

Prospects for radium molecules to search for new physics



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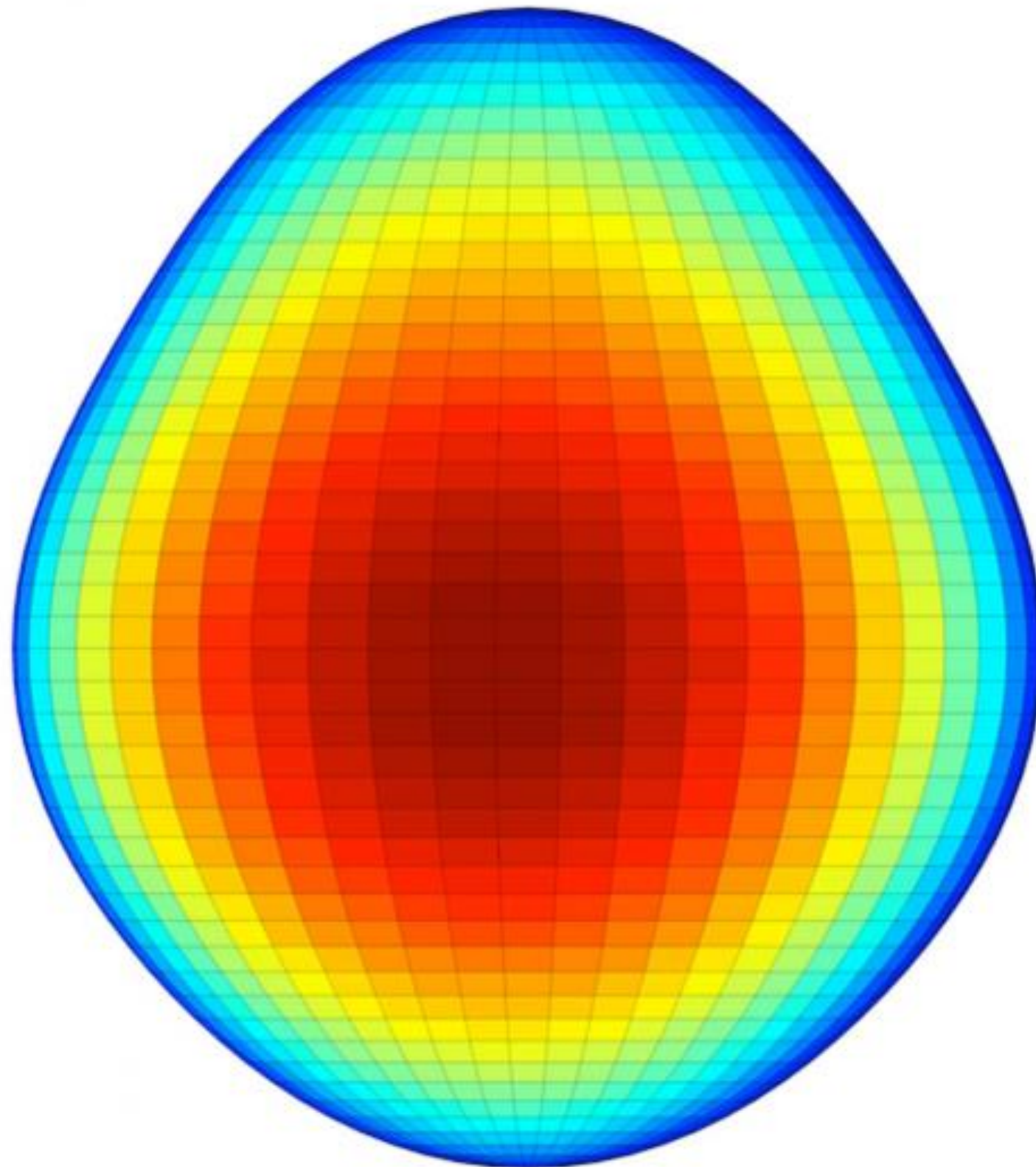




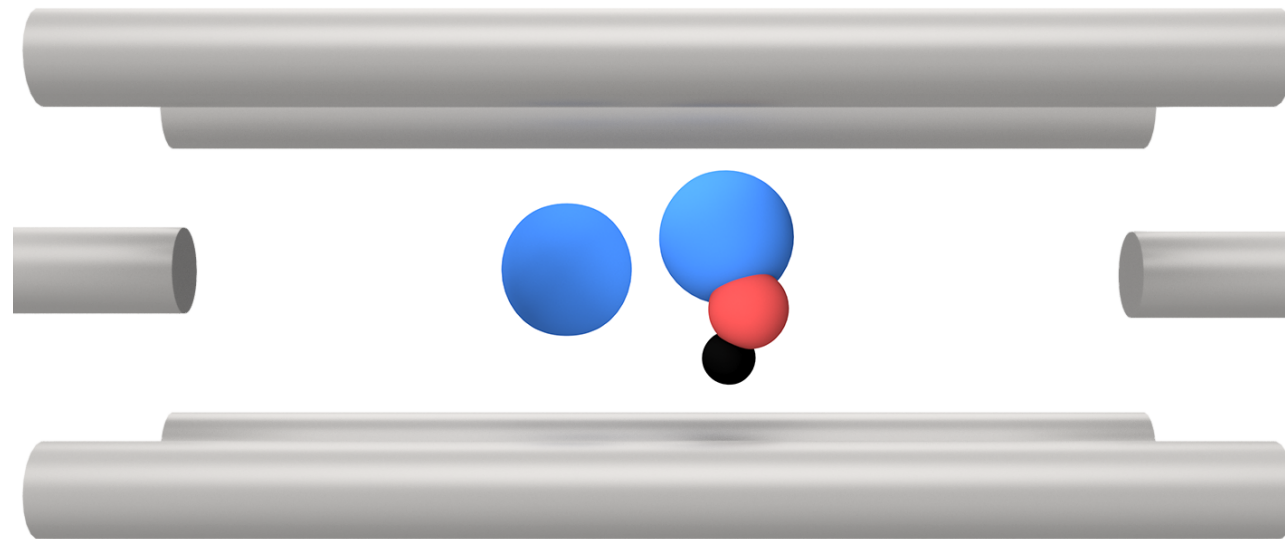
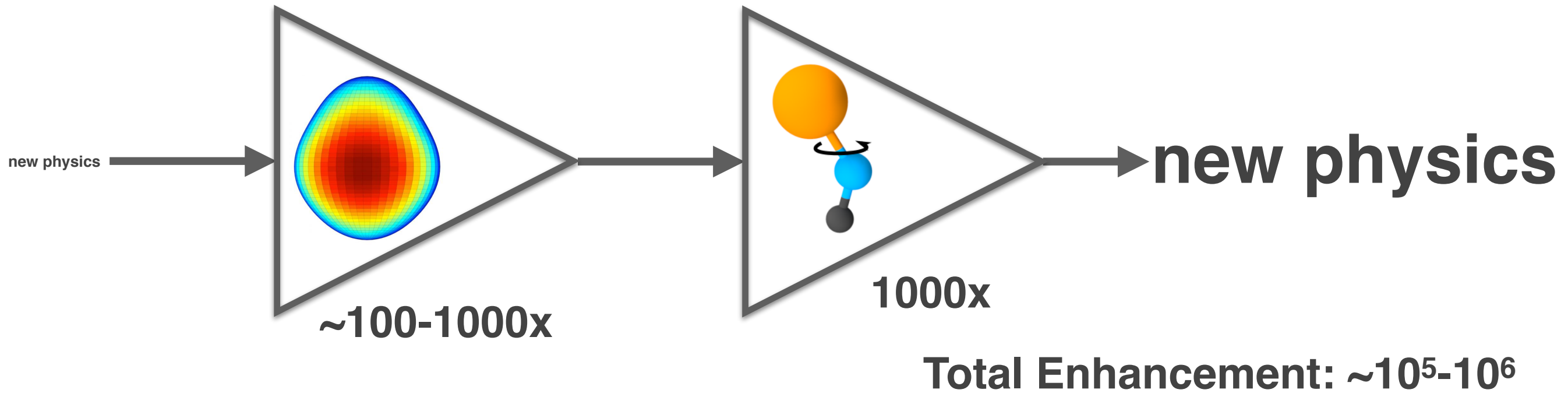
Radium

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og
		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
		Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

Radium nucleus



Amplifier



Verma, Jayich & Vutha, *PRL* **125**, 153201 (2020)

Cairncross *et al.*, *PRL* **119**, 153001 (2017)

Kozyryev & Hutzler, *PRL* **119**, 133002 (2017)

Flambaum, *PRC* **99**, 035501 (2019)

Haxton & Henley, *PRL* **51**, 1937 (1983)

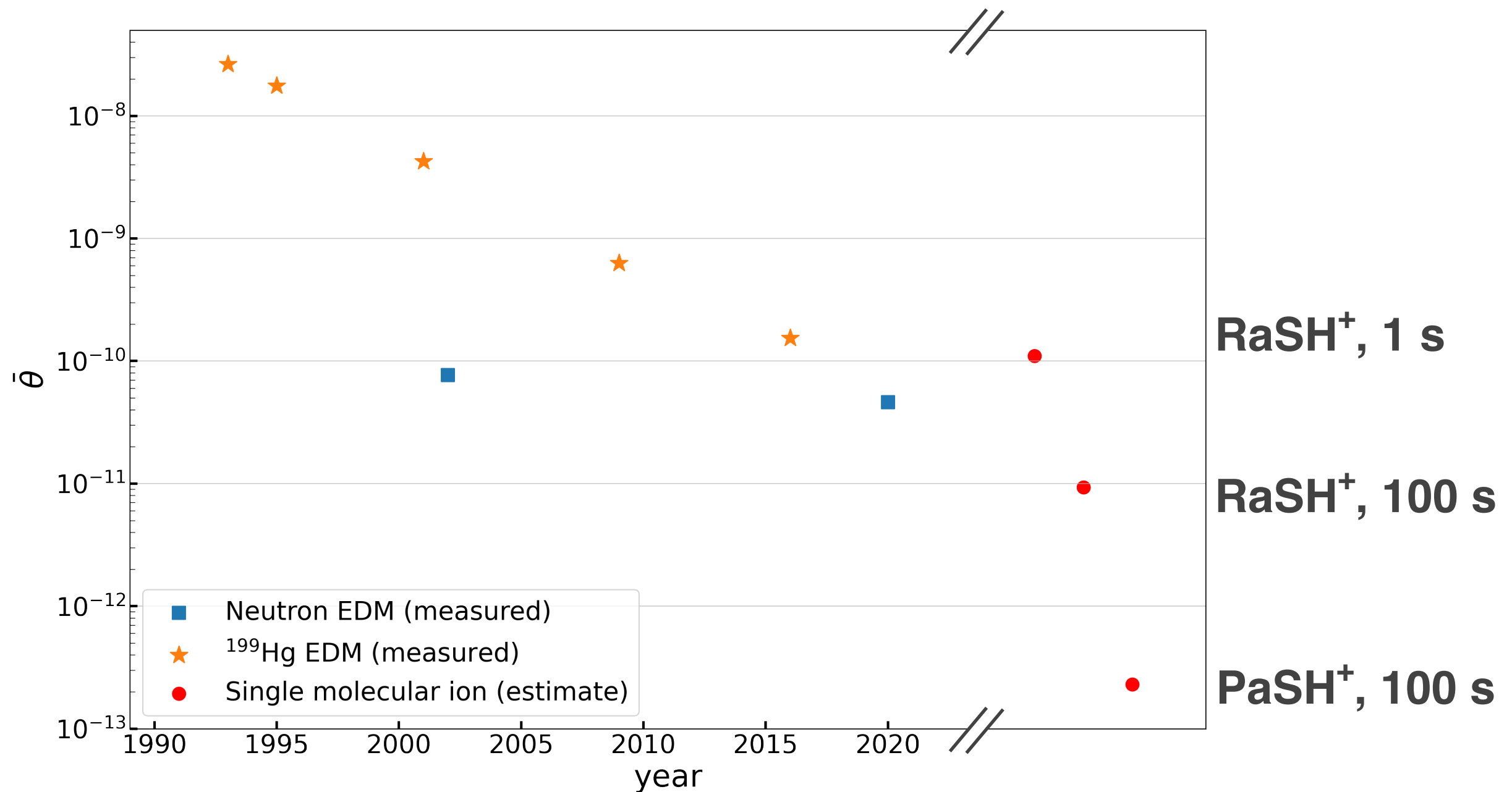
Chou *et al.*, *Nature* **545**, 203 (2017)

