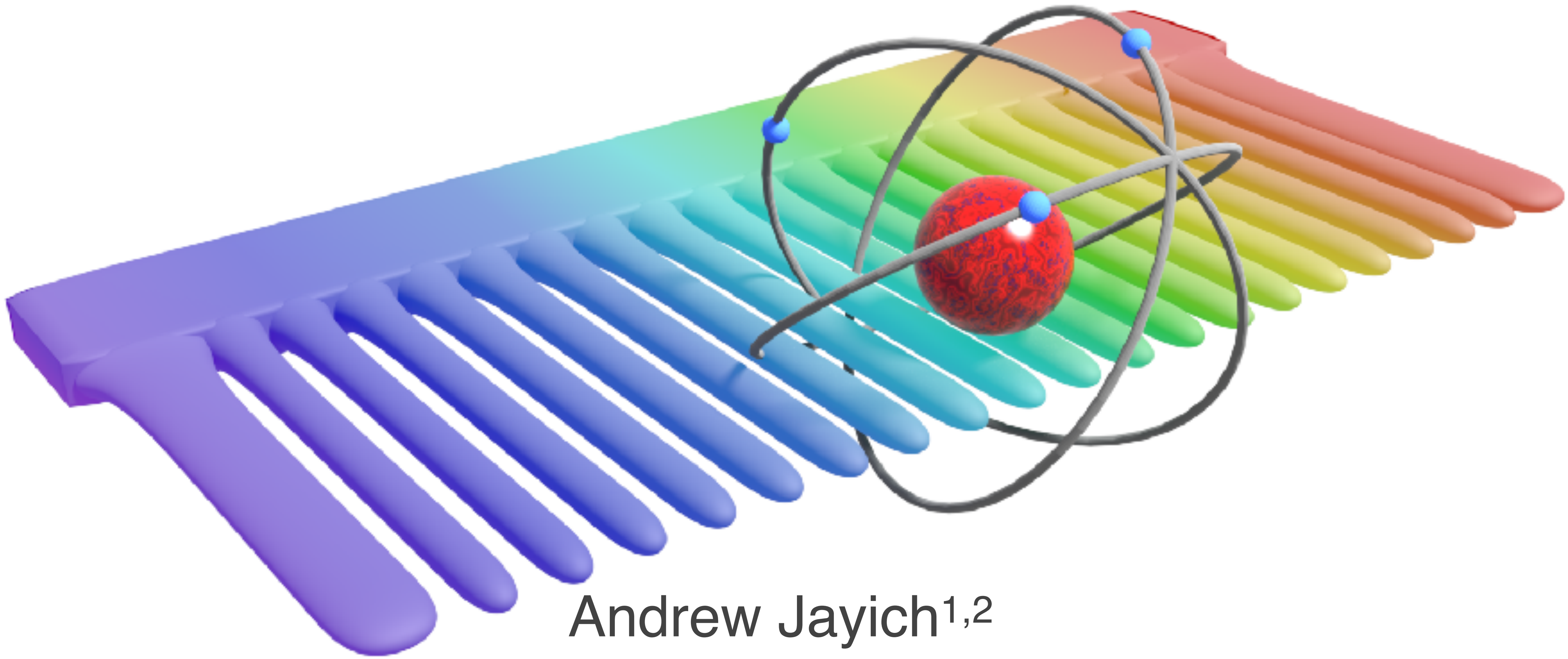
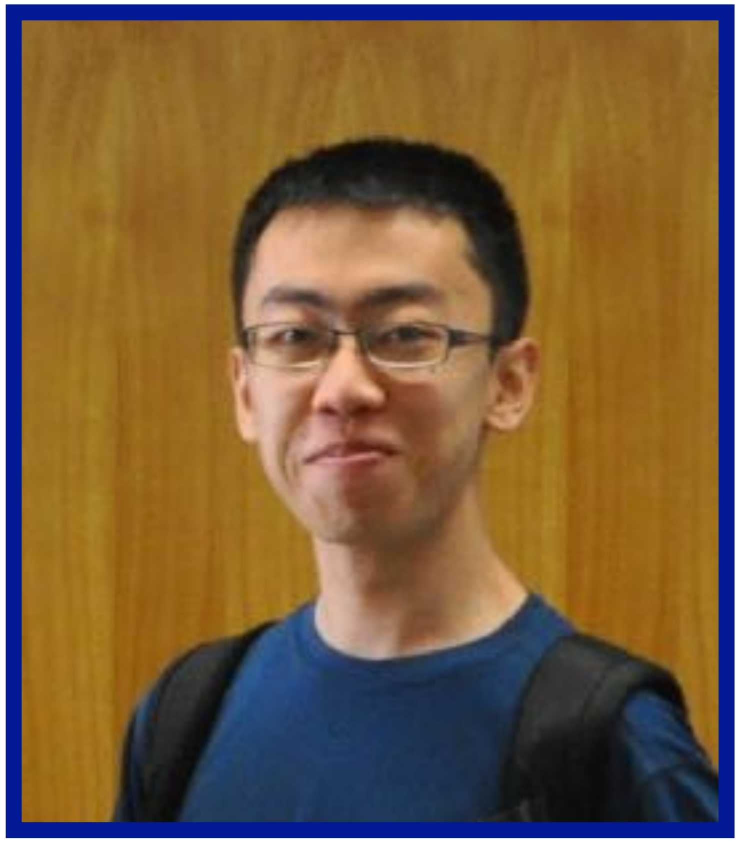
Trapping heavy and deformed nuclei… for a long, long time



Andrew Jayich[1,2]

UCSB Department of Physics, Santa Barbara, CA
California Institute for Quantum Emulation, Santa Barbara, CA

Acknowledgements



Mingyu Fan

Craig Holliman

Anna Wang (Stanford)

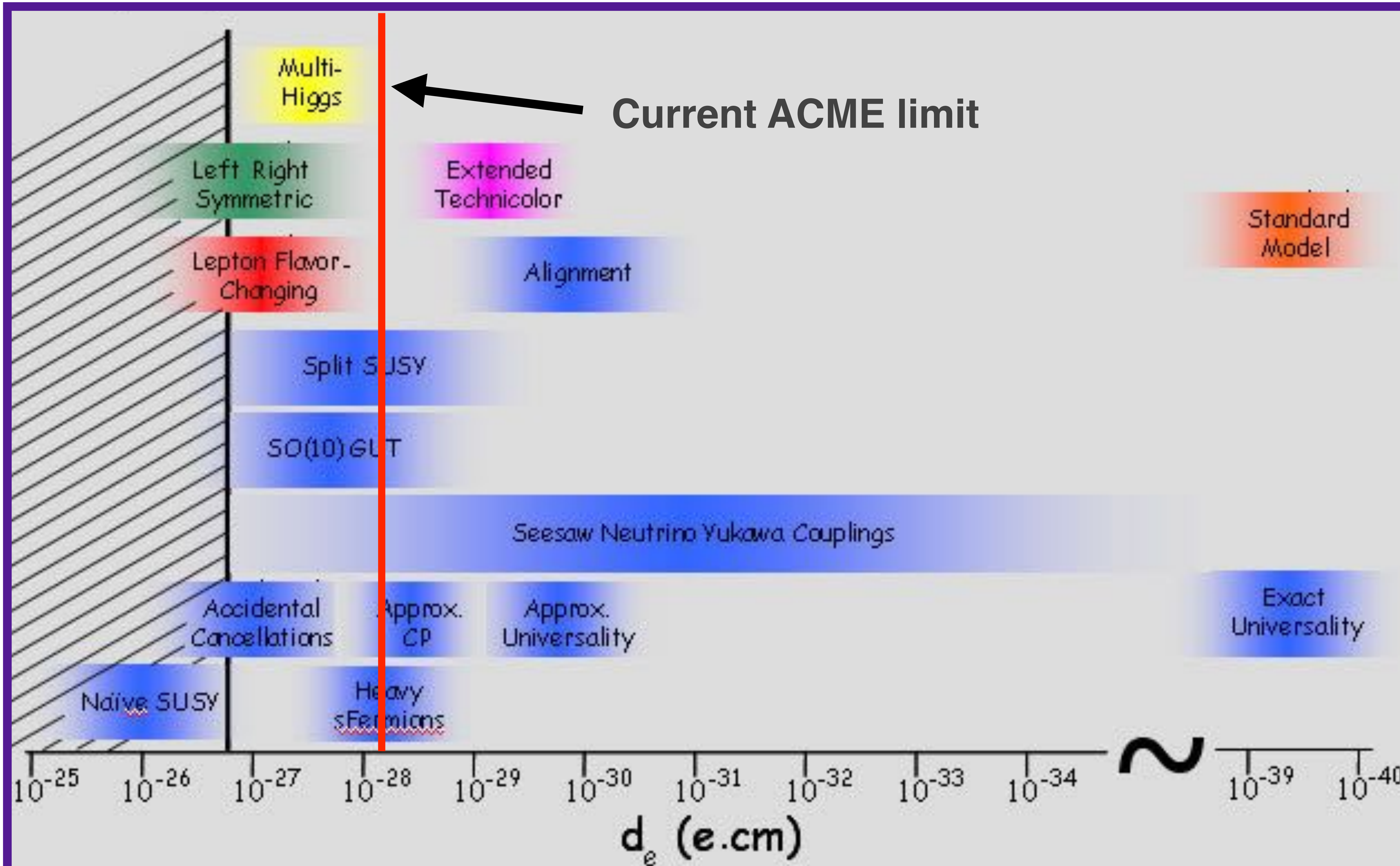
Sam Dutt

Jack Roten

Collaborators

- Amar Vutha (Toronto)
- Dave Patterson (UCSB)
- Matt Dietrich (ANL)
- Eric Hudson (UCLA)
- Wes Campbell (UCLA)

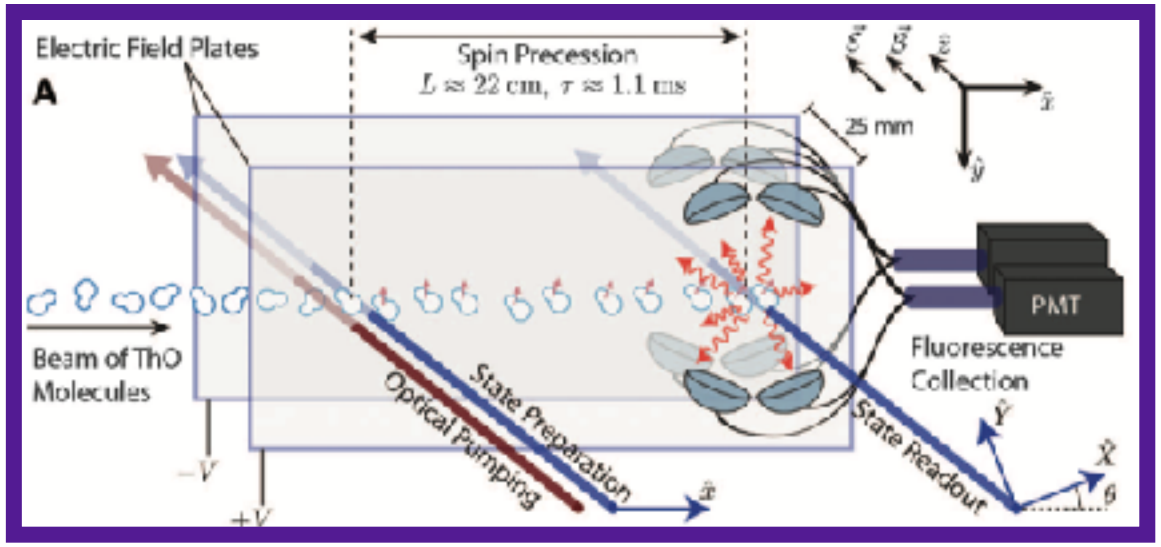
Science



Compiled by Dave DeMille

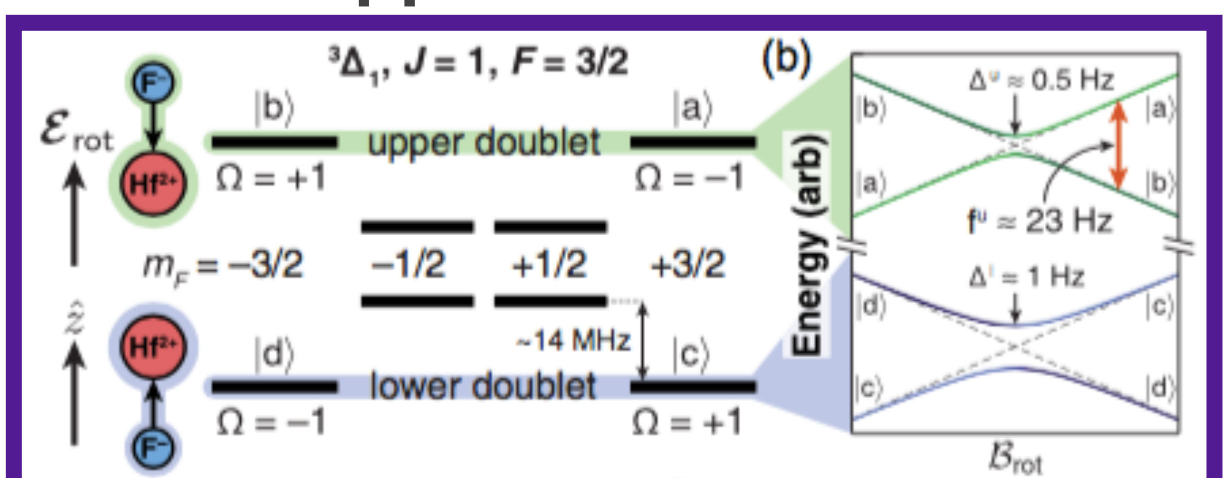
Active EDM searches

ACME - ThO beam



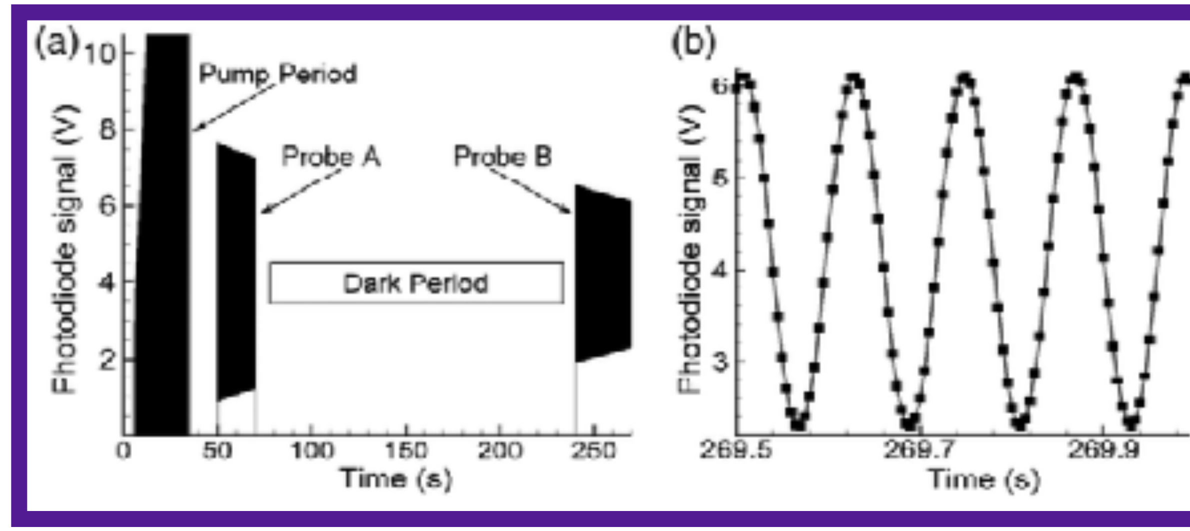
ACME collaboration, *Science* **343**, 6168 (2014)

