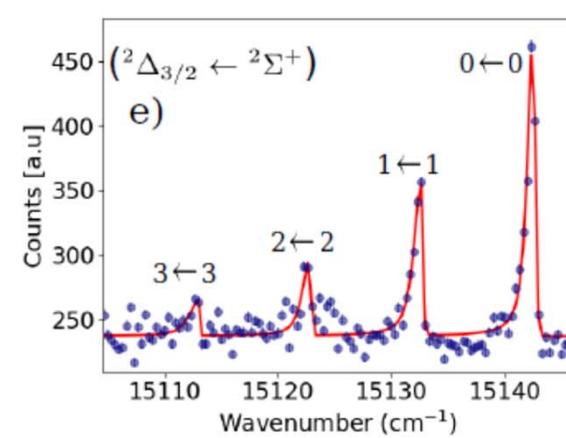
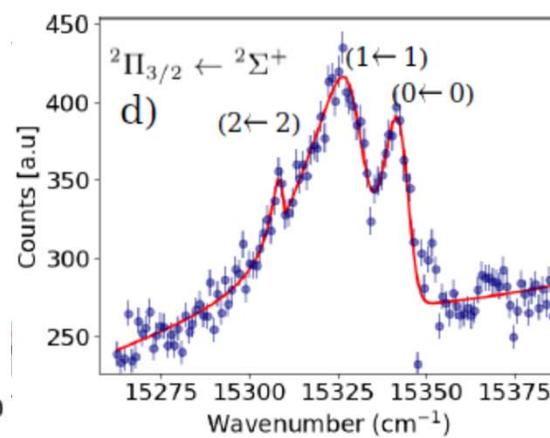
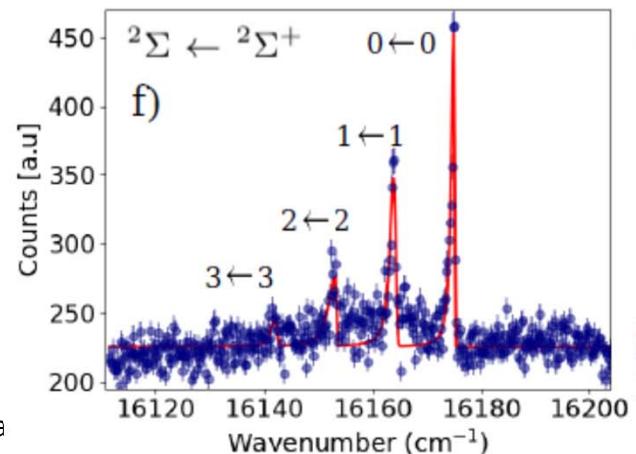
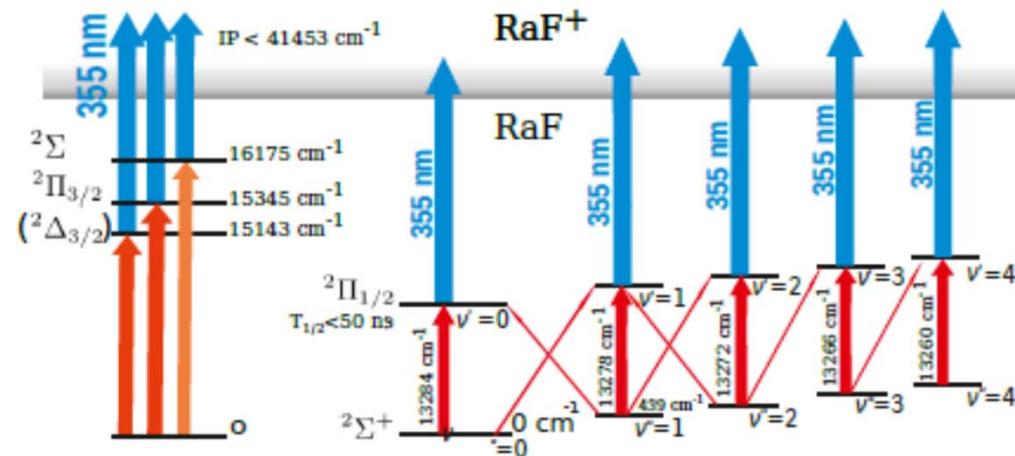


PRELIMINARY



RaF Results: suited for laser cooling

- I. Low-lying structure ✓
- II. Feasibility of laser cooling?
 1. Dominant f_{00} ? $\rightarrow f_{00}/f_{ij} > 0.97$ ✓
 2. Short-lived excited state ($T_{1/2}$)?
 3. Electronic states of lower energy (E)?



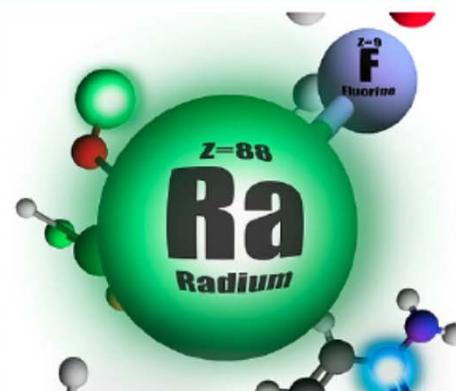
Conclusions and Outlook

First laser spectroscopy on short-lived RaF molecules demonstrated suitable level scheme for laser cooling

- Radioactive molecules → New window to study the atomic nucleus

Molecules: Electroweak structure

- Anapole moment: AM
- Magnetic Quadrupole Moment: MQM
- Schiff Moment: S_{schiff}
- eEDM, nEDM, ...



- “Hot” molecules can be super cool!