Schmidt *et al.*, *Nature* **530**, 457 (2016)

Patterson, *PRA* **97**, 033403 (2018)

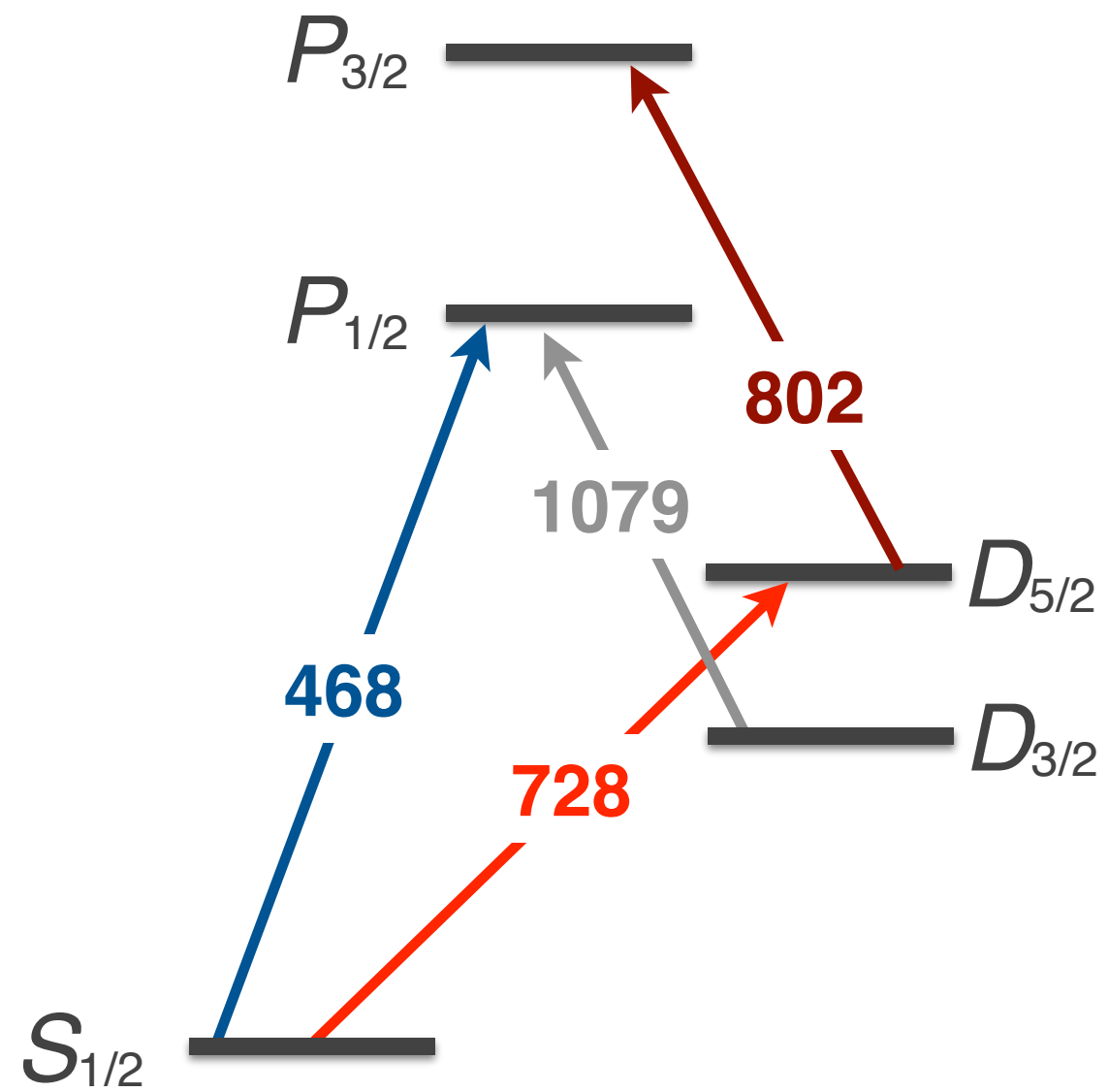
T-violation benchmark

strong CP problem: $\bar{\theta}$ is small.



$\sim 10^{-12}$: YbOH , TlF , ^{225}Ra , Xe , ...

Ra⁺ in 2018: uncertainties abound



Laser-cooled radium



Lifetimes and branching fractions

Ra ⁺ state	Lifetime	Branching fractions
$7p\ ^2P_{1/2}$	$\geq 7.3^{+?}_{-1}(1)$ ns	0.9104(7), 0.0896(7)
$7p\ ^2P_{3/2}$	$\geq 3.8^{+?}_{-1}(1)$ ns	0.87678(20), 0.10759(10), 0.01563(21)
$6d\ ^2D_{5/2}$	$301.5^{+1.5}_{-1.3}(1.6)$ ms	n/a
$6d\ ^2D_{3/2}$	625^{+20}_{-40} ms	n/a

Fan *et al.*, *PRL* **122**, 223001 (2019)

Fan *et al.*, *PRA* **100**, 062504 (2019)

Versolato *et al.*, *Hyper. Interact.* **199**, 9 (2011)

Collaboration with Marianna Safronova & Sergey Porsev

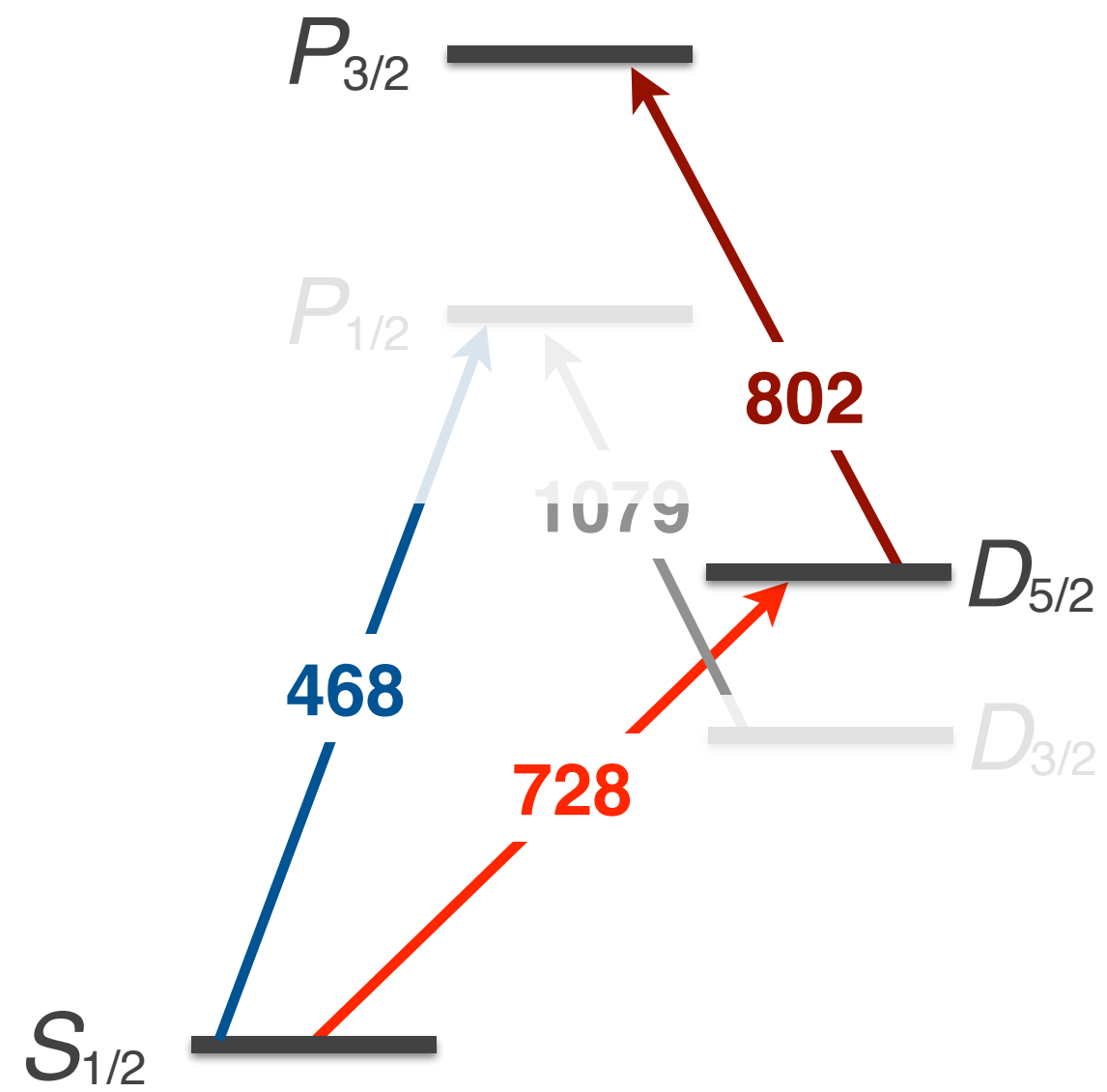
Ra-226 transition frequencies

Ra-226 Transitions	Pre-2019 (GHz)	Current (GHz)
$S_{1/2} \rightarrow P_{3/2}$	785 723(4)	785 722.11(3)
$S_{1/2} \rightarrow P_{1/2}$	640 092(7)	640 096.63(6)
$D_{3/2} \rightarrow P_{3/2}$	423 438(6)	423 444.39(3)
$S_{1/2} \rightarrow D_{5/2}$	...	412 007.701(18)
$D_{5/2} \rightarrow P_{3/2}$	373 717(5)	373 714.40(2)
$S_{1/2} \rightarrow D_{3/2}$	...	362 277.68(5)
$D_{3/2} \rightarrow P_{1/2}$	...	277 818.95(8)

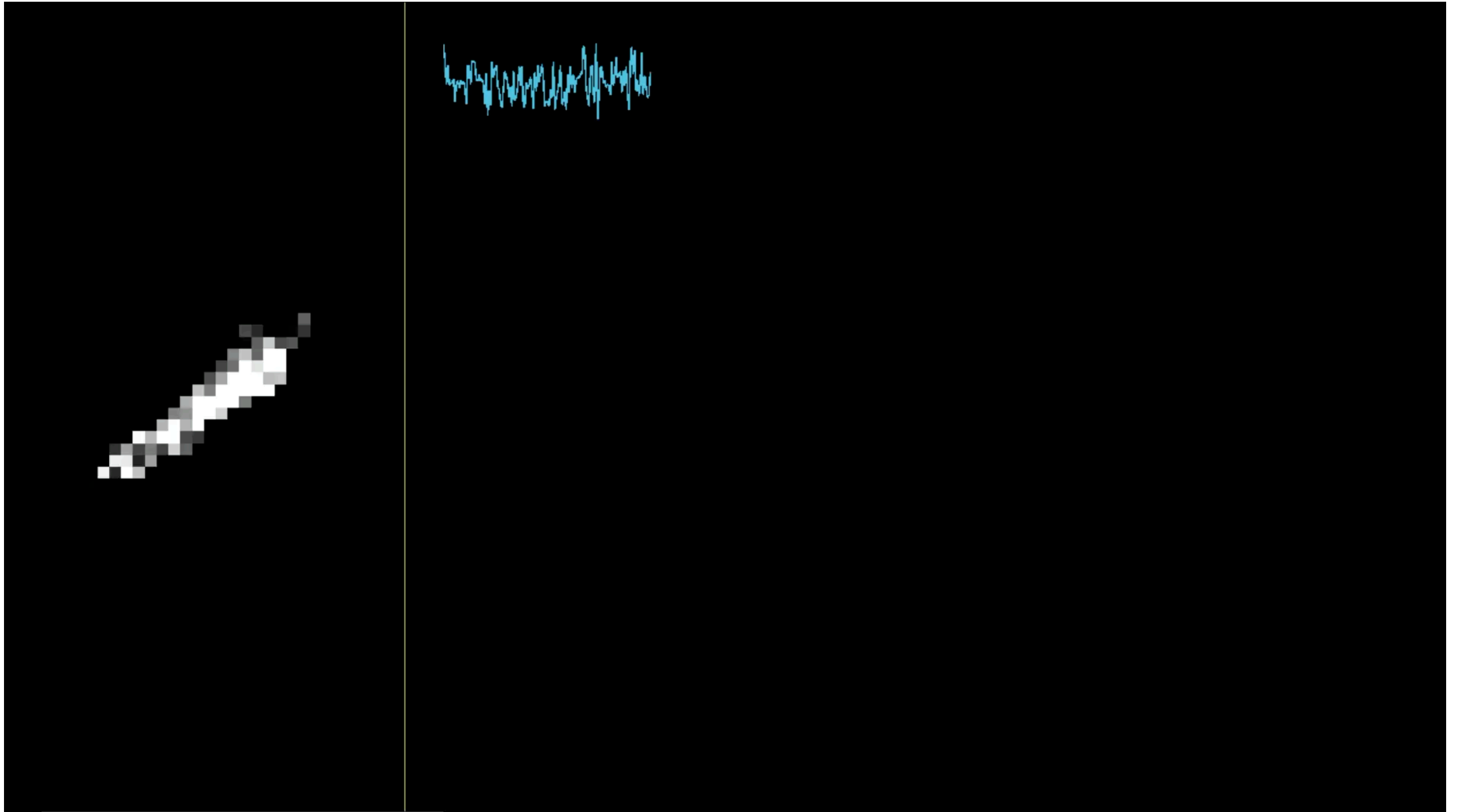
Rasmussen, *ZP* **86**, 24 (1933)