JILA - Trapped HfF+



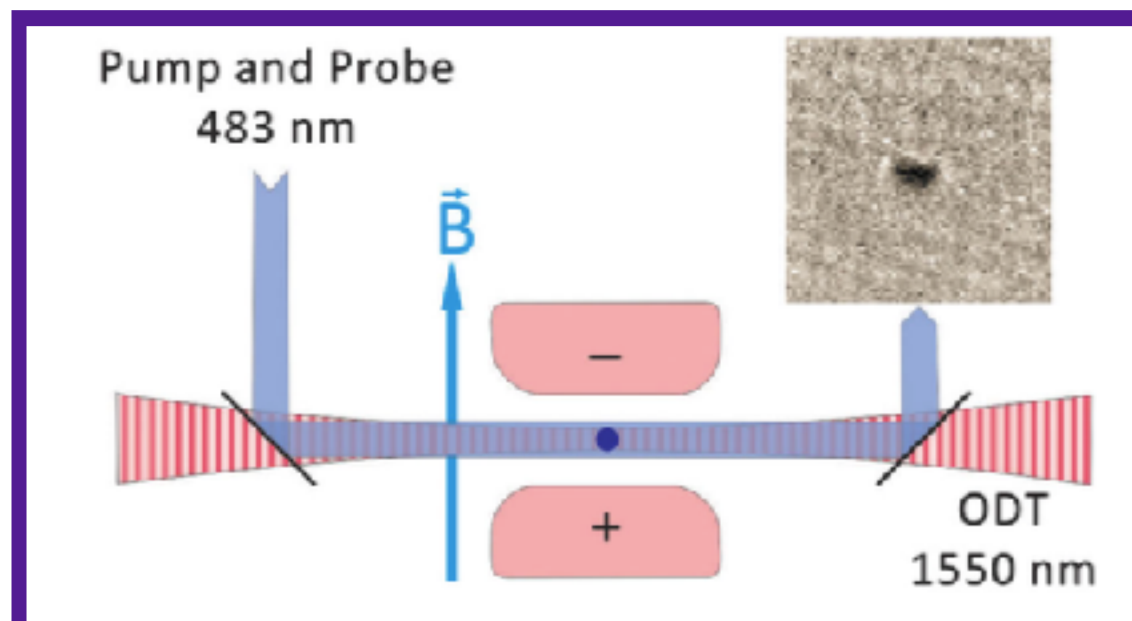
Cairncross *et al*, *PRL* **119**, 153001 (2017)

Washington - Hg vapor



Graner *et al*, *PRL* **116**, 161601 (2016)

Argonne - Ultracold radium



Parker *et al.*, *PRL* **114**, 6168 (2015)

Fishing

New directions

electron EDM (atoms in molecules):

^{232}Th: I=0

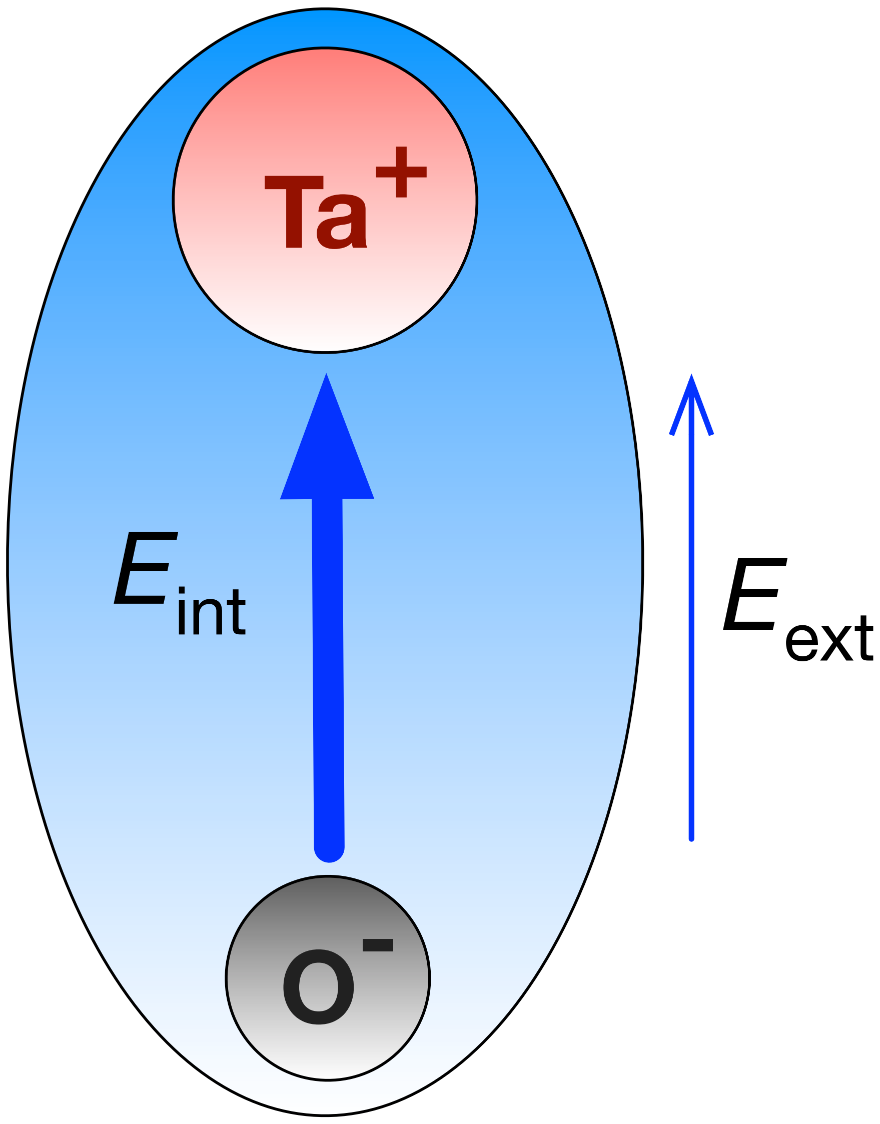
^{180}Hf: I=0

nuclear EDM (atoms):

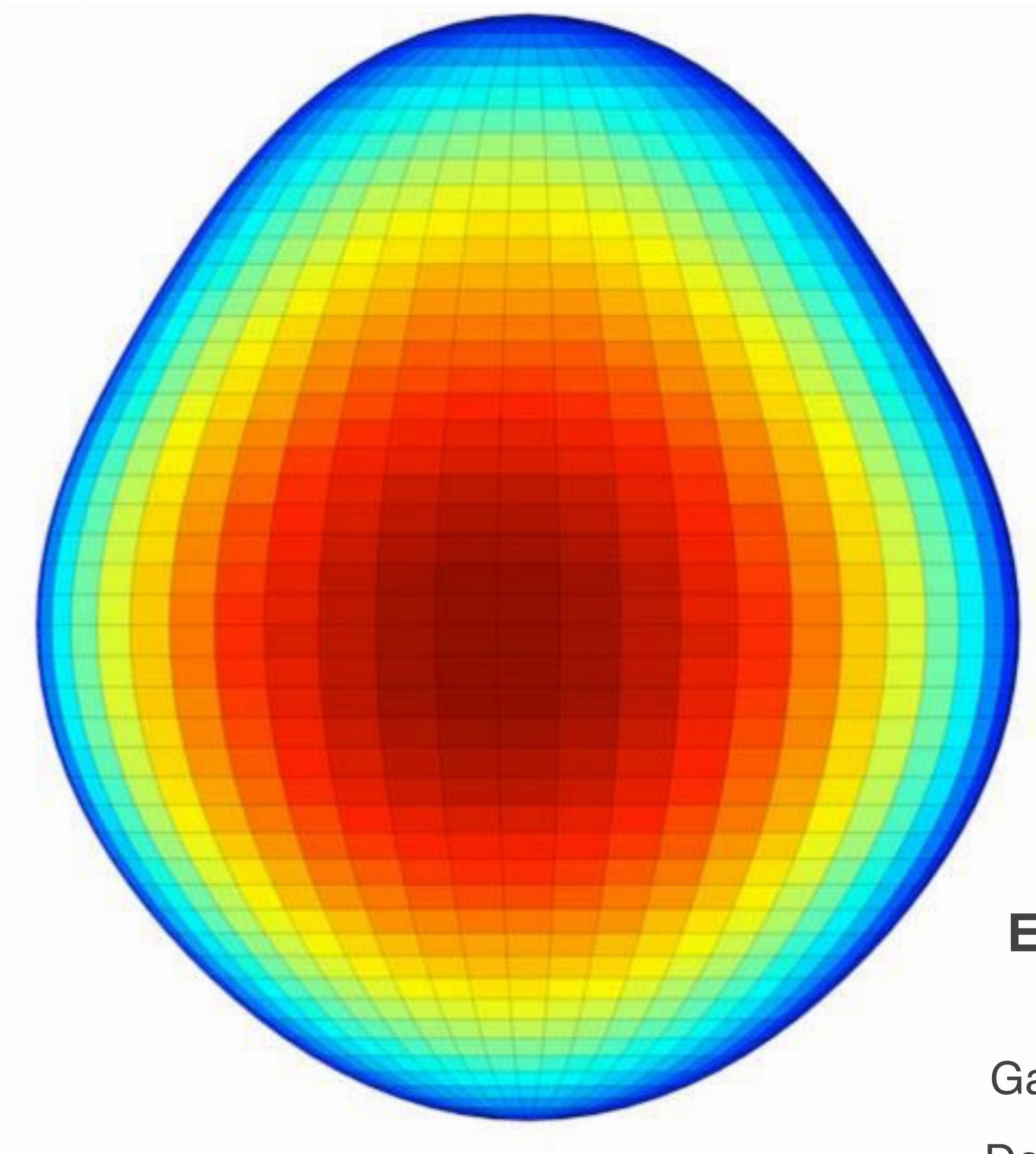
^{199}Hg: I=1/2

^{225}Ra: I=1/2

14.9-day half-life



Octupole enhancement



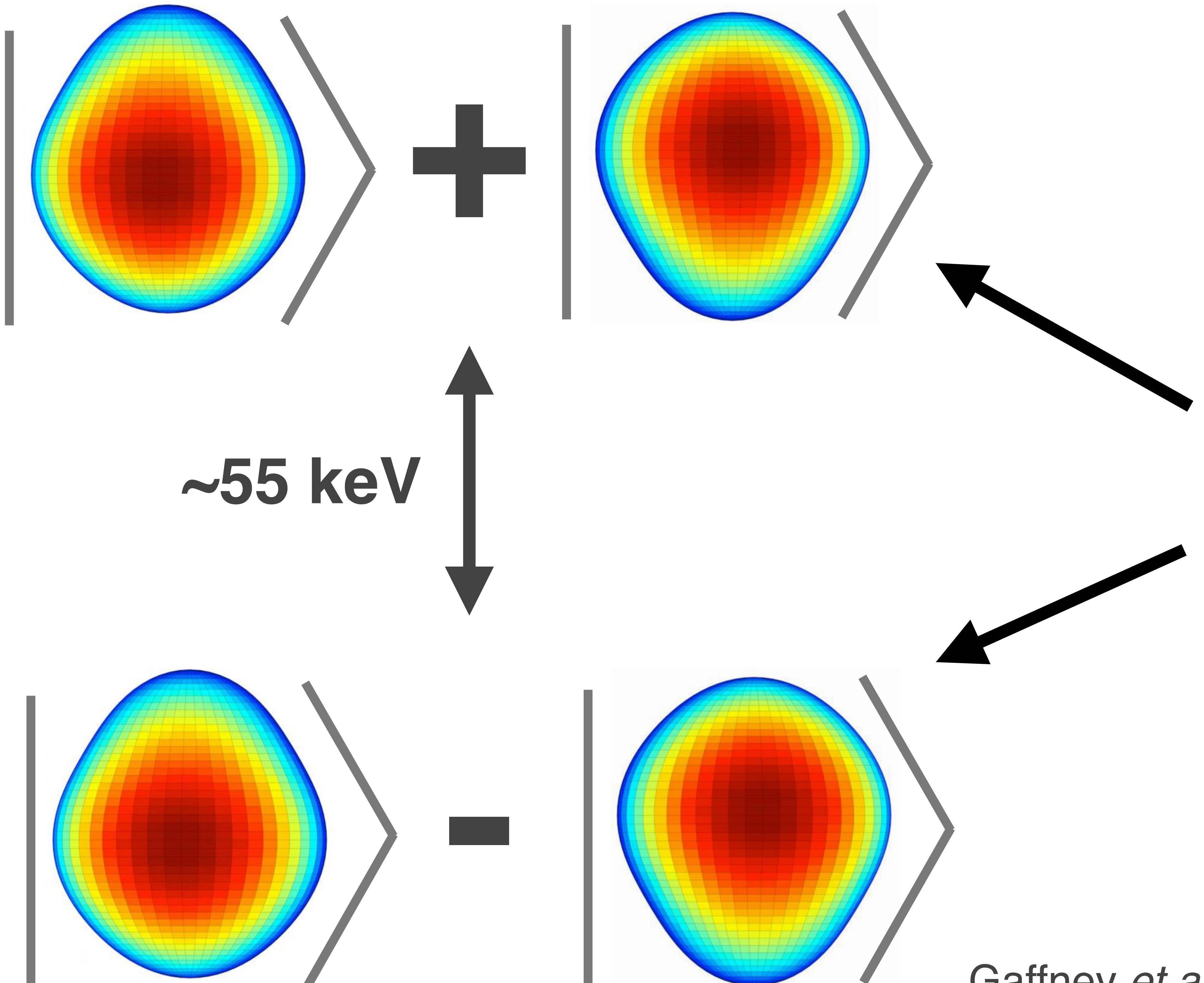
Enhancement: ~100-1000x

Gaffney *et al.*, *Nature* **497**, 199 (2013)