Fan *et al.*, *PRL* **122**, 223001 (2019)
Holliman *et al.*, *PRA* **100**, 062512 (2019)
Holliman *et al.*, *PRA* **102**, 042822 (2020)

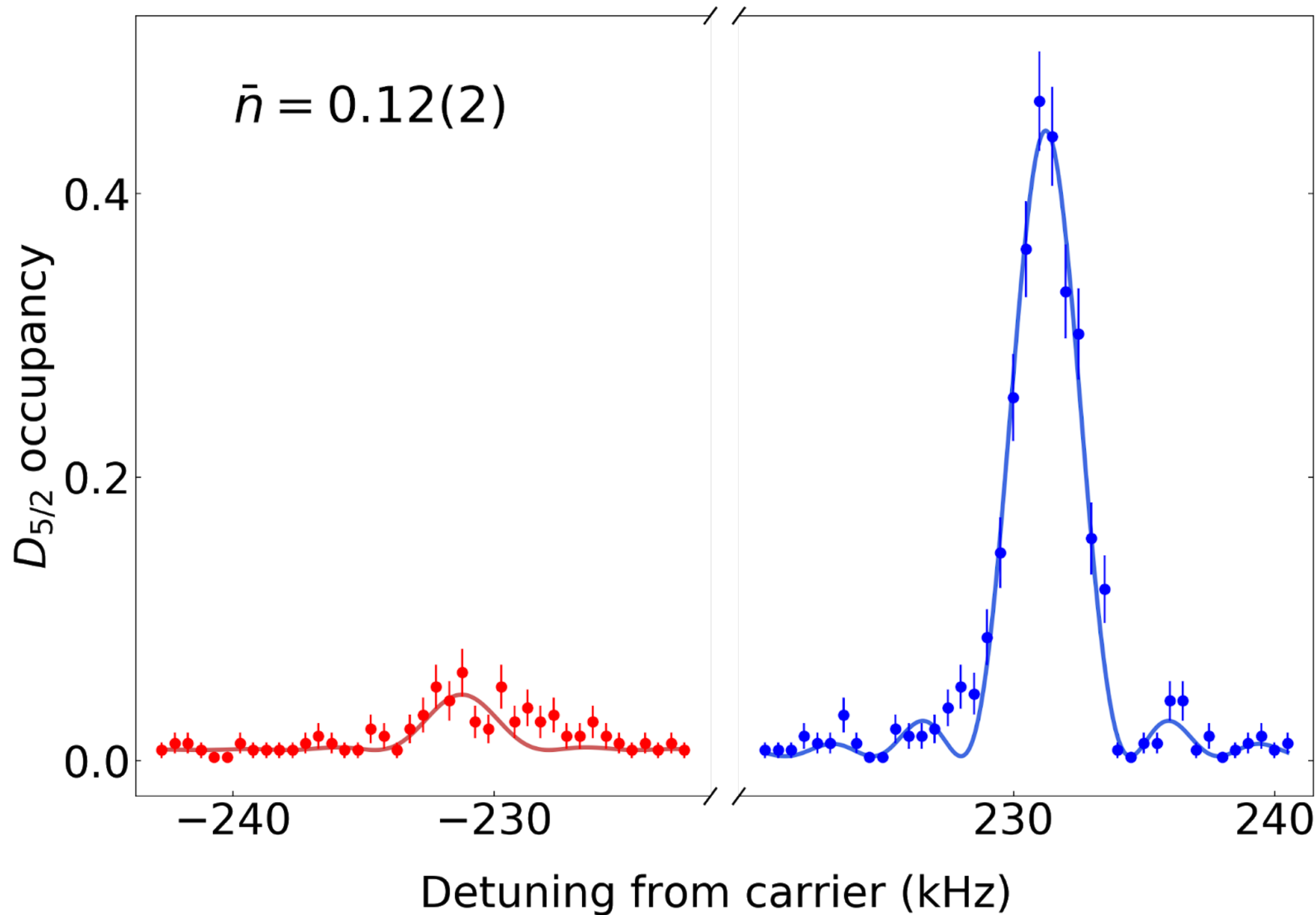
Ra⁺



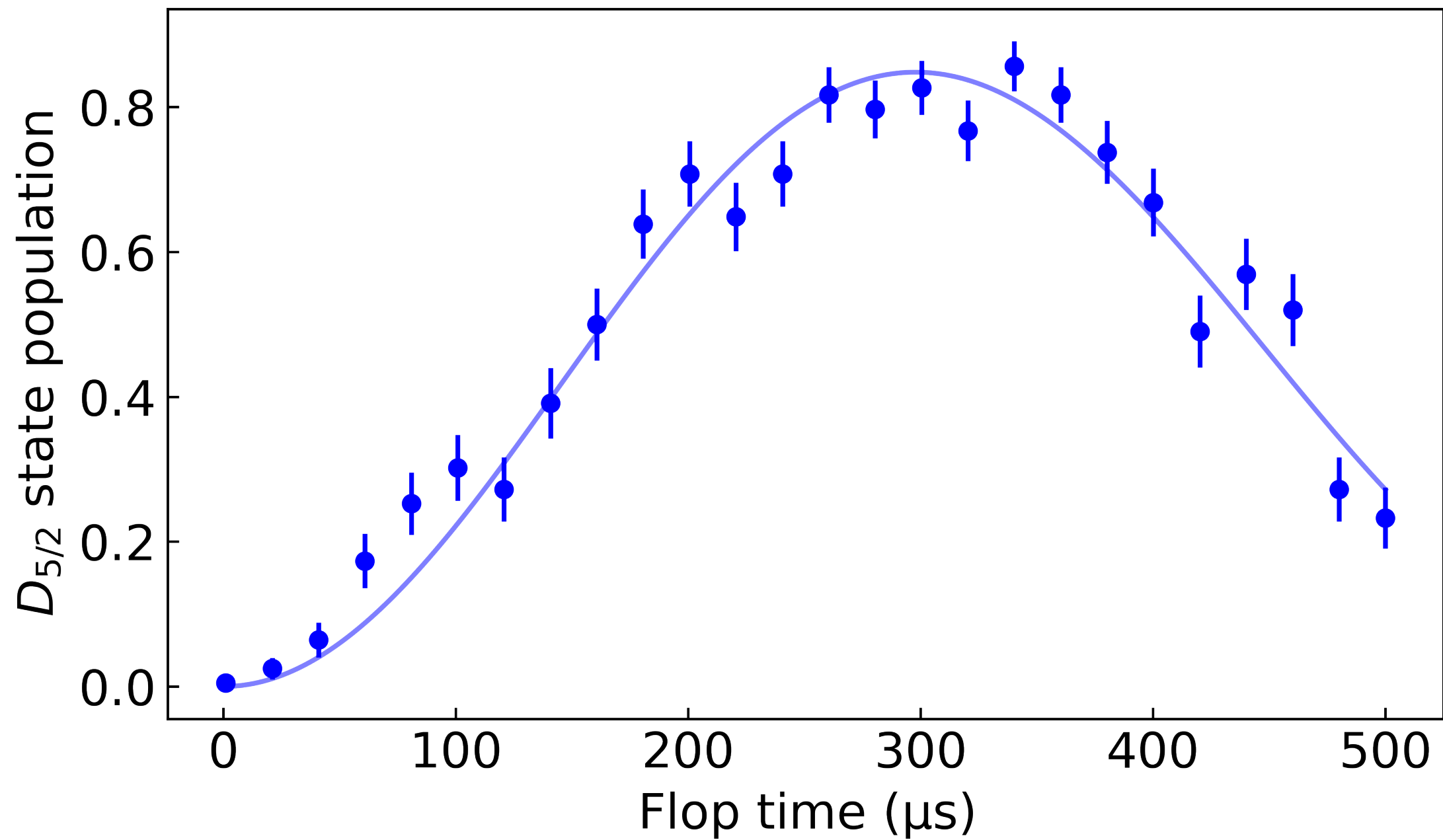
Quantum jumps