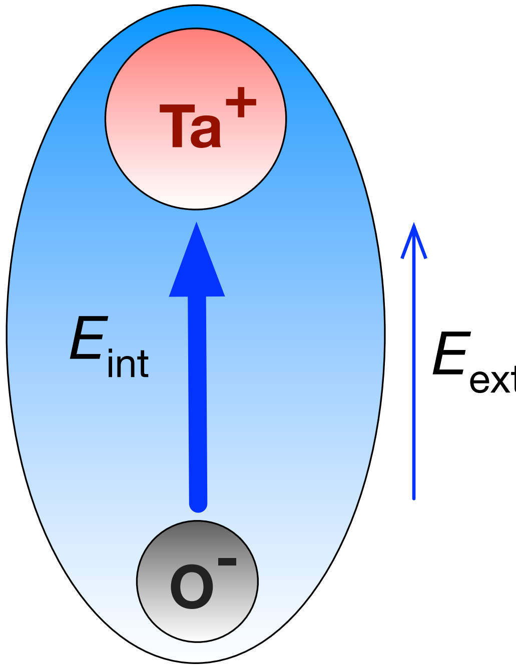
Dobaczewski *et al.*, *PRL* **94**, 23 (2005)

Octupole enhancement

1st nuclear excited state



nuclear ground state



Mixing gives an enhancement in the lab frame analogous to molecular Omega doubling

Gaffney *et al.*, *Nature* **497**, 199 (2013)

Dobaczewski *et al.*, *PRL* **94**, 23 (2005)

New directions

electron EDM (atoms in molecules):

^{232}Th: I=0

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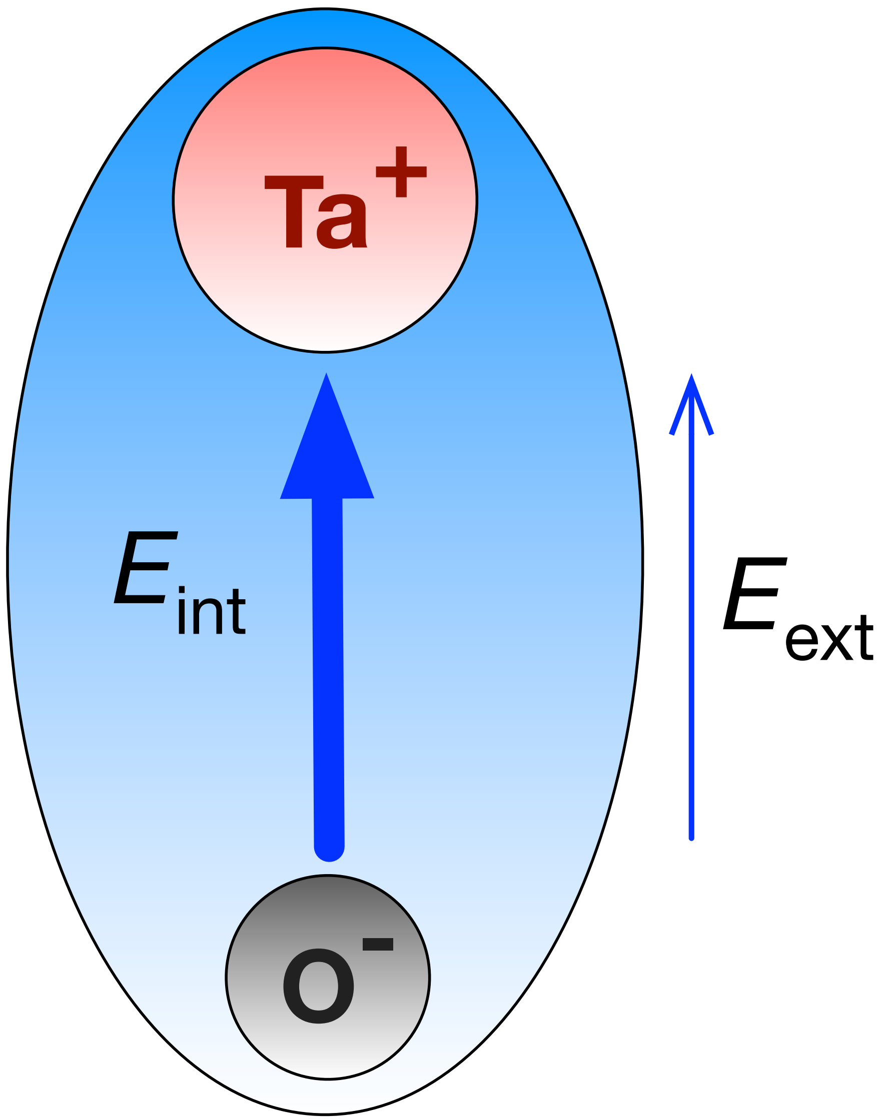
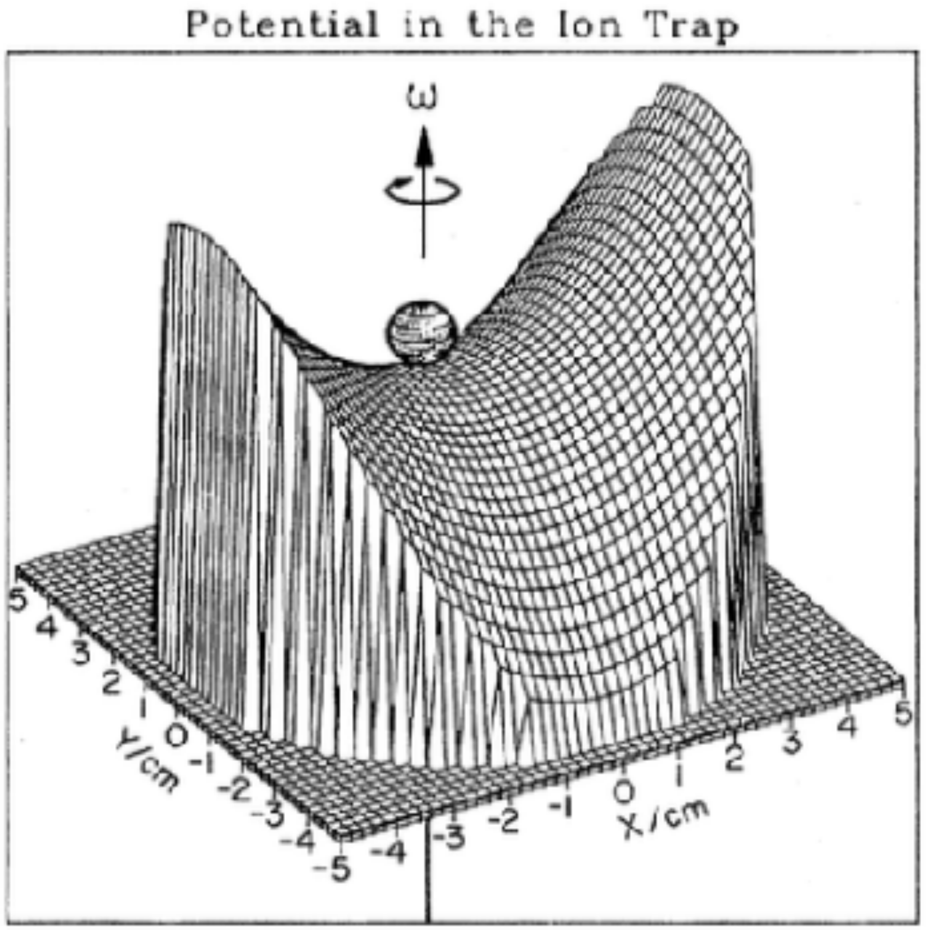


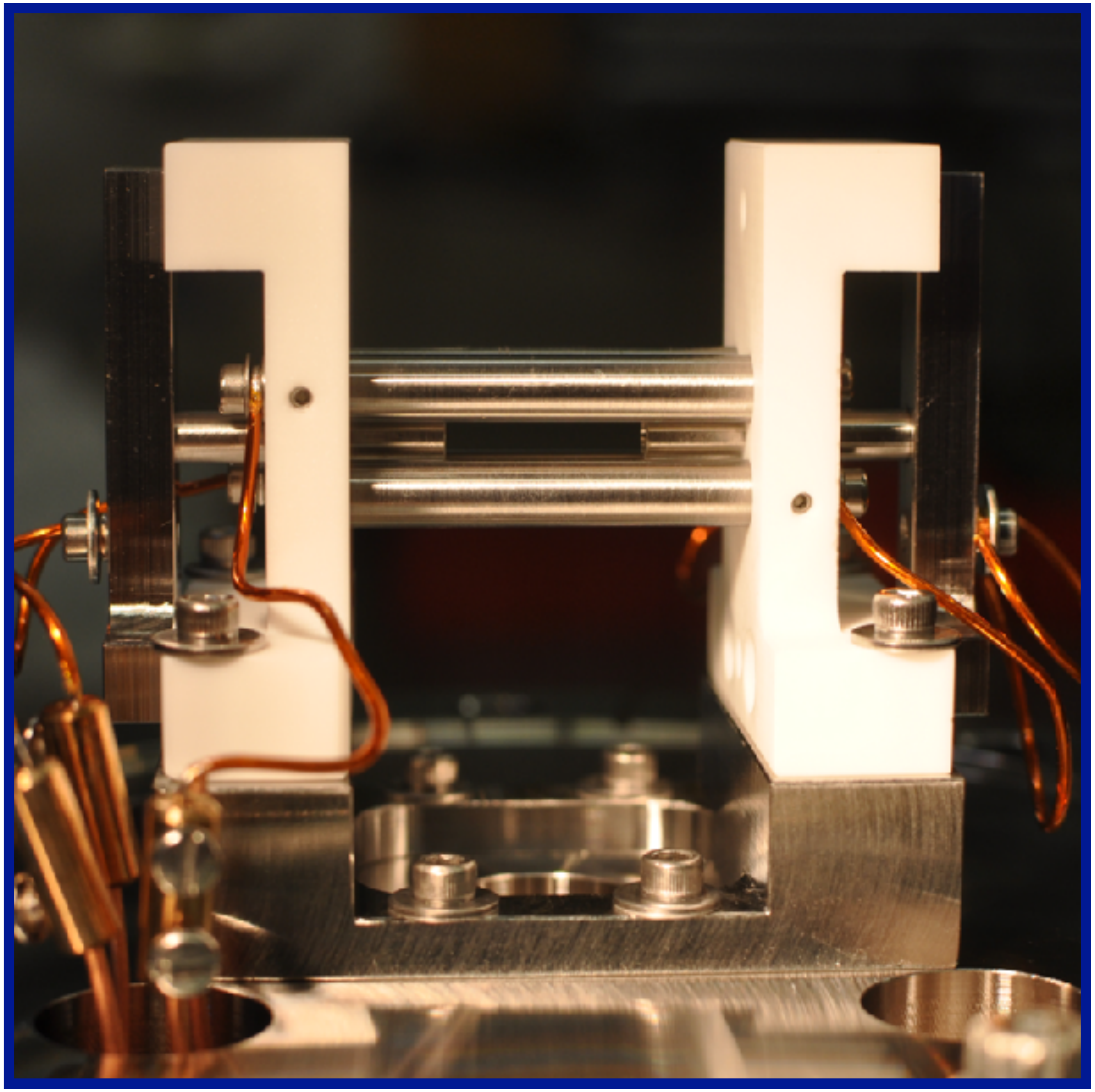
Sensitivity

$$\delta d \propto \frac{1}{\tau\sqrt{N}}$$

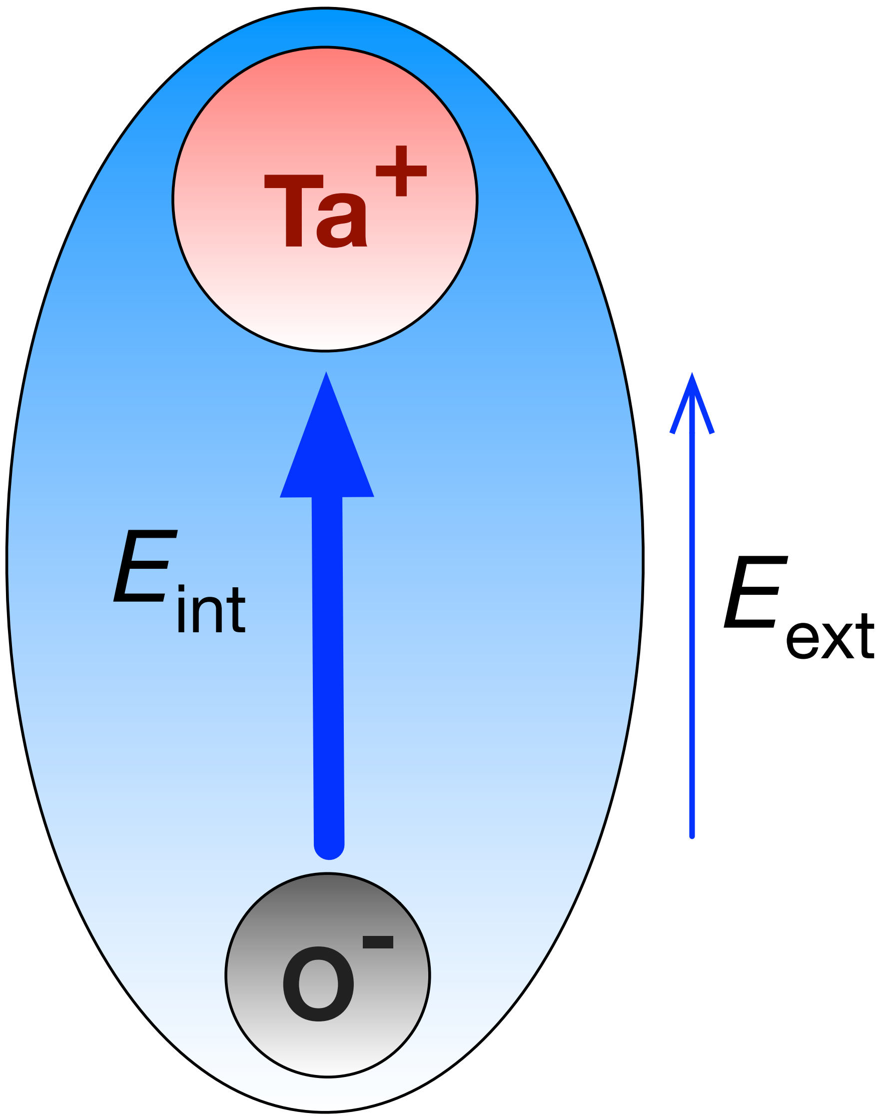
Ion trapping



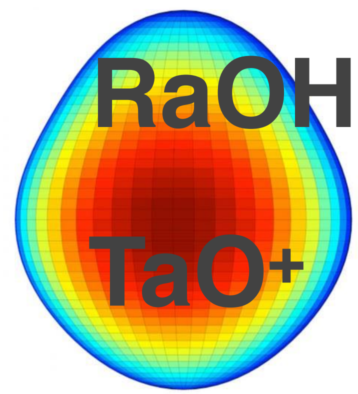
W. Paul, *RMP* **62**, 531 (1990)