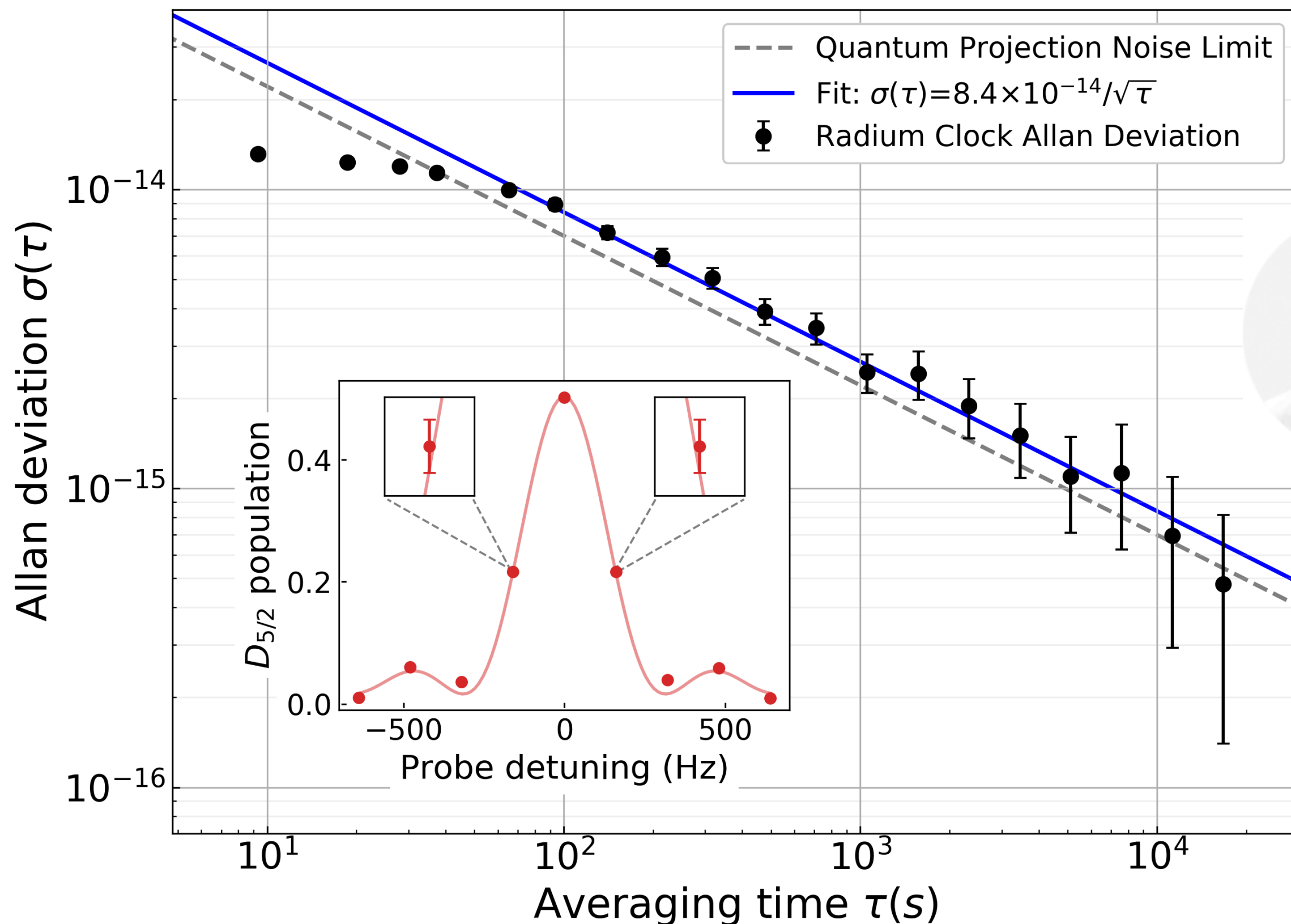
Motional ground state cooling



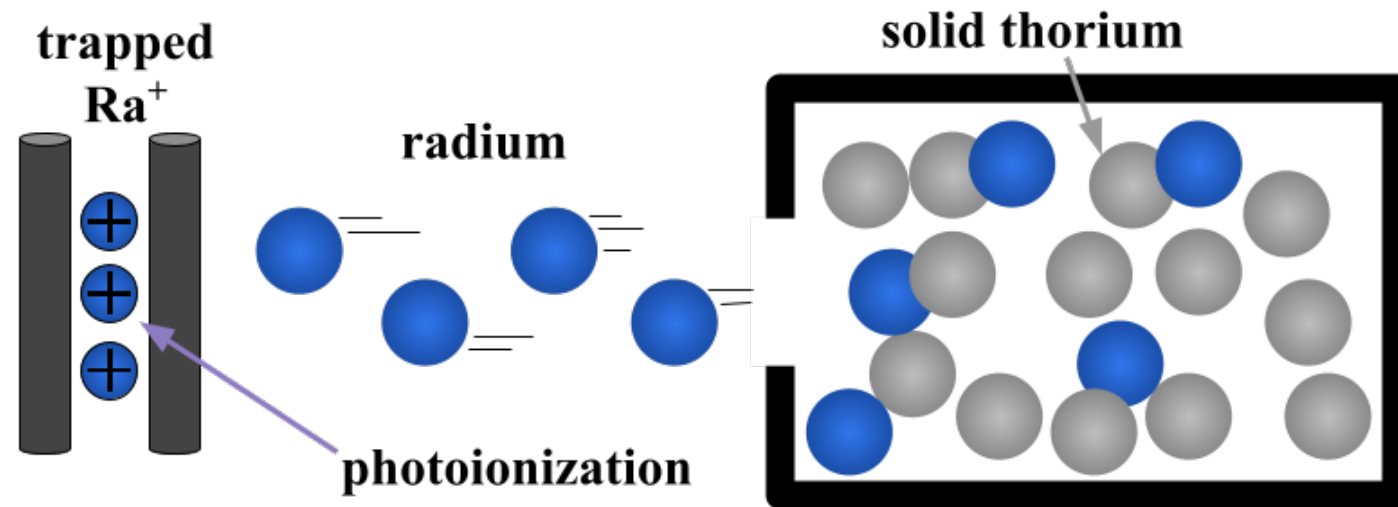
Fock state engineering



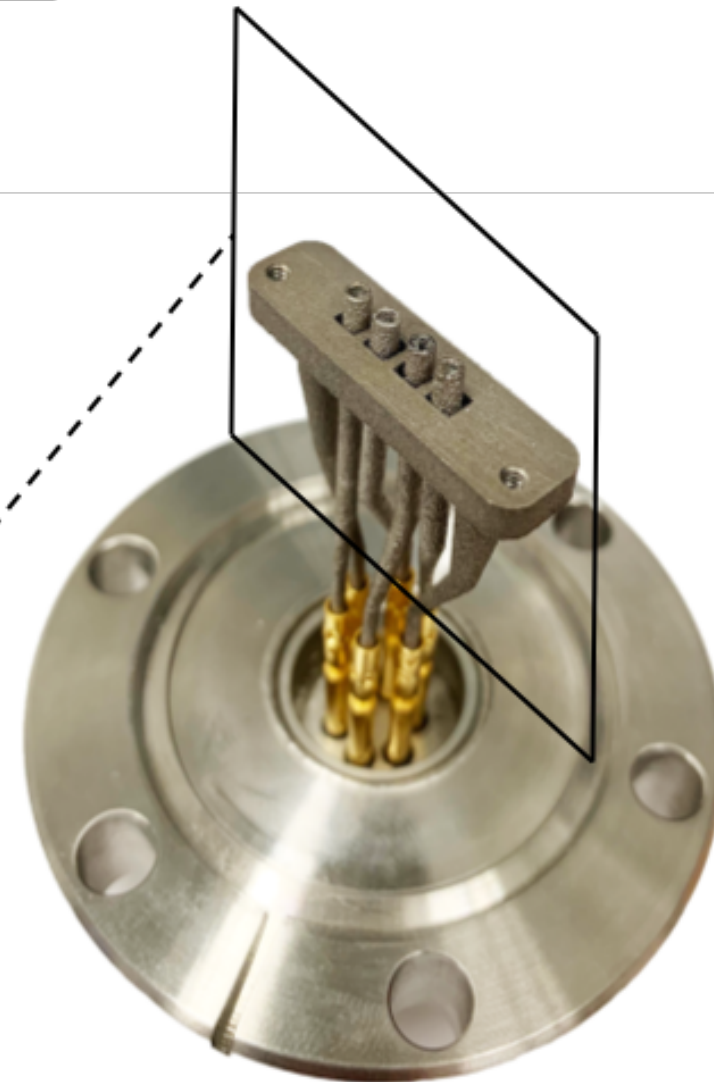
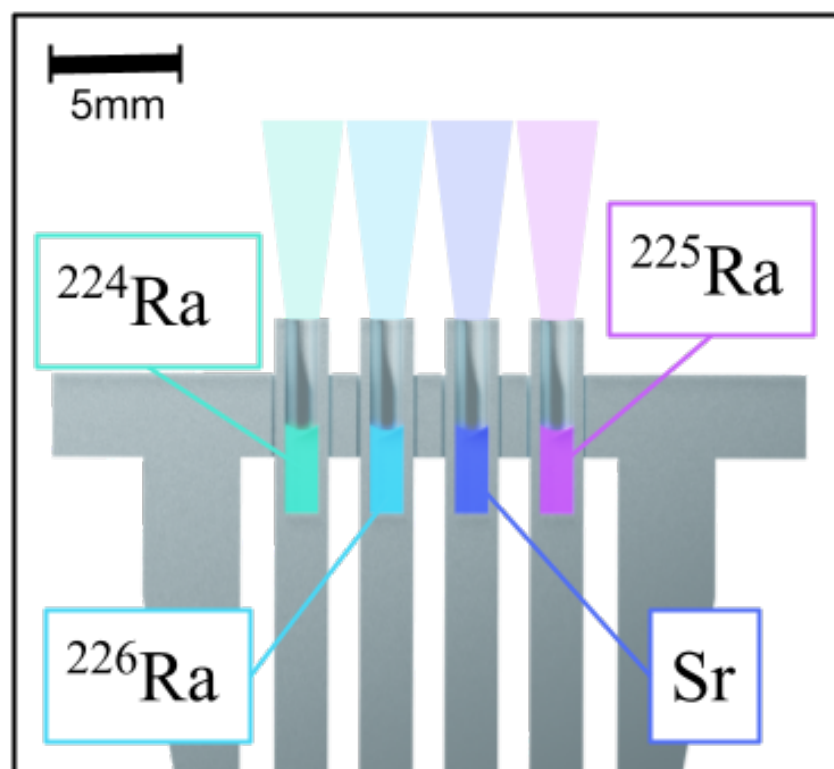
A radioactive optical clock



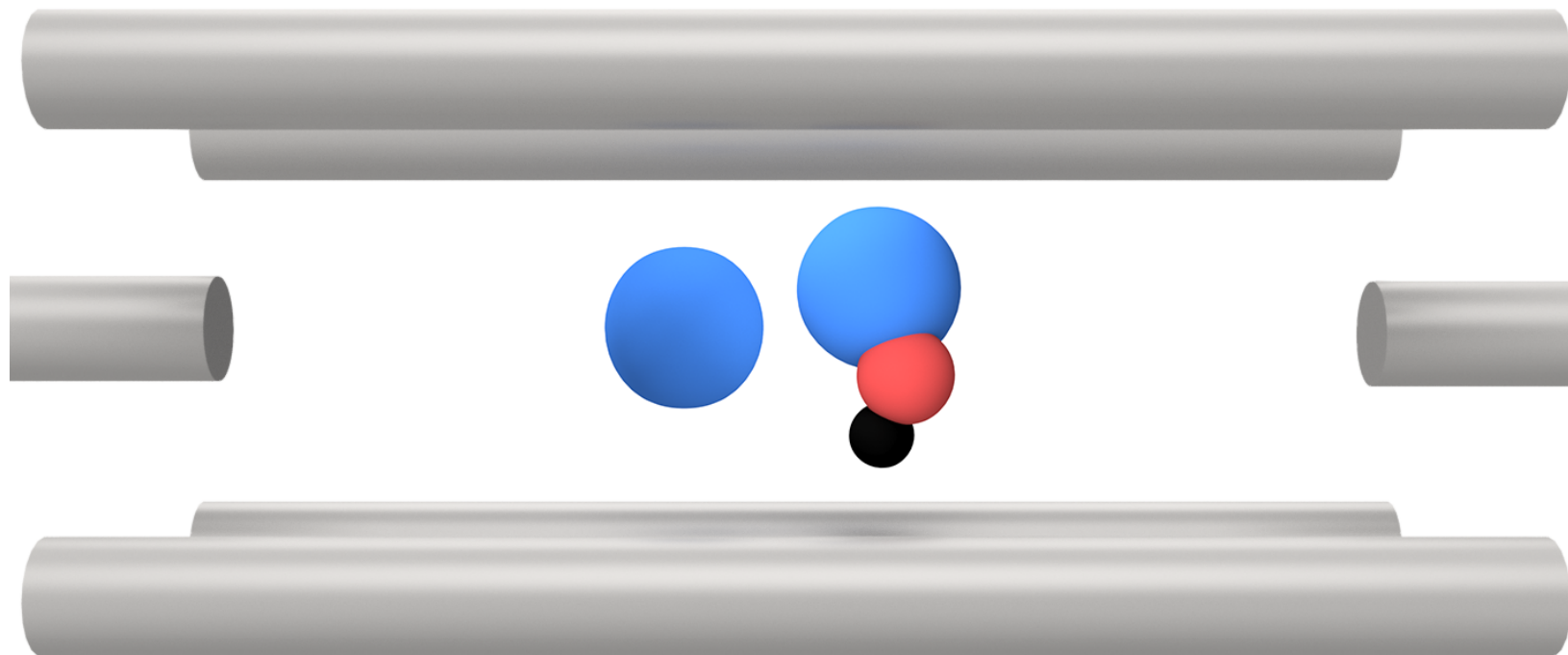
Radium-225



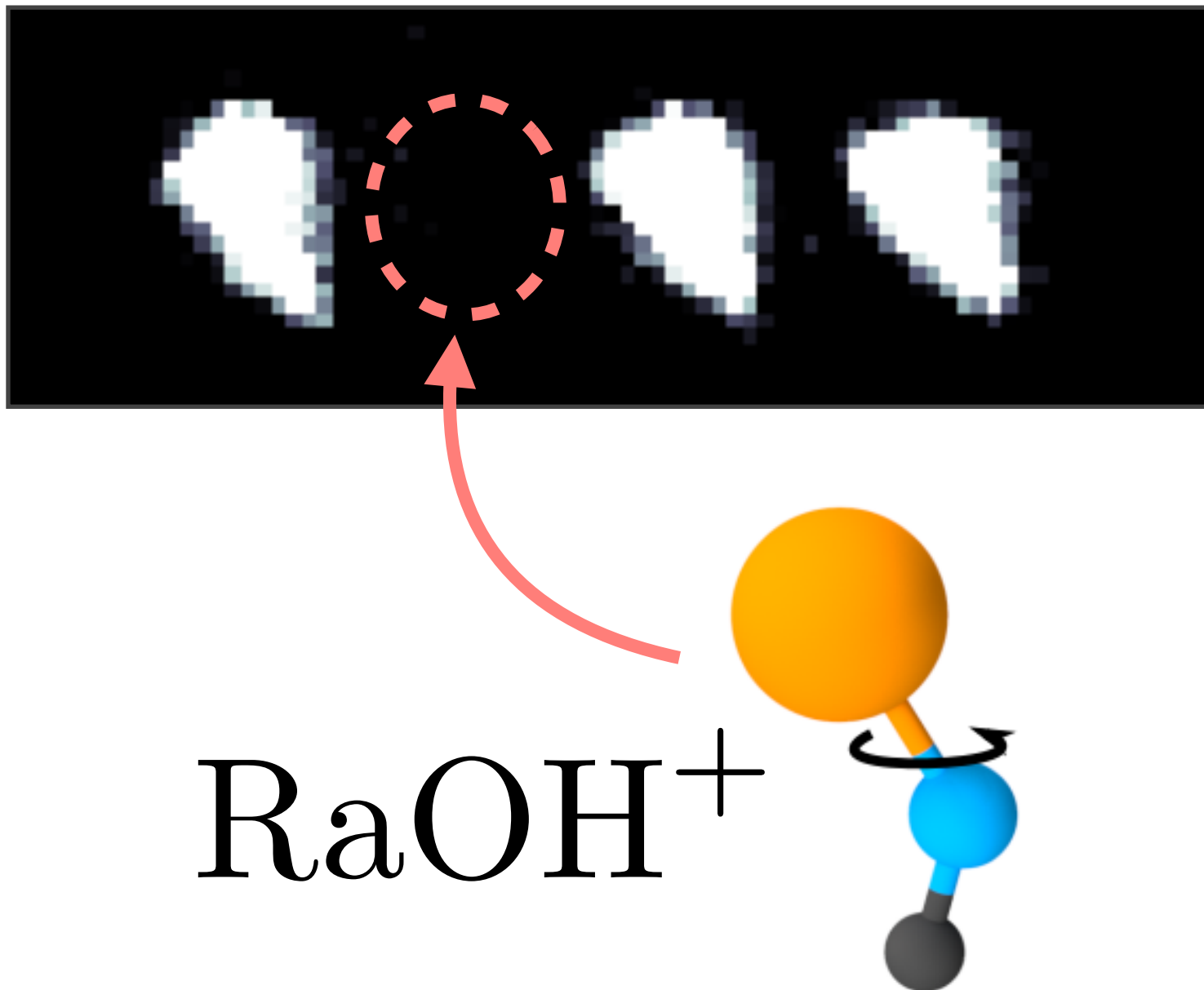
Radium	half-life	parent	parent half-life
224	3.6 d	Thorium 228	1.9 y
225	14.9 d	Thorium 229	7900 y
226	1600 y	Thorium 230	75000 y



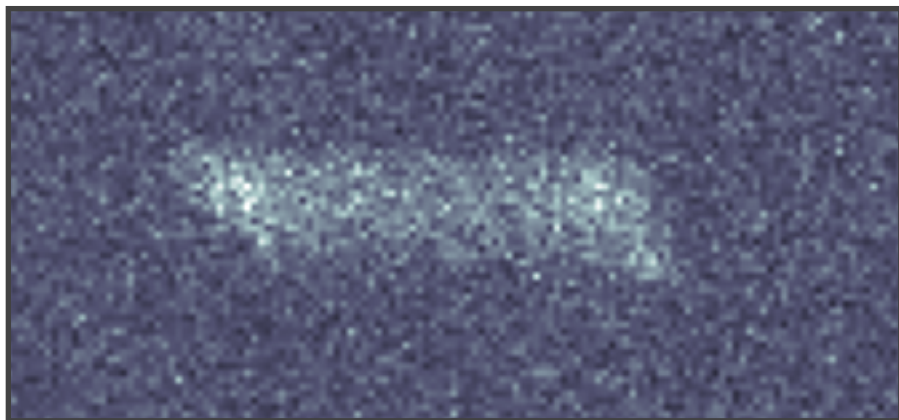
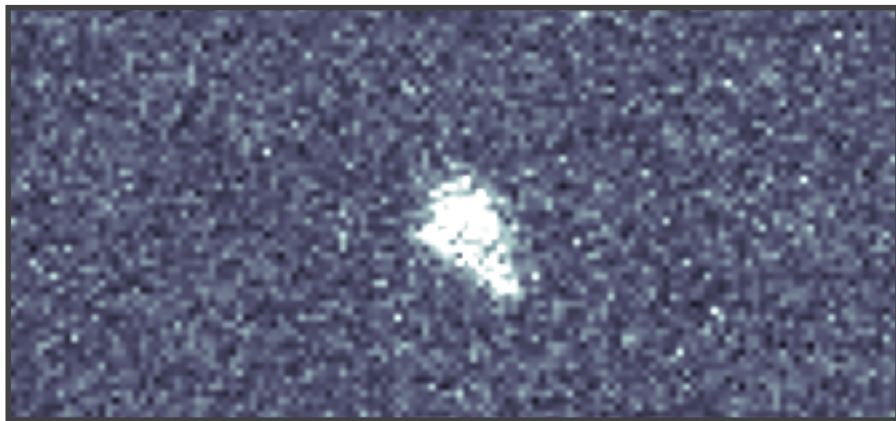
Desiderata



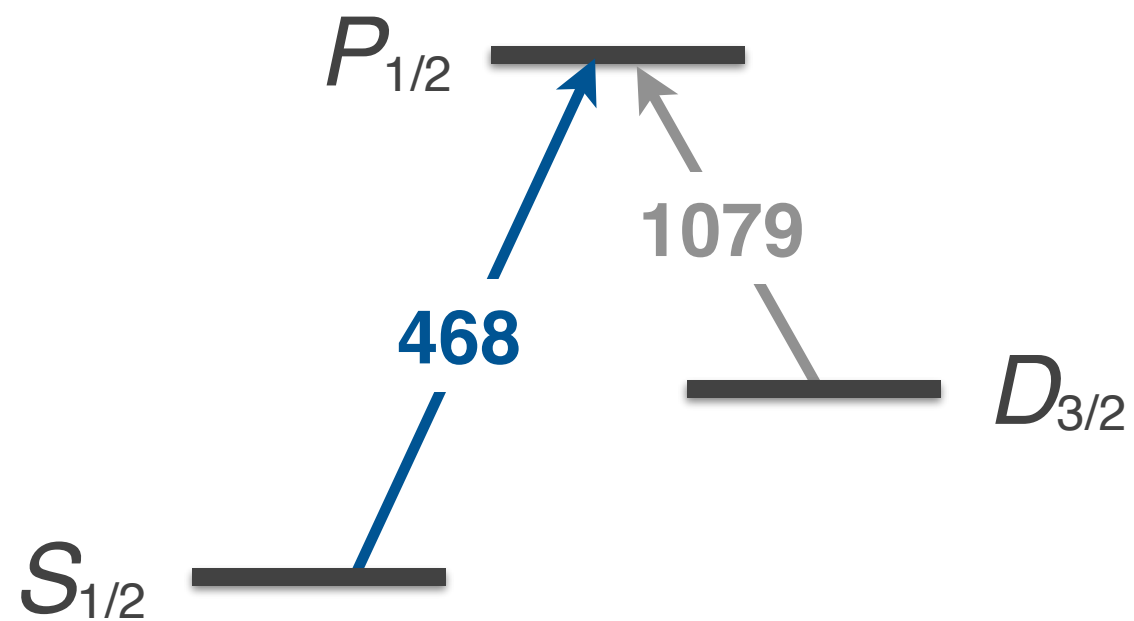
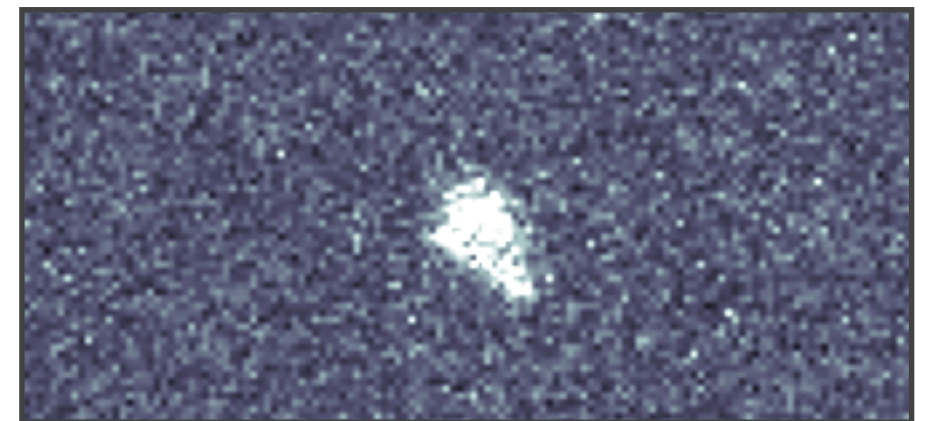
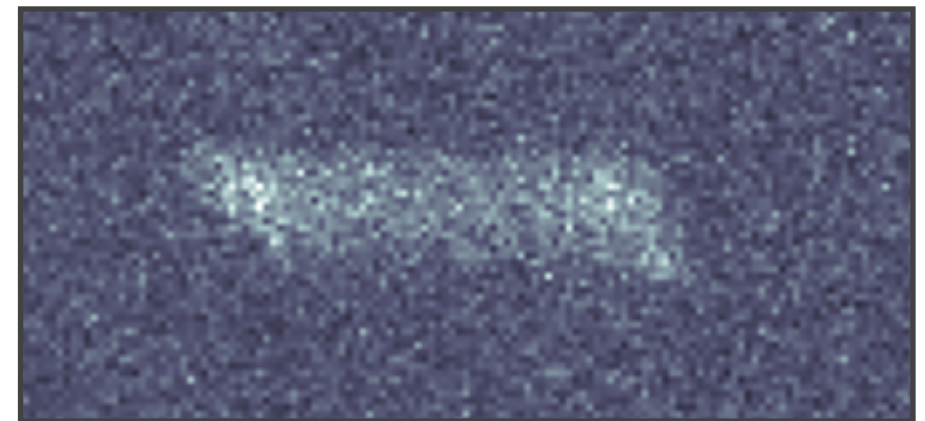
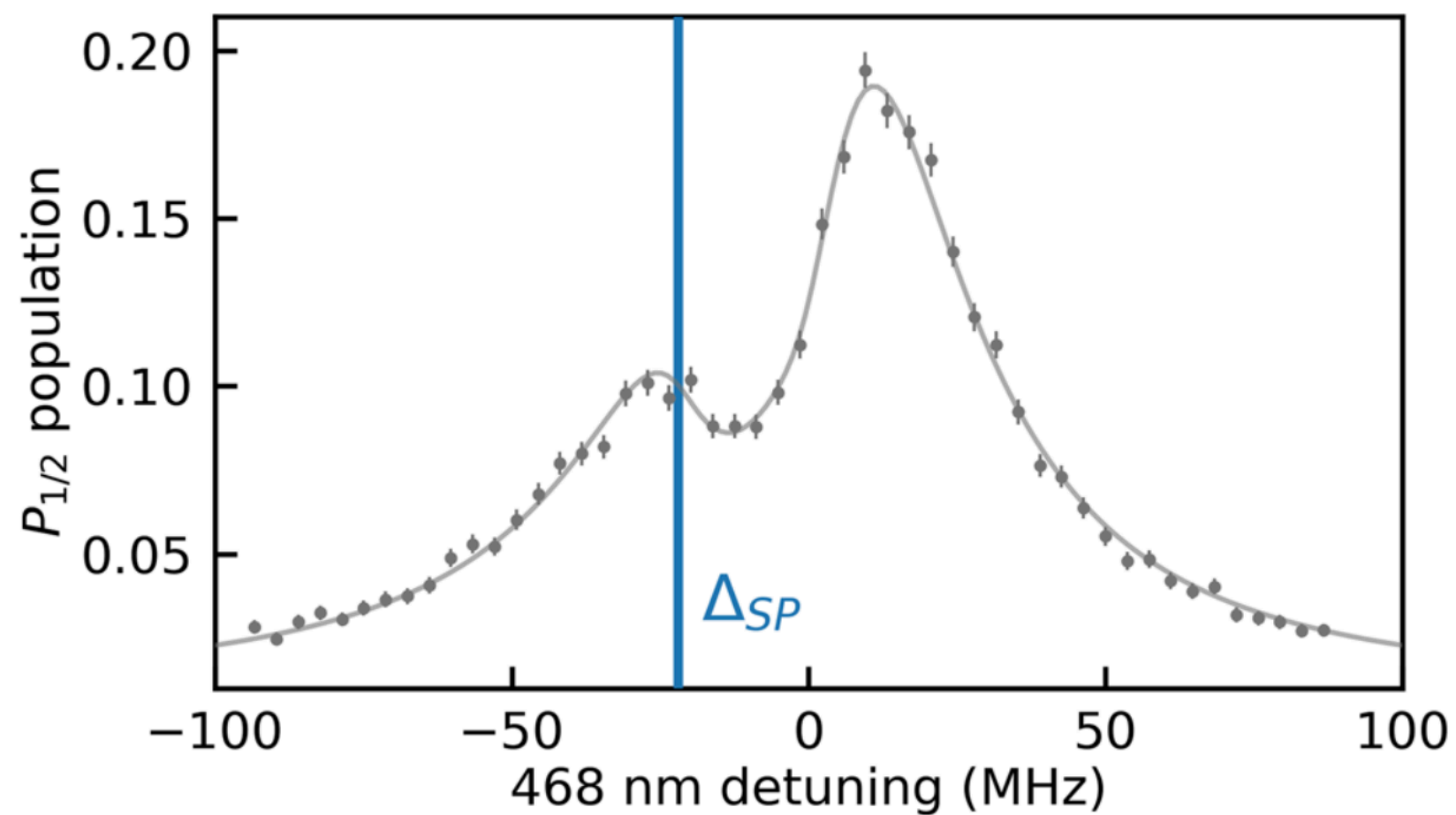
Molecules