Deformation enhancement



Molecular ions:



$RaOH^+$ Kozyryev and Hutzler, *PRL,* (2017)

TaO^+ Fleig, *PRA,*(2017)

WN^+

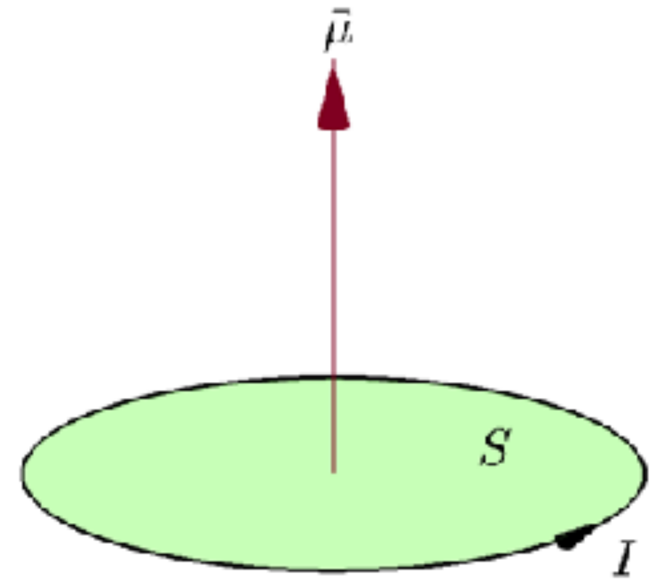
Enhancement: ~100-1000x

Easily polarizable

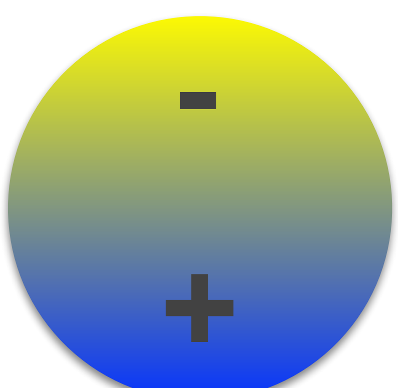
nuclear MQM

monopole charge

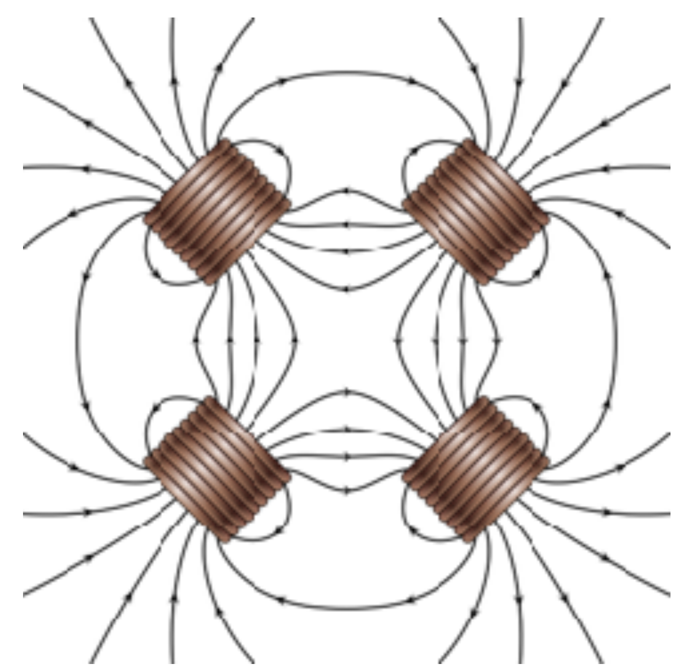
magnetic dipole



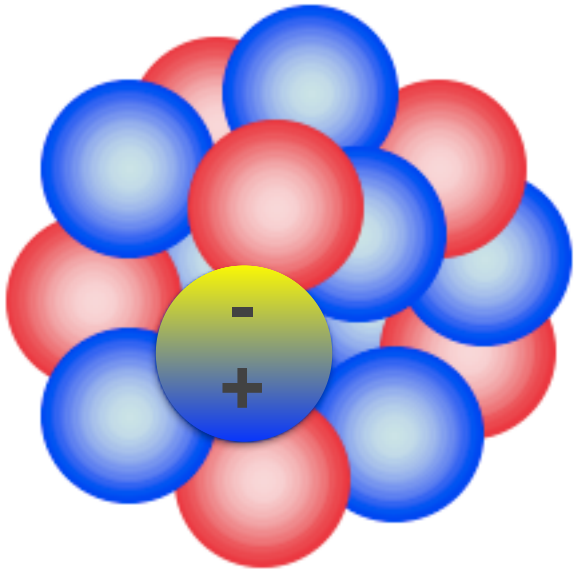
electric dipole



magnetic quadrupole



nuclear MQM - physics sensitivity



Collective enhancement: $A^{2/3}$ ~100x

not screened (compare to Schiff moment)

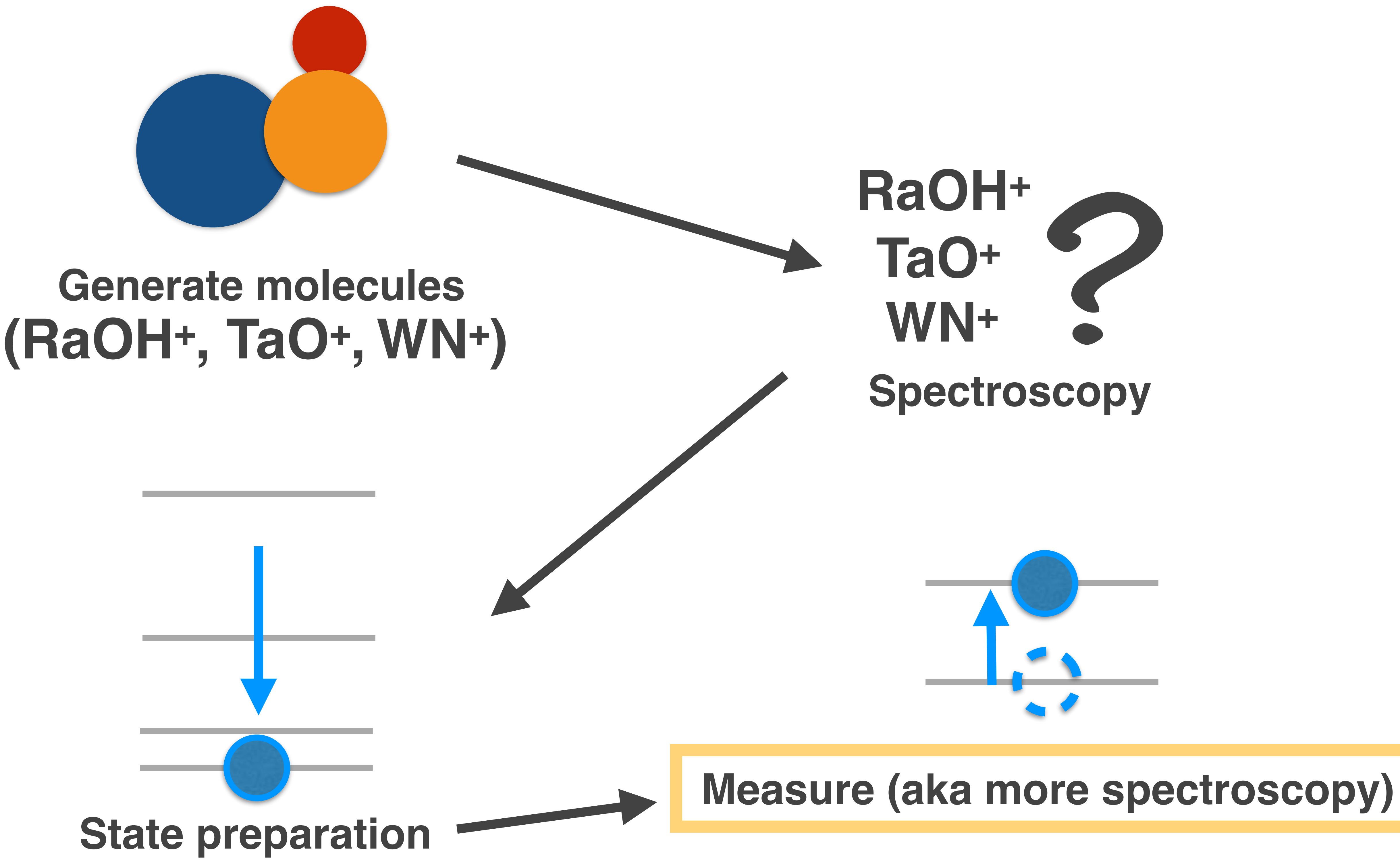
sensitive to pi_0 meson exchange

Sushkov *et al*, *JETP* **60**, 873 (1984)

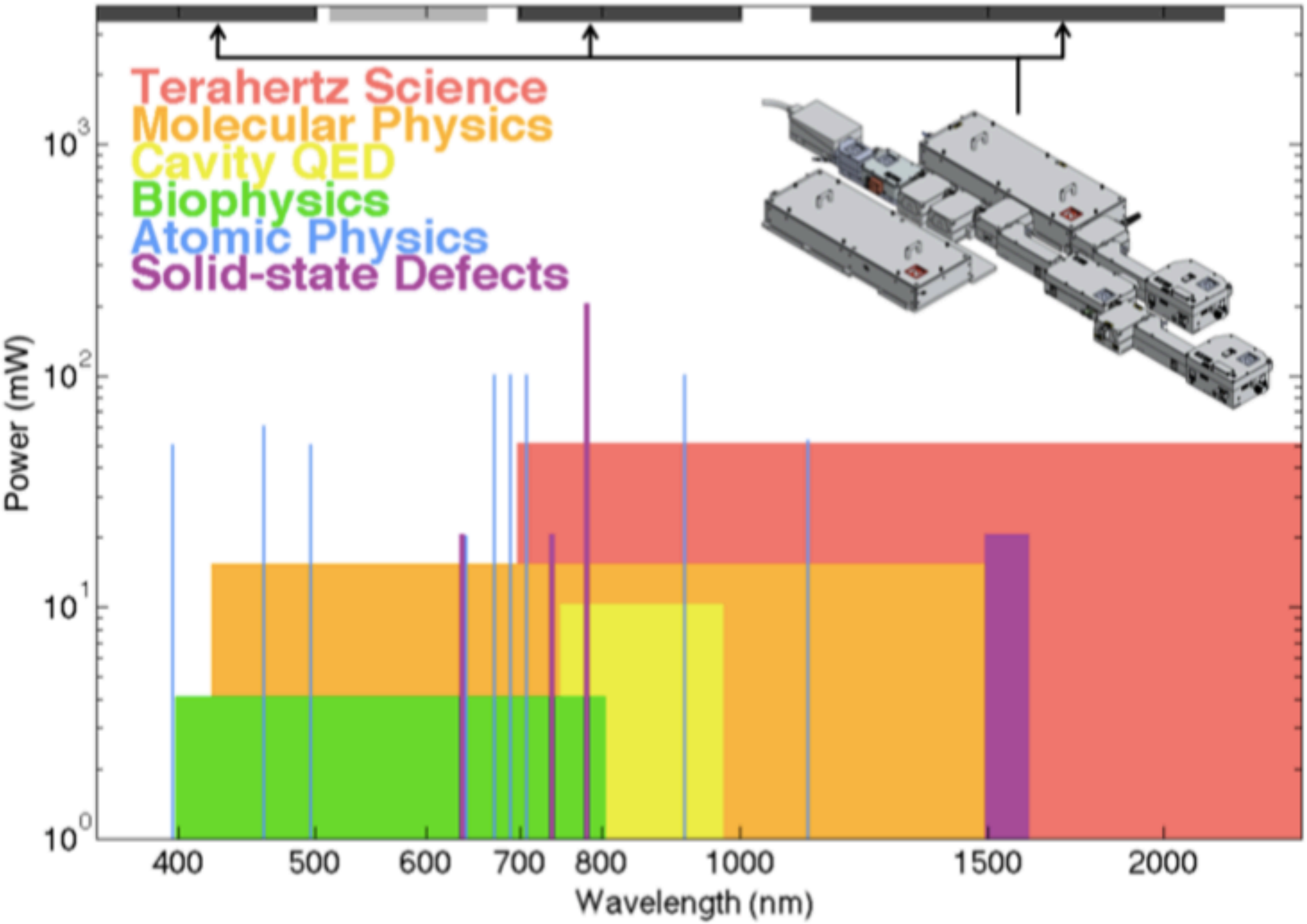
Flambaum, *Phys Lett. B* **320**, 211 (1994)

Flambaum *et al.*, *PRL* **113**, 103003 (2014)

Steps towards an MQM measurement



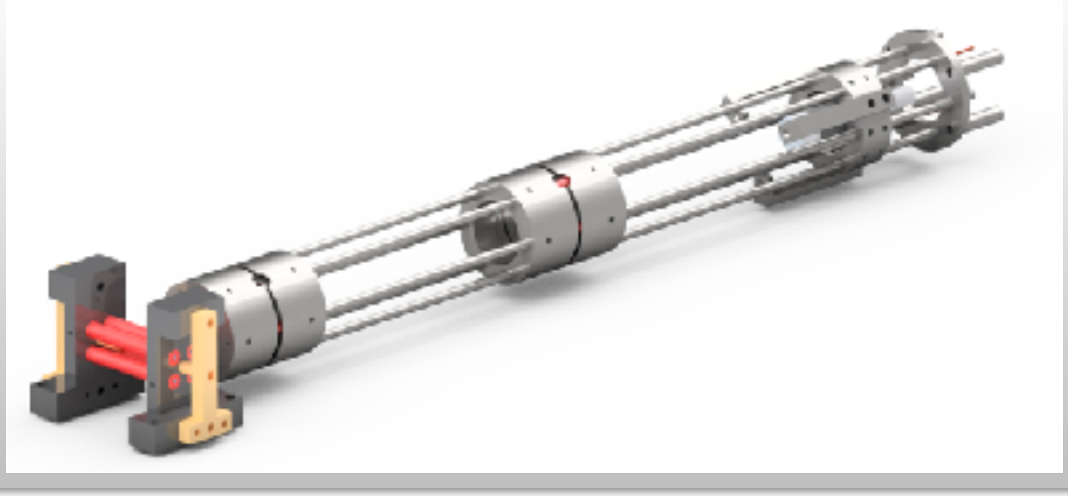
UCSB BiFROST



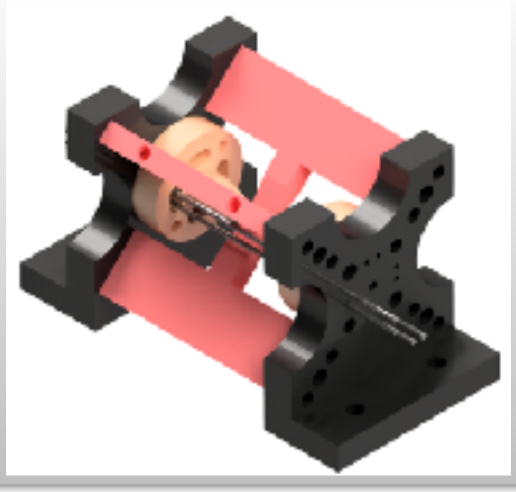
David Weld led proposal. Installing now.