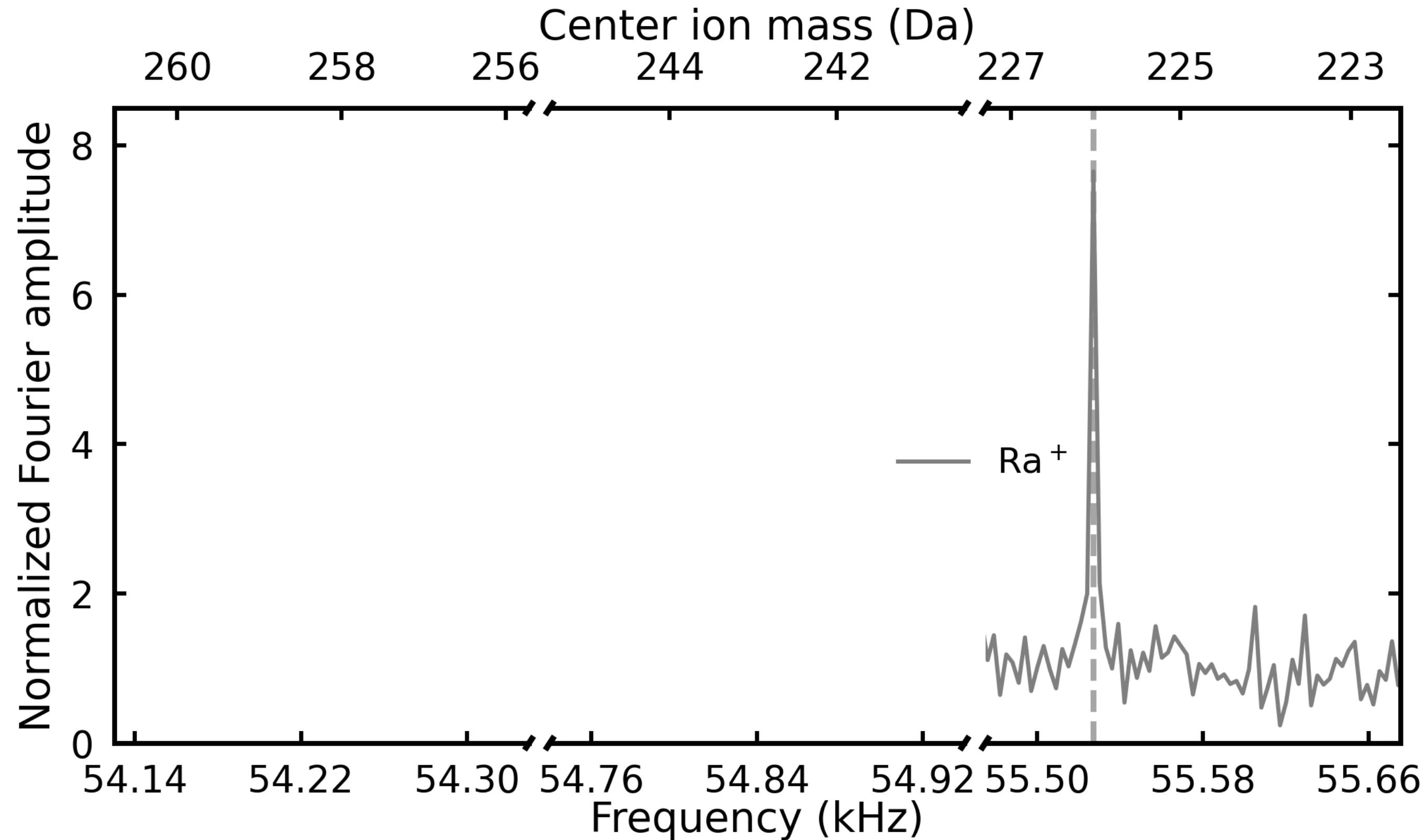
Optical mass spectrometry



Optical mass spectrometry



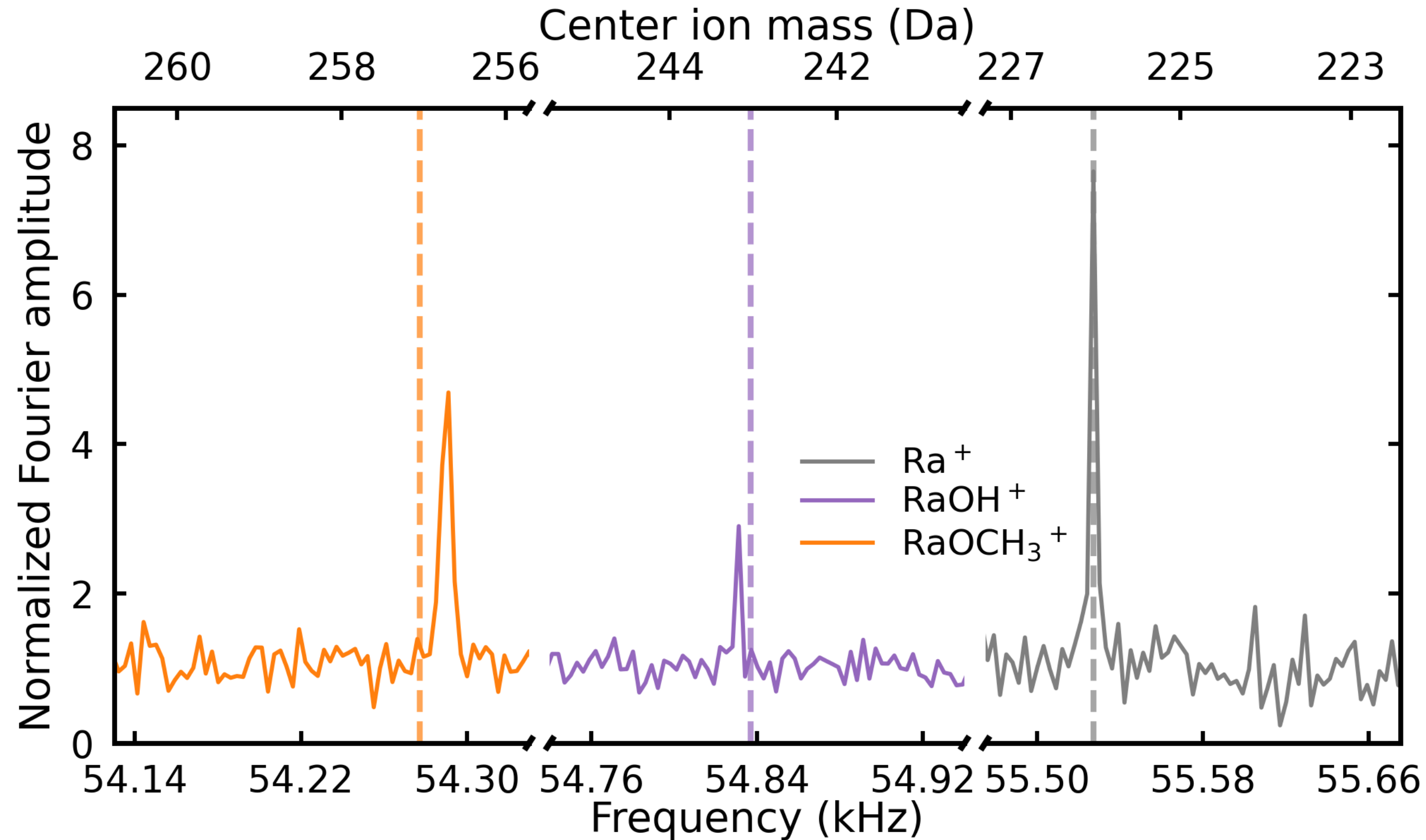
Optical mass spectrometry



Yu & Hutzler, *PRL* **126**, 023003 (2021)

Fan *et al.*, *PRL* **126**, 023002 (2021)

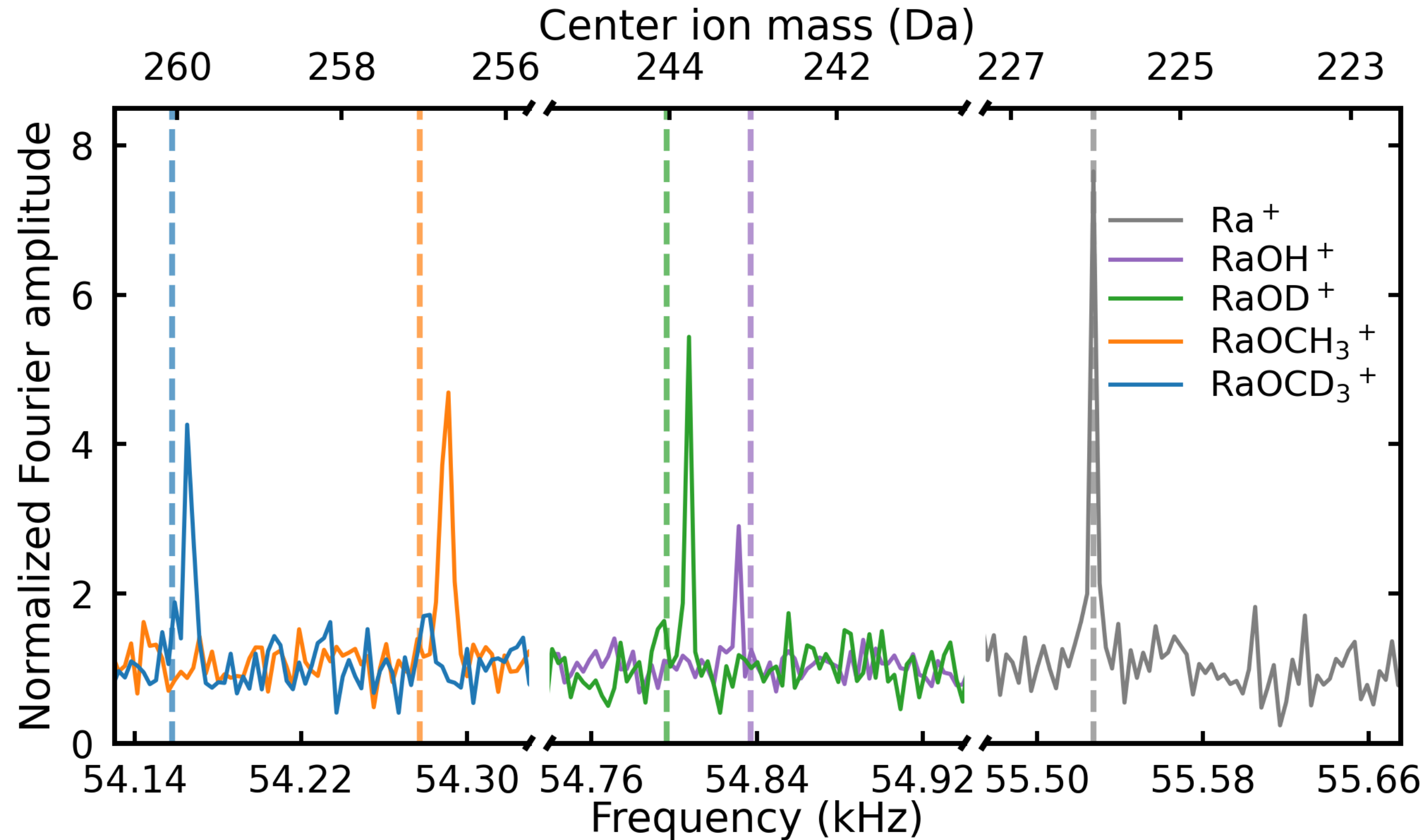
Optical mass spectrometry



Yu & Hutzler, *PRL* **126**, 023003 (2021)

Fan *et al.*, *PRL* **126**, 023002 (2021)

Optical mass spectrometry

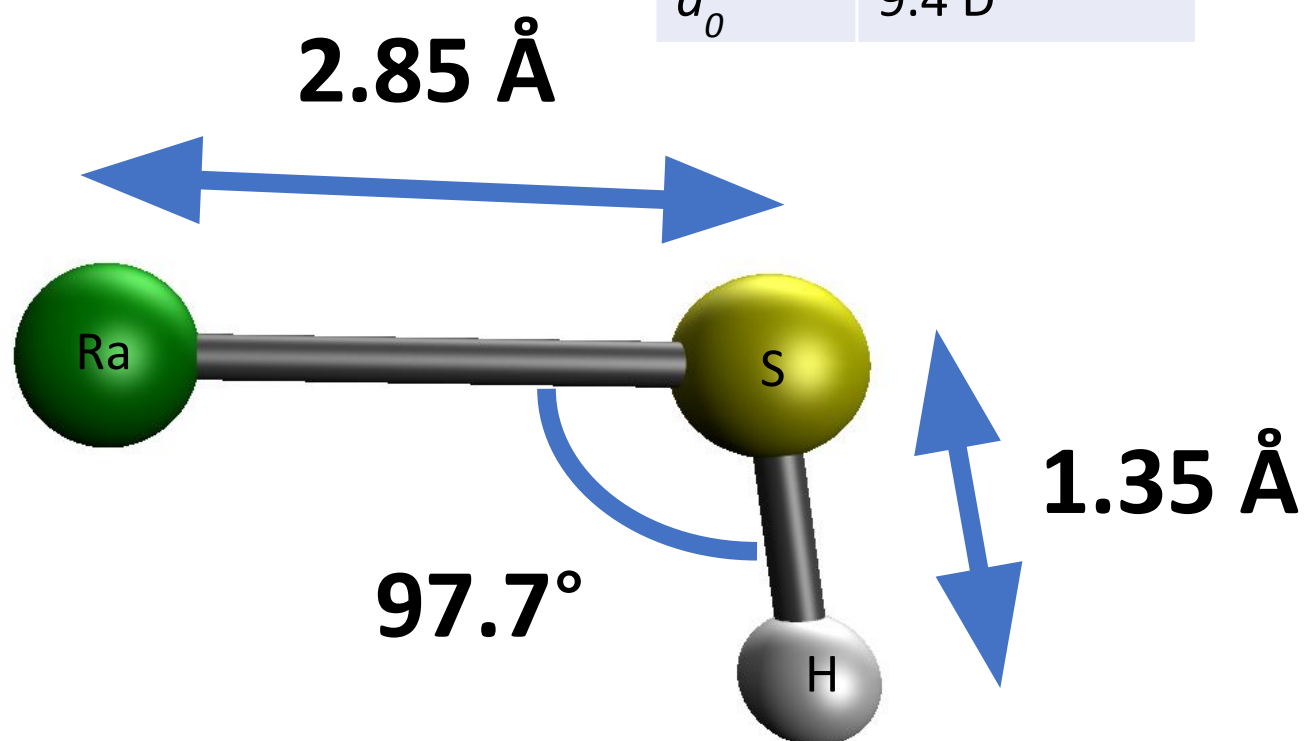


Yu & Hutzler, *PRL* **126**, 023003 (2021)

Fan *et al.*, *PRL* **126**, 023002 (2021)

RaSH⁺

Molecular constants	
A	291 GHz
B	2.183 GHz
C	2.166 GHz
d_0	9.4 D



Ab initio estimate:
DFT/B3LYP
cc-pVTZ/ECP78MDF



Three unequal rotational moments:

$A > B \approx C \Rightarrow$ Prolate (slightly) asymmetric top

Rotational Hamiltonian:

$$H_{rot} = A N_A^2 + B N_B^2 + C N_C^2$$

States approximately parameterized as $|N, K_a, K_c\rangle$.

Each level has rotational doubling that scales with dimensionless asymmetry parameter:

$$\varepsilon = \frac{B - C}{2(2A - B - C)}$$

For RaSH⁺:

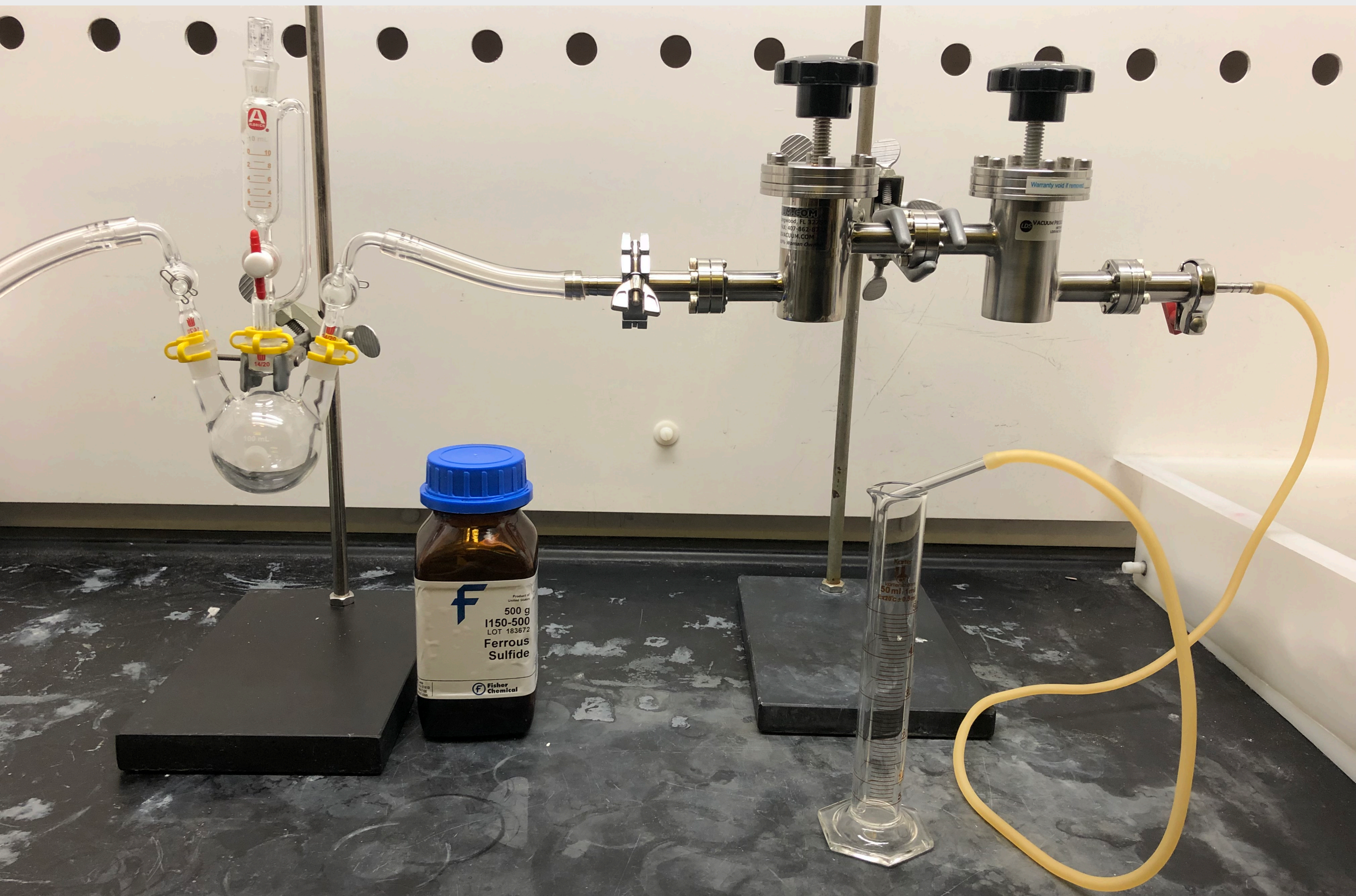
$$\varepsilon \cdot \underbrace{\left[A - \frac{1}{2}(B + C) \right]}_{H_{rot} \text{ energy scale}} \approx 4.2 \text{ MHz}$$

Comparable results with RaNC⁺, RaCN⁺, etc..

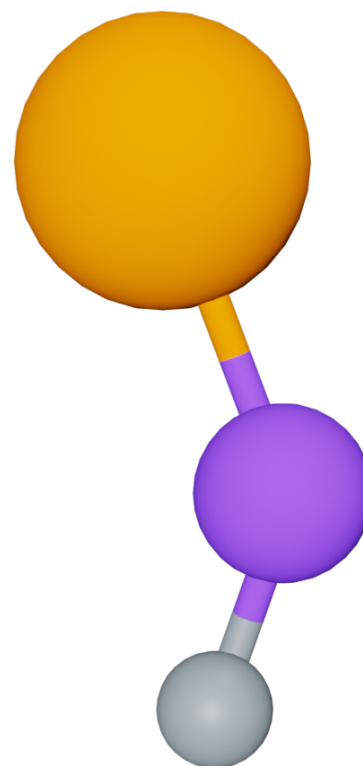
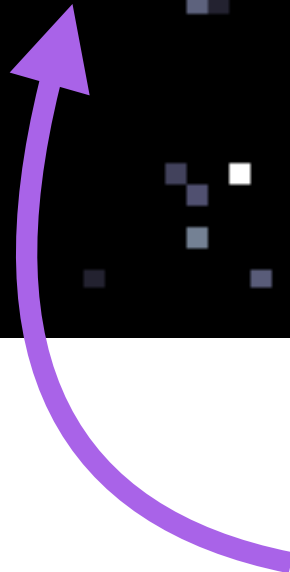
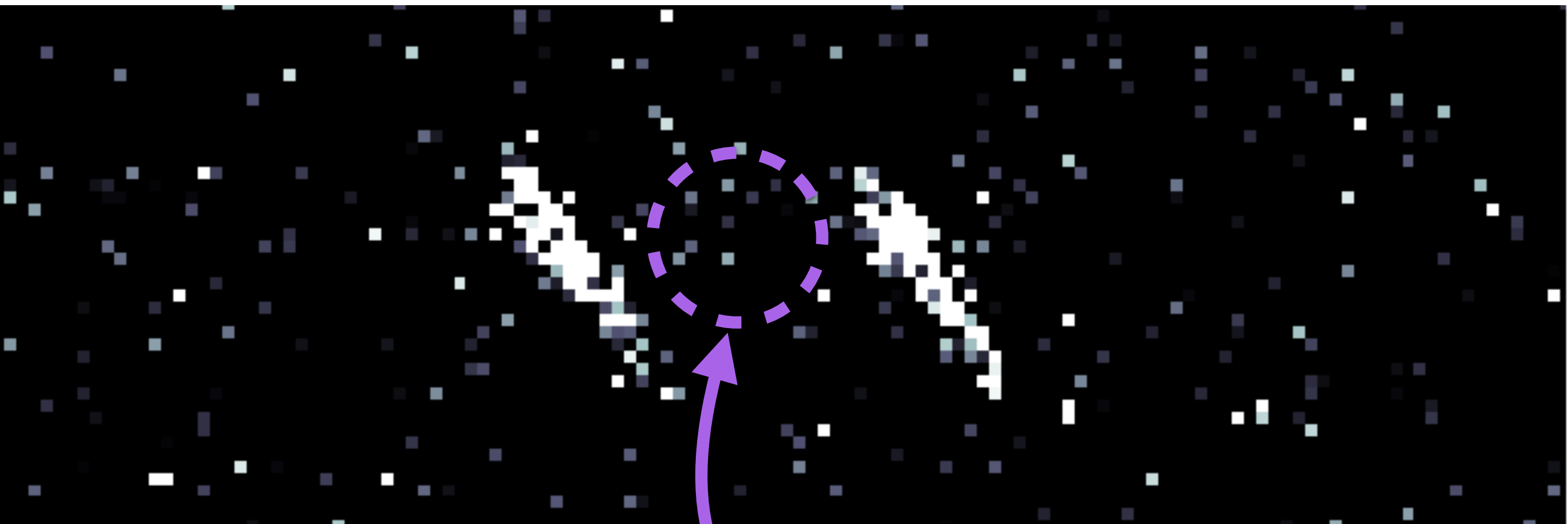
Ref: S.R. Polo *CJ Phys* 35,880 (1957)