Complementary ion trapping systems

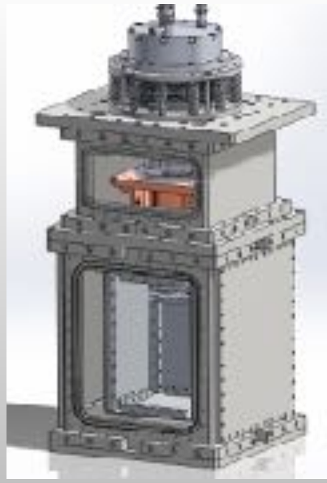
1.) Time-of-flight mass spec.
Linear motion feedthrough
Precision leak valve



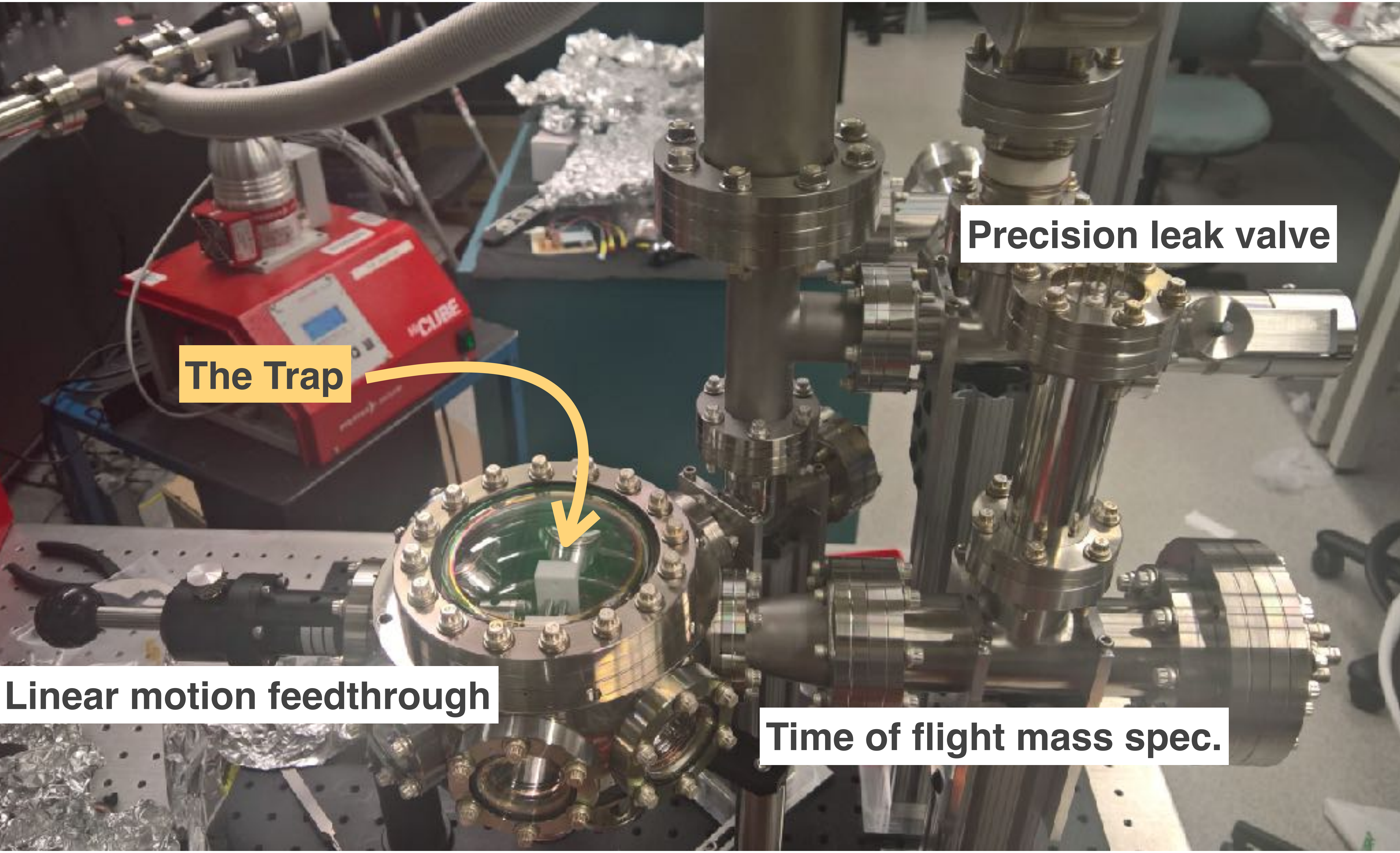
2.) High frequency trap
Entanglement, metrology, etc.
Quantum logic spectroscopy
Direct comb spectroscopy



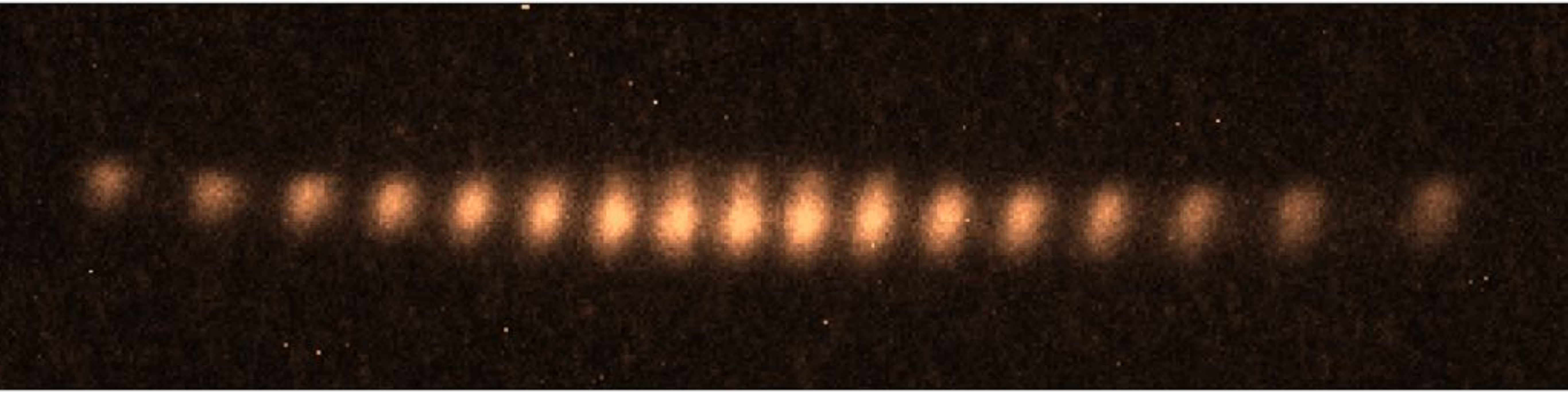
3.) Cryogenic molecular ion trap
Reduce rotational phase space
Extremely low vacuum