Credit: Phelan Yu & Nick Hutzler

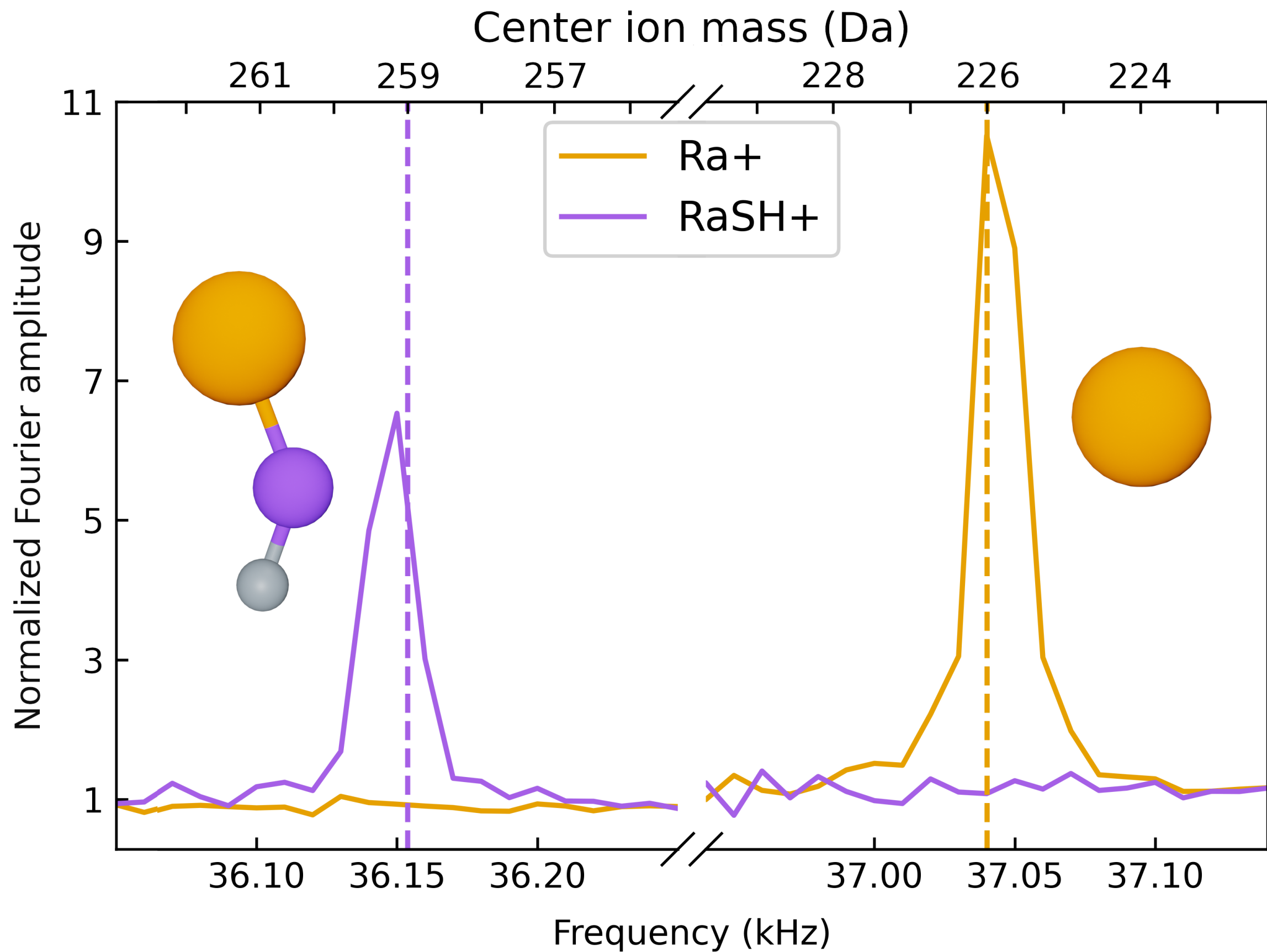
Last week's chemistry project: H_2S



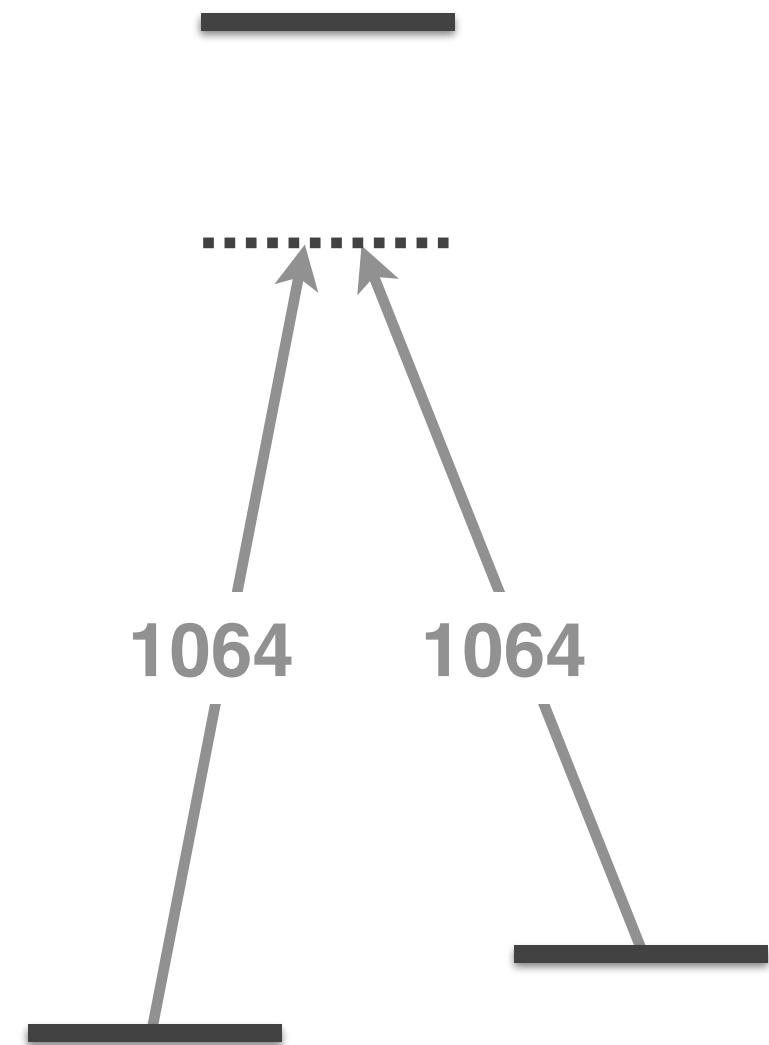
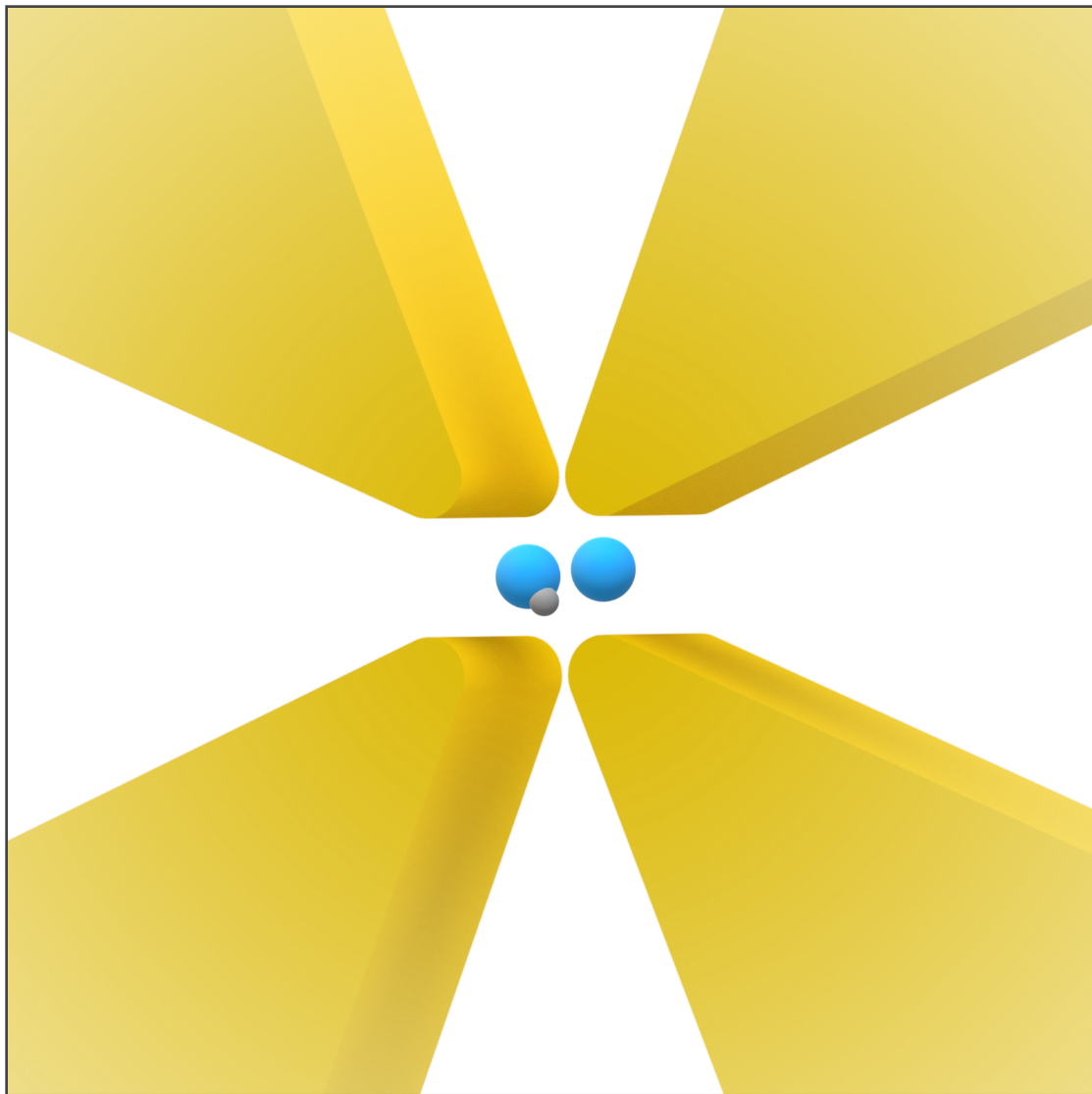
RaSH⁺ ??



RaSH⁺.



New trap and stimulated Raman transitions



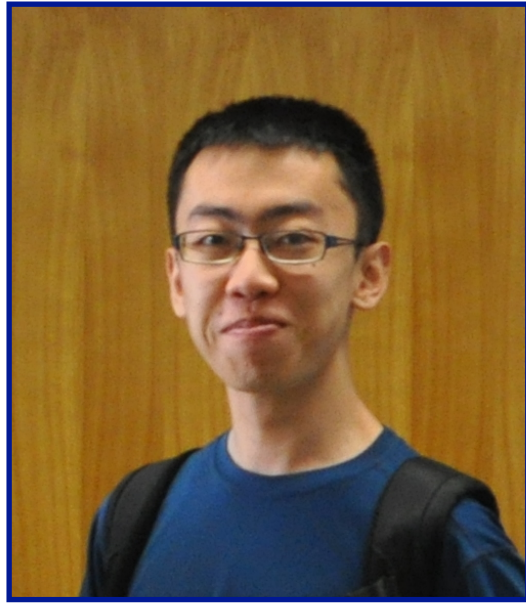
Brewer *et al.*, *PRL* **123**, 033201 (2019)

Chou *et al.*, *Nature* **545**, 203 (2017)

Lin *et al.*, *Nature* **581**, 273 (2020)

The Lab

Grad students:



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Craig Holliman



Sean Buechele

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Asad Contractor
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Max Ladabaum
Ganden Schaffner
Chaoshen Zhang
Rei Landsberger

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Sam Brewer (Colorado State)
Nick Hutzler (Caltech)
Jaideep Singh (MSU/FRIB)
Marianna Safronova (U. Delaware)
Sergey Porsev (U. Delaware)
Leonid Skripnikov (PNPI)