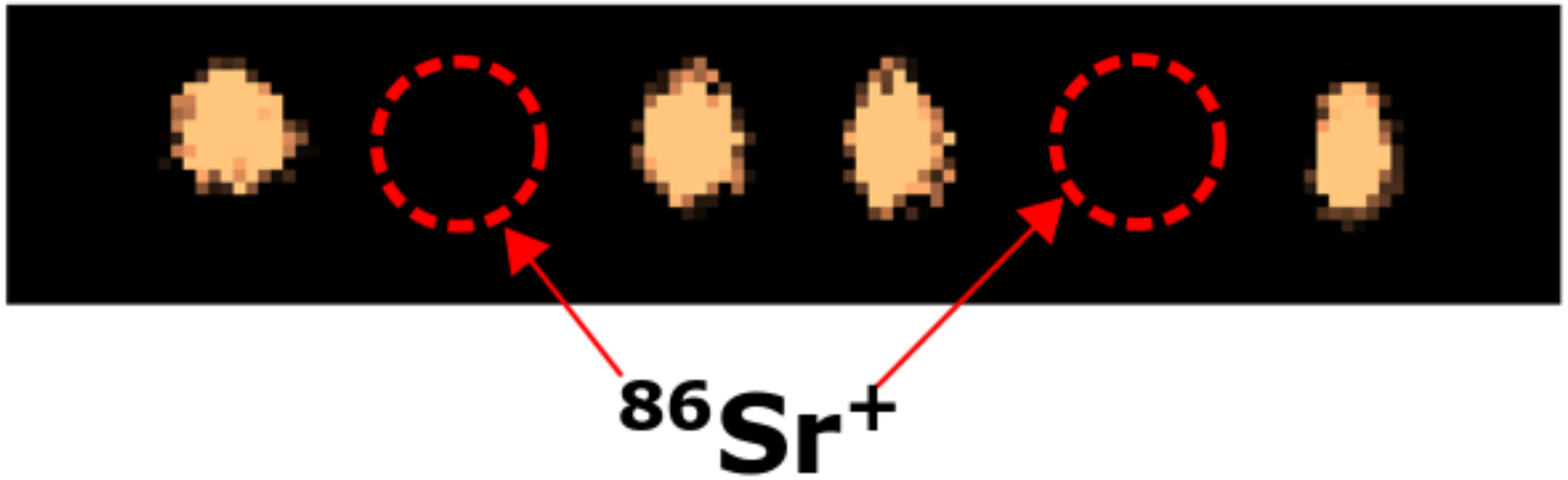
Molecular ion and radium ion factory



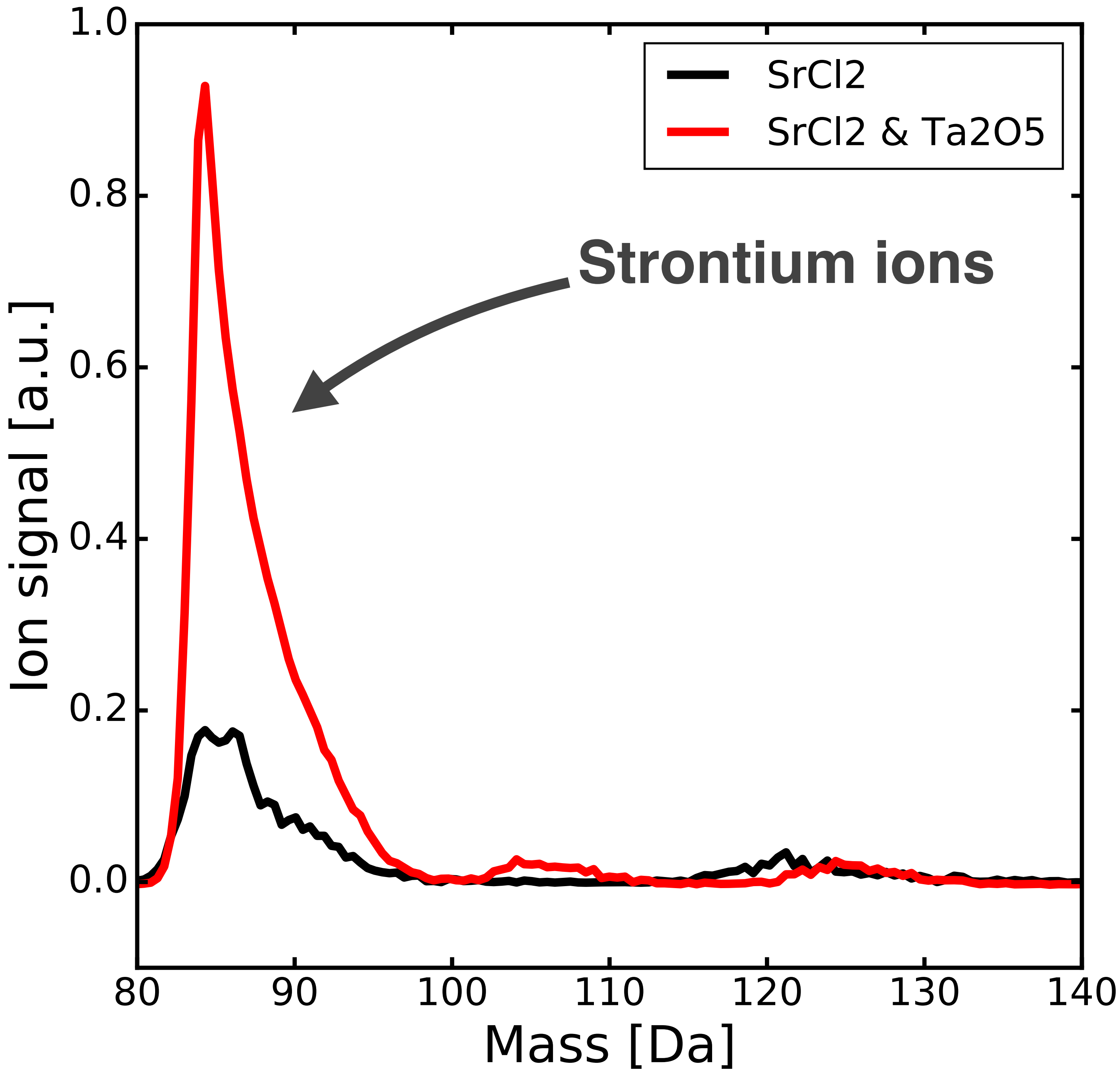
Strontium ions in the lab



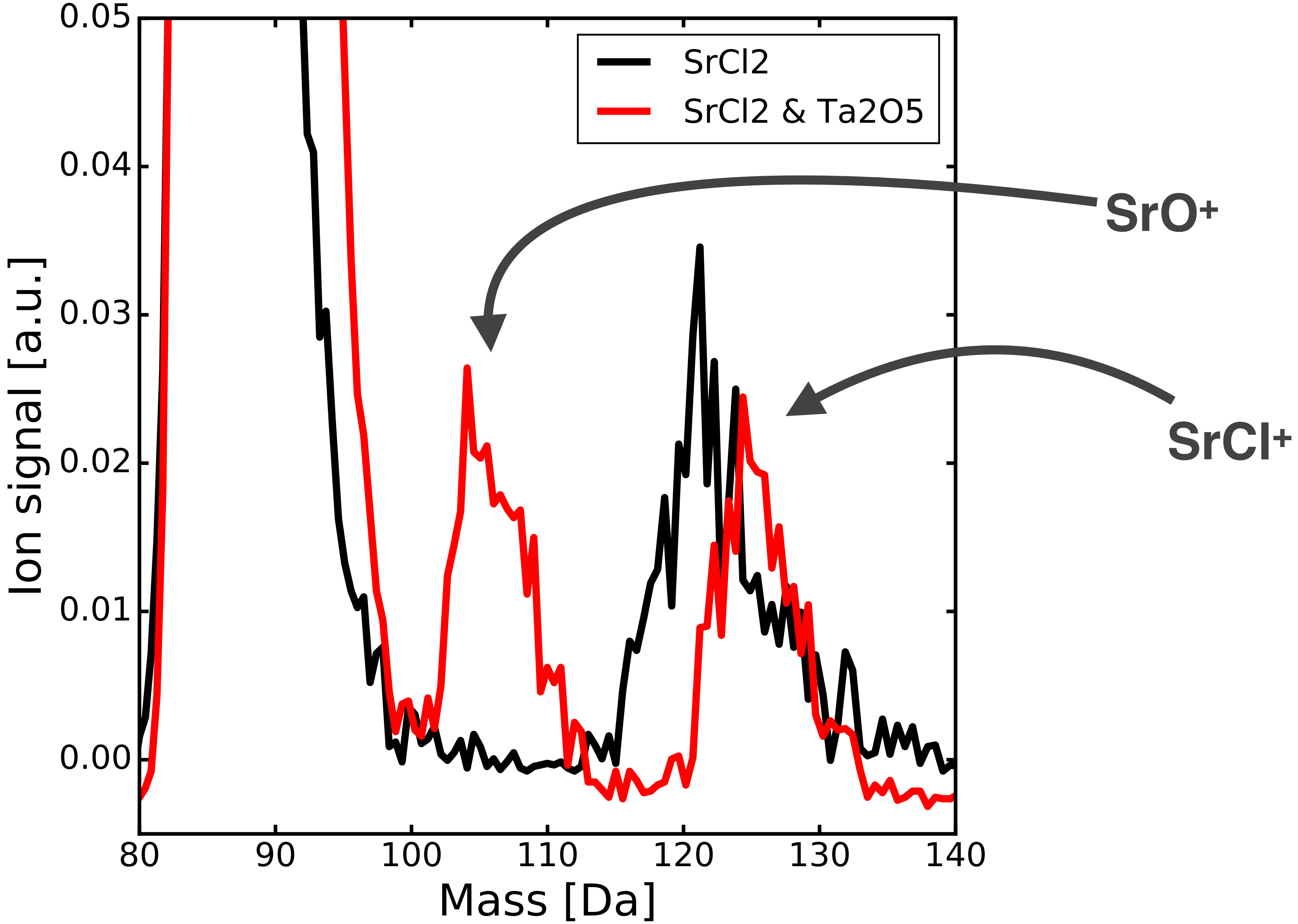
Controlled Sr isotope loading



Time of flight mass spectrometry



Time of flight mass spectrometry



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	

Atomic parity nonconservation

$$\geq Z^3$$

Fortson, *PRL* **70**, 2383 (1993)

Atomic parity nonconservation

- **Constrain Z boson masses arising from new physics**
- **Resolve discrepancies with single previous anapole moment**
- **Meson-nucleon couplings (poorly understood)**
- **Neutron skin**
- **Nuclear matter equation of state**
- **Axions**
- **Muon's anomalous magnetic moment**

$$\geq Z^3$$

Fortson, *PRL* **70**, 2383 (1993)

Haxton *et al.*, *ARNPS* **51**, 261 (2001)

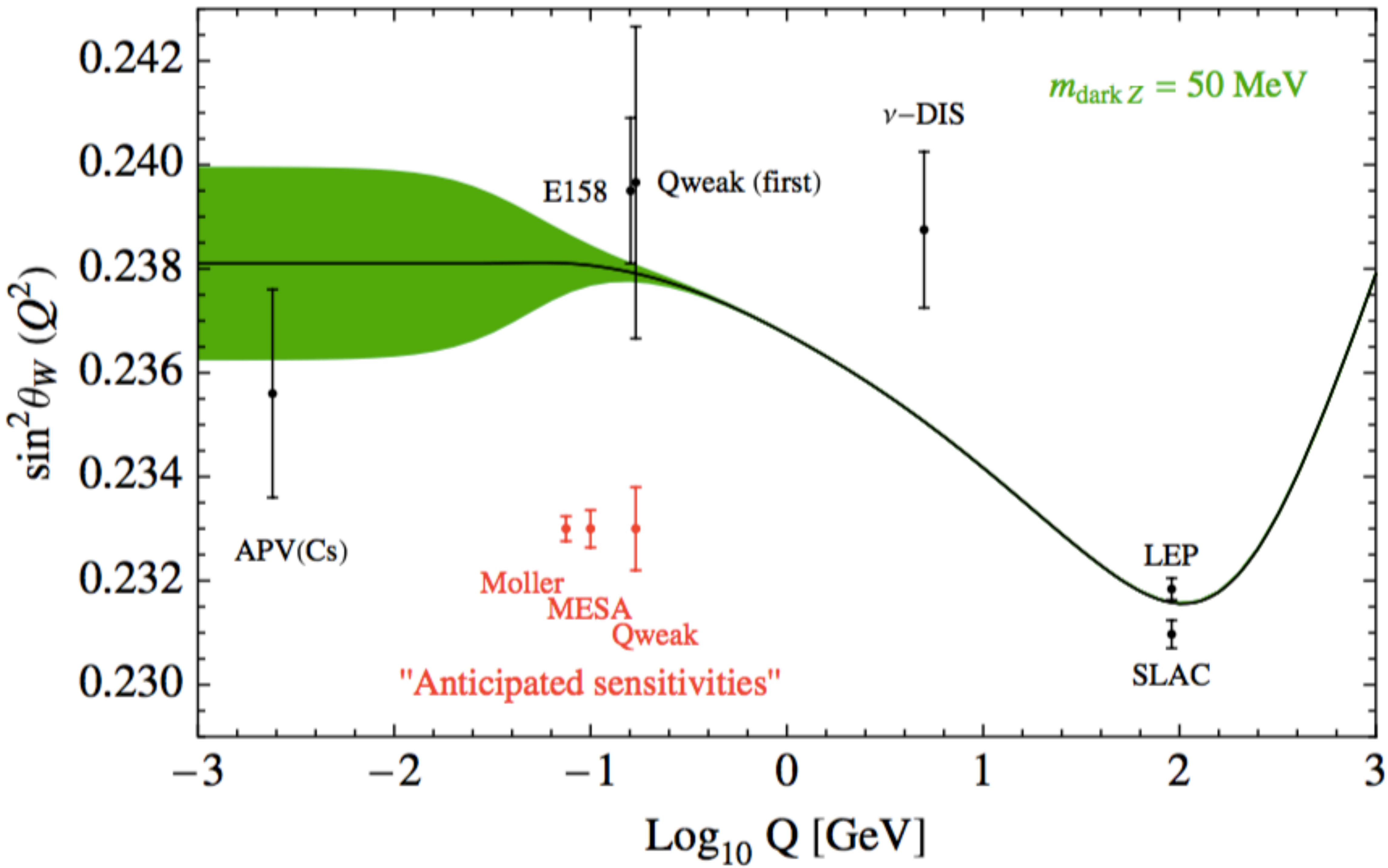
Arkani-Hamed *et al.*, *PRD* **79**, 015014 (2009)

Davoudiasl *et al.*, *PRD* **89**, 095006 (2014)

Roberts *et al.*, *PRD* **90**, 096005 (2014)

Flambaum *et al.*, *PRA* **96**, 012516 (2017)

Atomic parity nonconservation

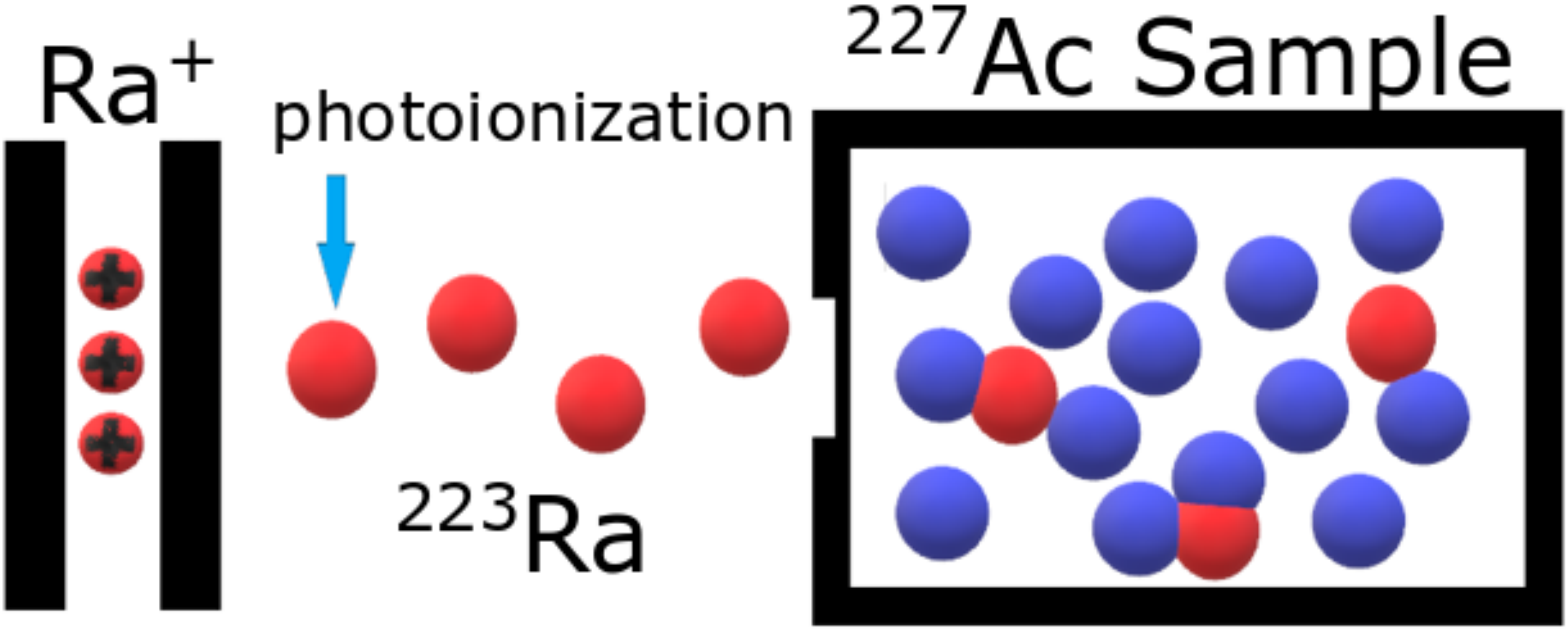


Davoudiasl *et al.*, *PRD* **89**, 095006 (2014)

Radium isotopes we can use

Radium	half-life	nuclear spin	parent	parent's half-life
223	11.4 d	3/2	Actinium 227	21.8 y
224	3.6 d	0	Thorium 228	1.9 y
225	14.9 d	1/2	Thorium 229	7900 y
226	1600 y	0	-	-
228	5.8 y	0	Thorium 232	10^{10} y

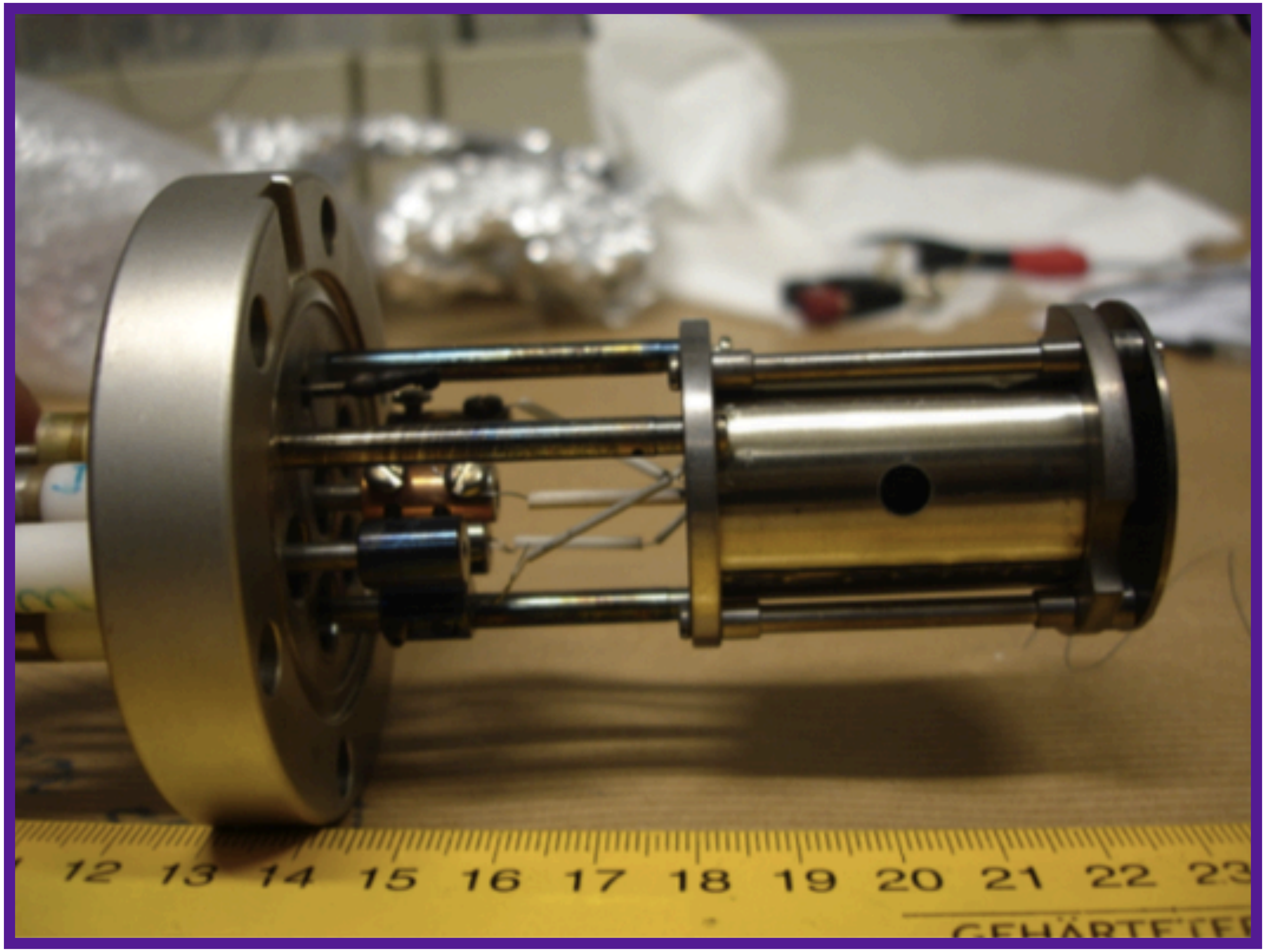
Q: Short half-lives? A: Ion trap



Actinium 22y half-life

Ra 225 at KVI (oven example)

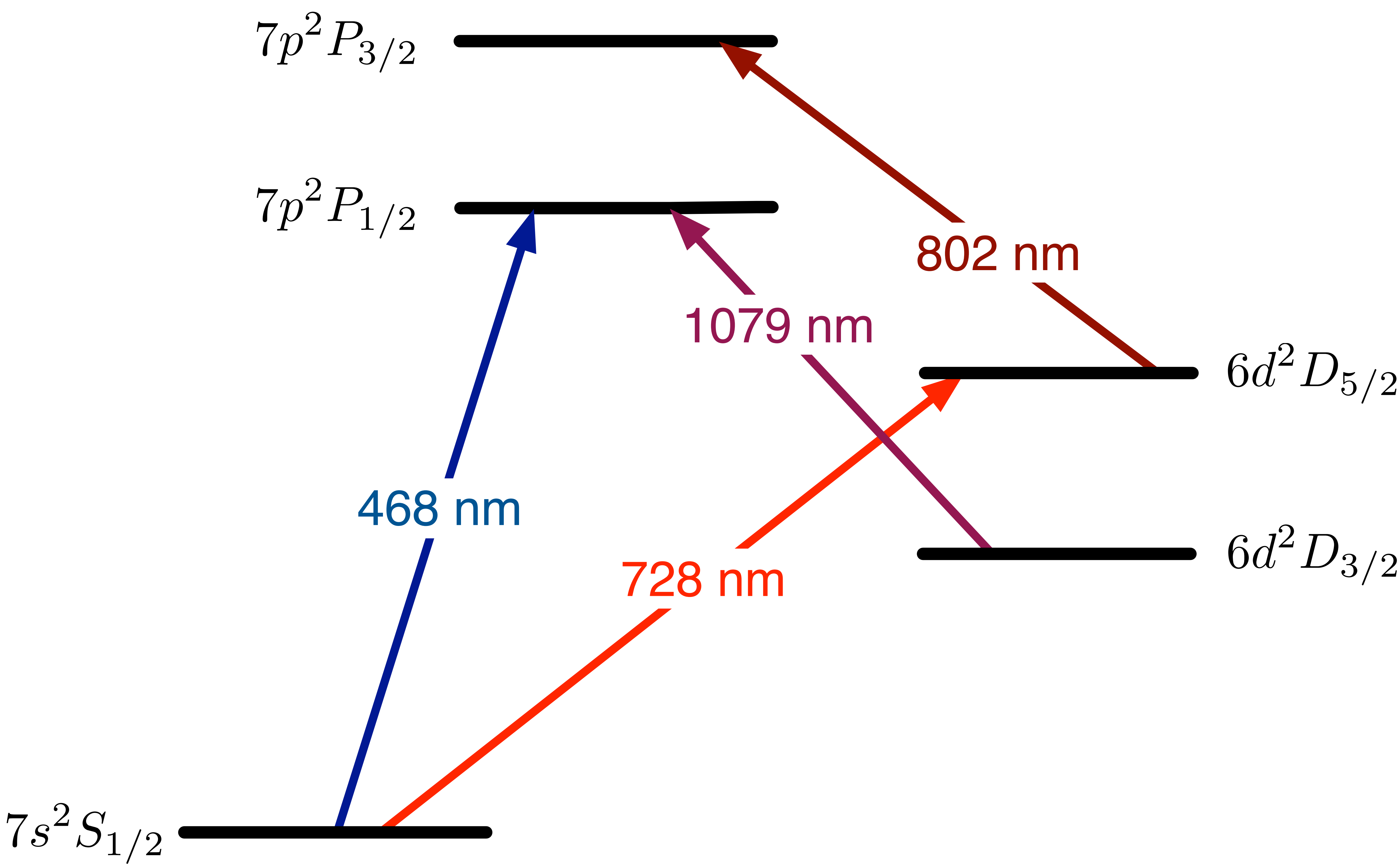
Thorium 229 → **Radium 225**



Santra *et al.*, *PRA* **90**, 040501(R) (2014)

Santra, PhD thesis (2013)

The Radium Ion



The unknown

Ra^+ state	Lifetime	Branching ratio
$7p\,^2P_{1/2}$	?	?
$7p\,^2P_{3/2}$	?	?
$6d\,^2D_{5/2}$	≥ 232 ms	
$6d\,^2D_{3/2}$	?	

(Avg. atomic physicist)

Radium radioactivity

$^{226}\mathrm{Ra}$ **1600 yr half life**

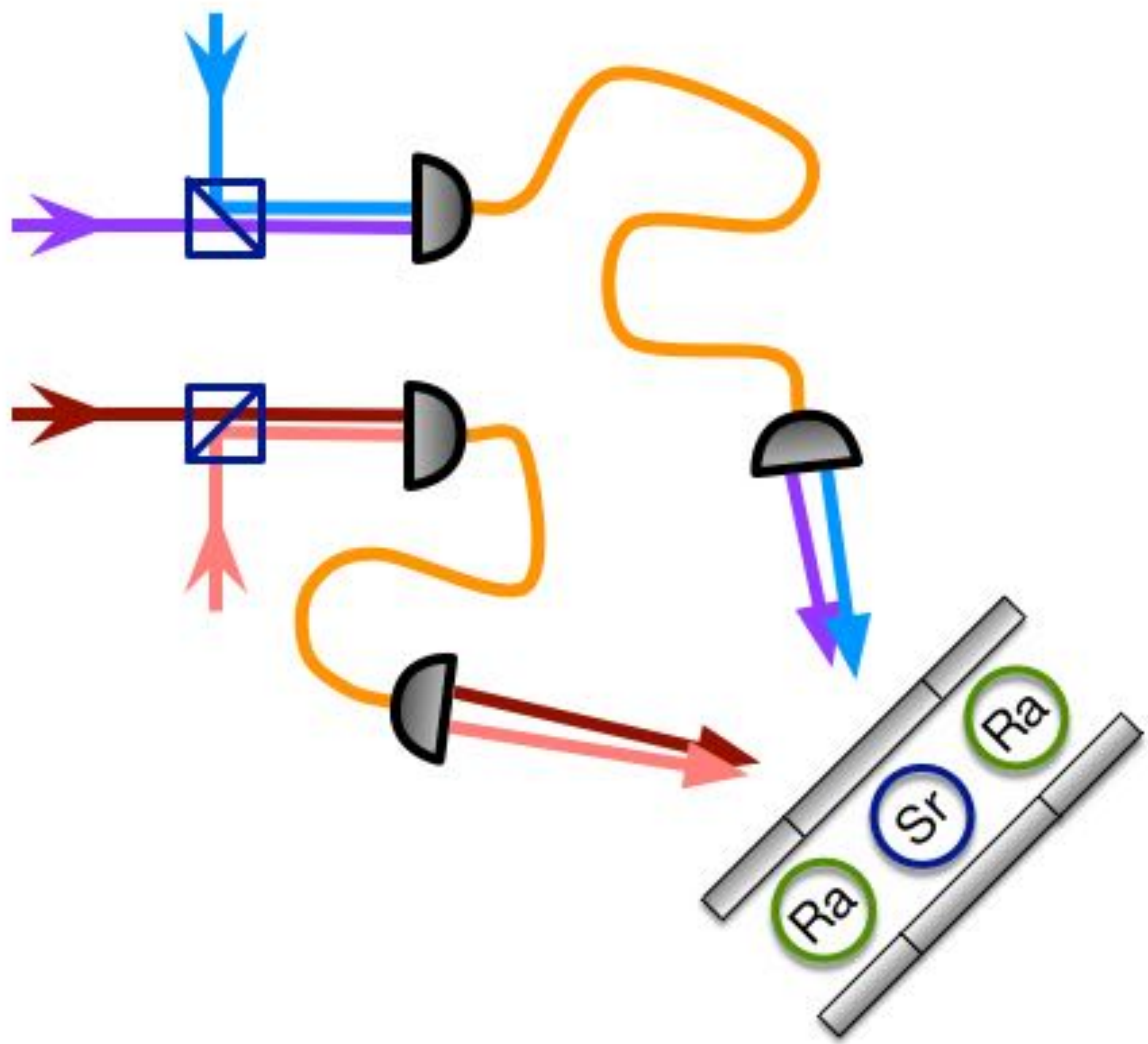
$$\alpha \quad \beta \quad \gamma$$

10 micro Curie sample

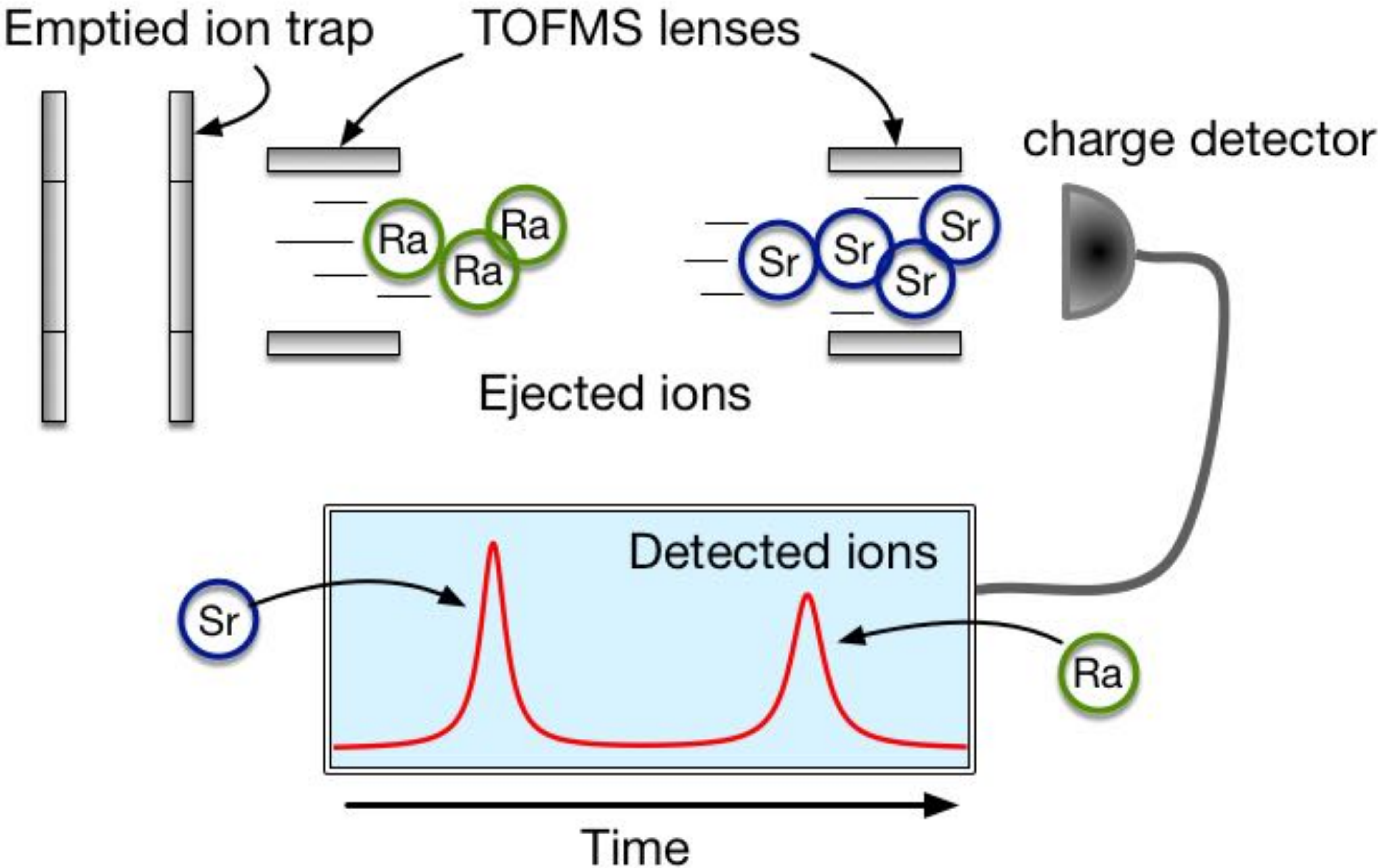
equivalent: activity of ~50 people

or:

Co-trap radium with strontium

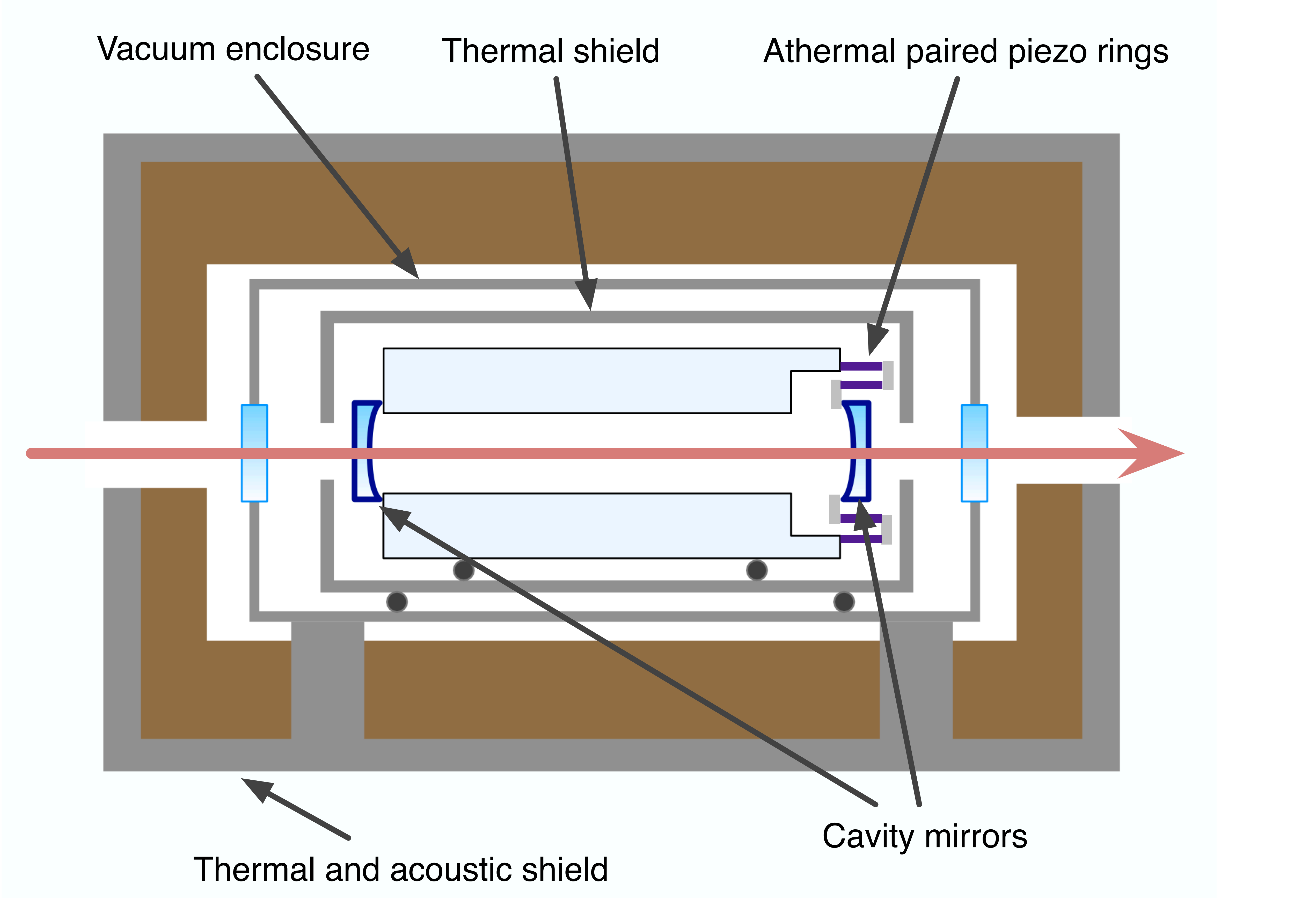


TOFMS

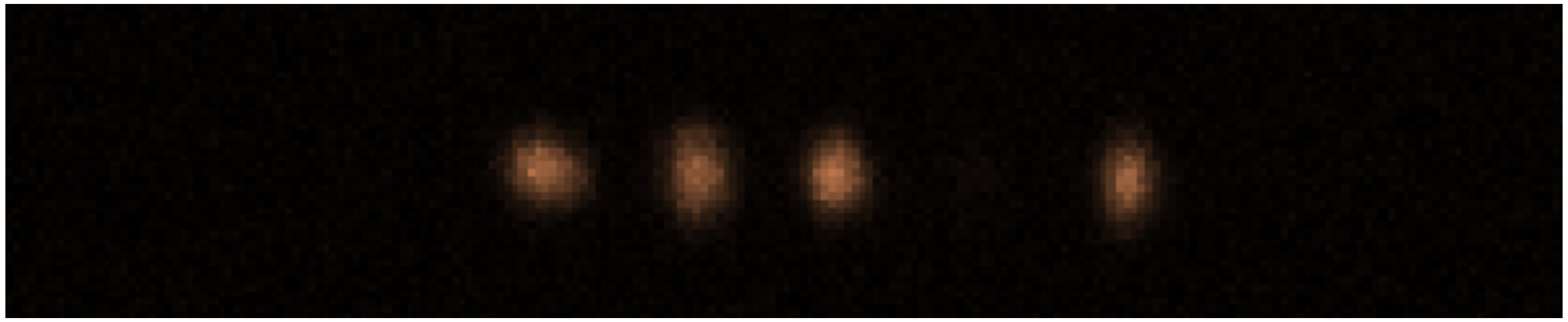


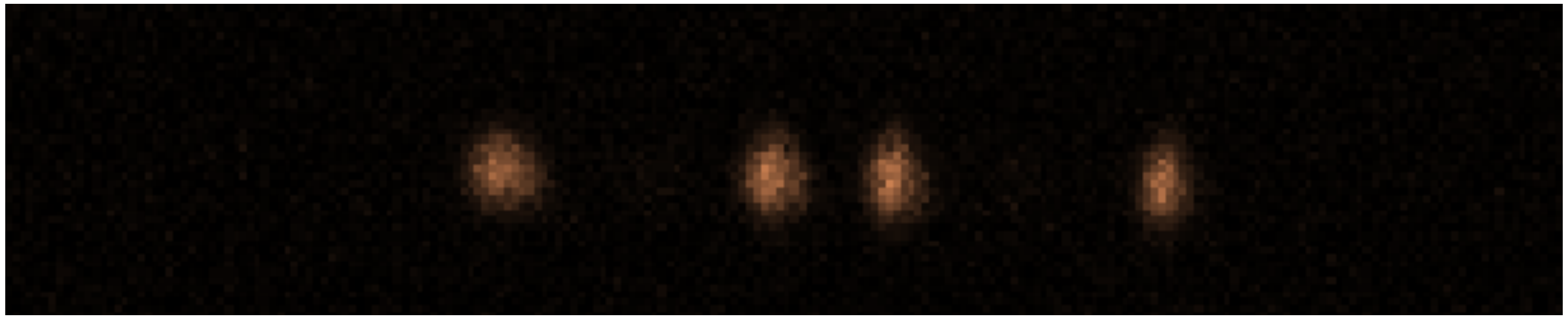
Emptied ion trap
TOFMS lenses
charge detector
Ra
Ra
Ra
Sr
Sr
Sr
Sr
Ejected ions
Detected ions
Sr
Ra
Time

Laser stabilization (unique for ions)



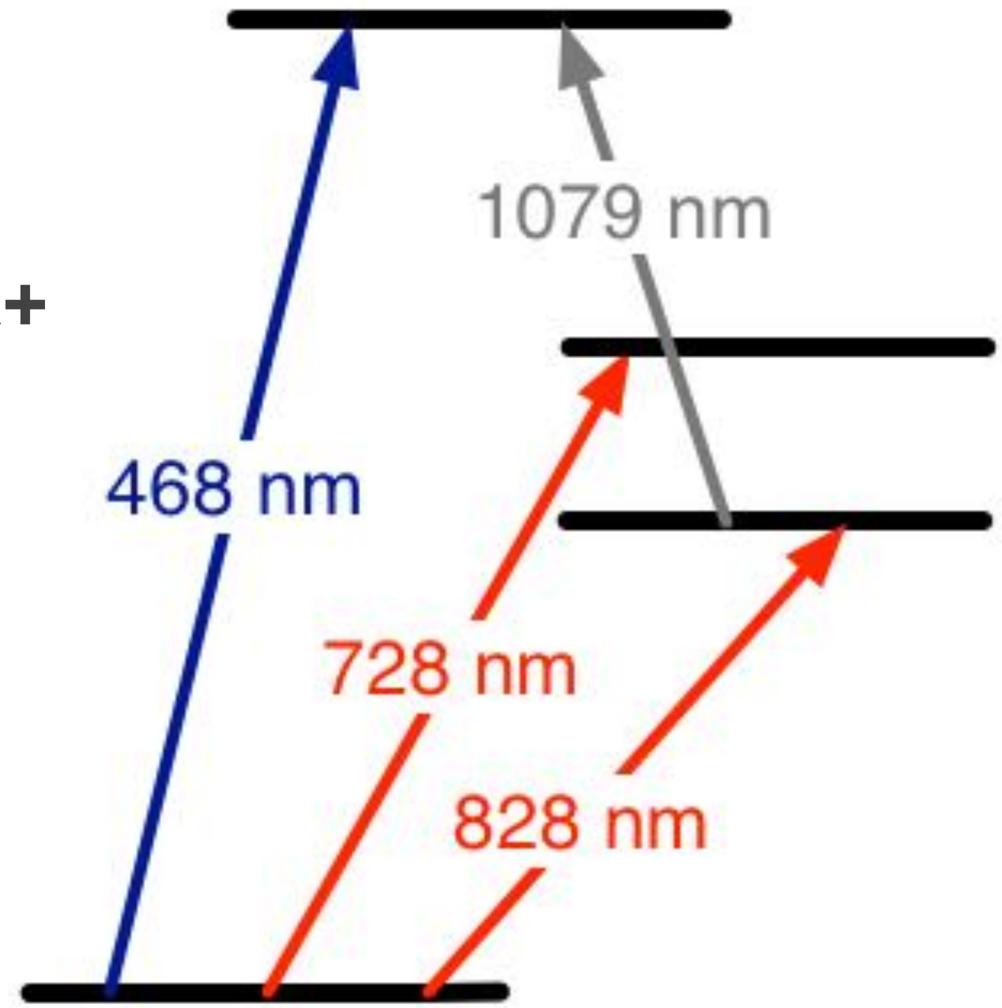
Expected signal (dark ions)

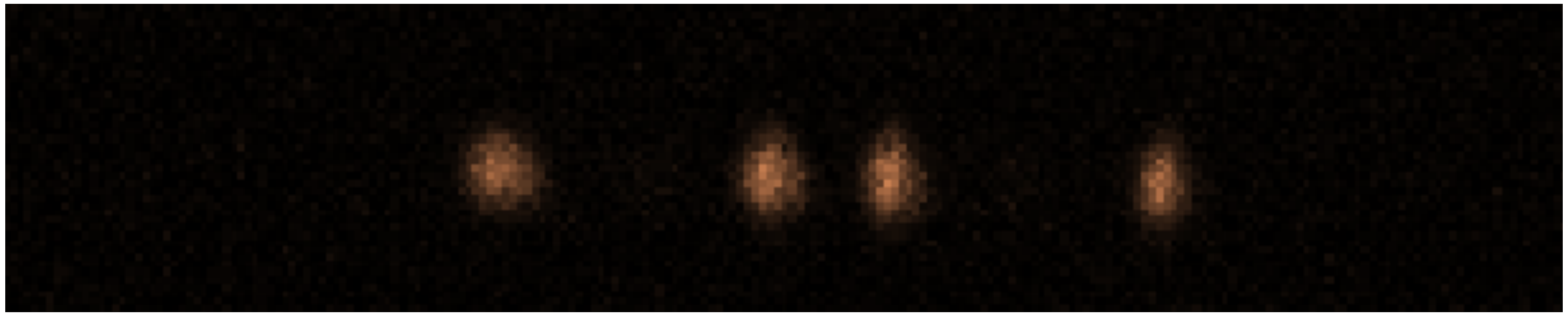




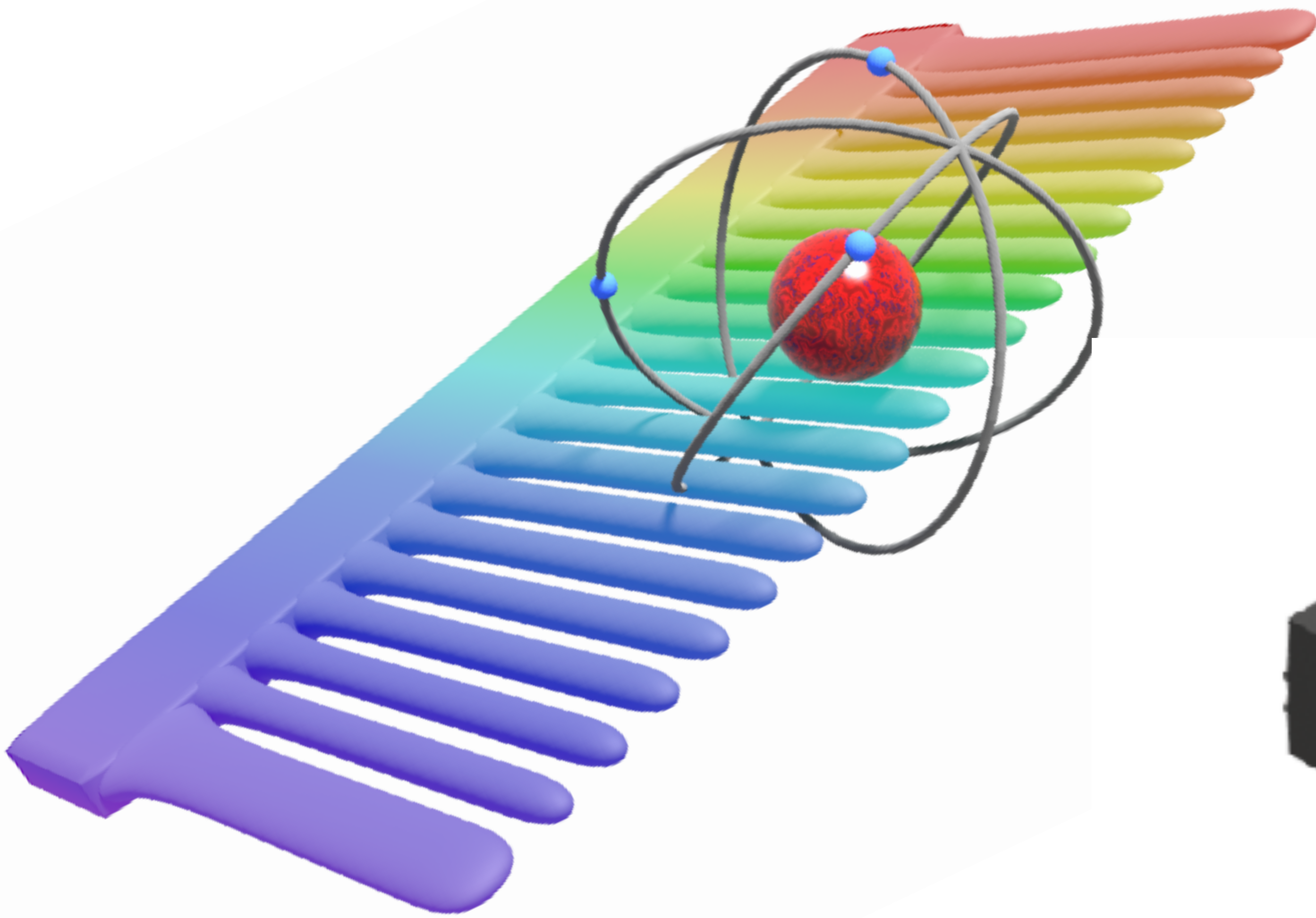
With cold radium…

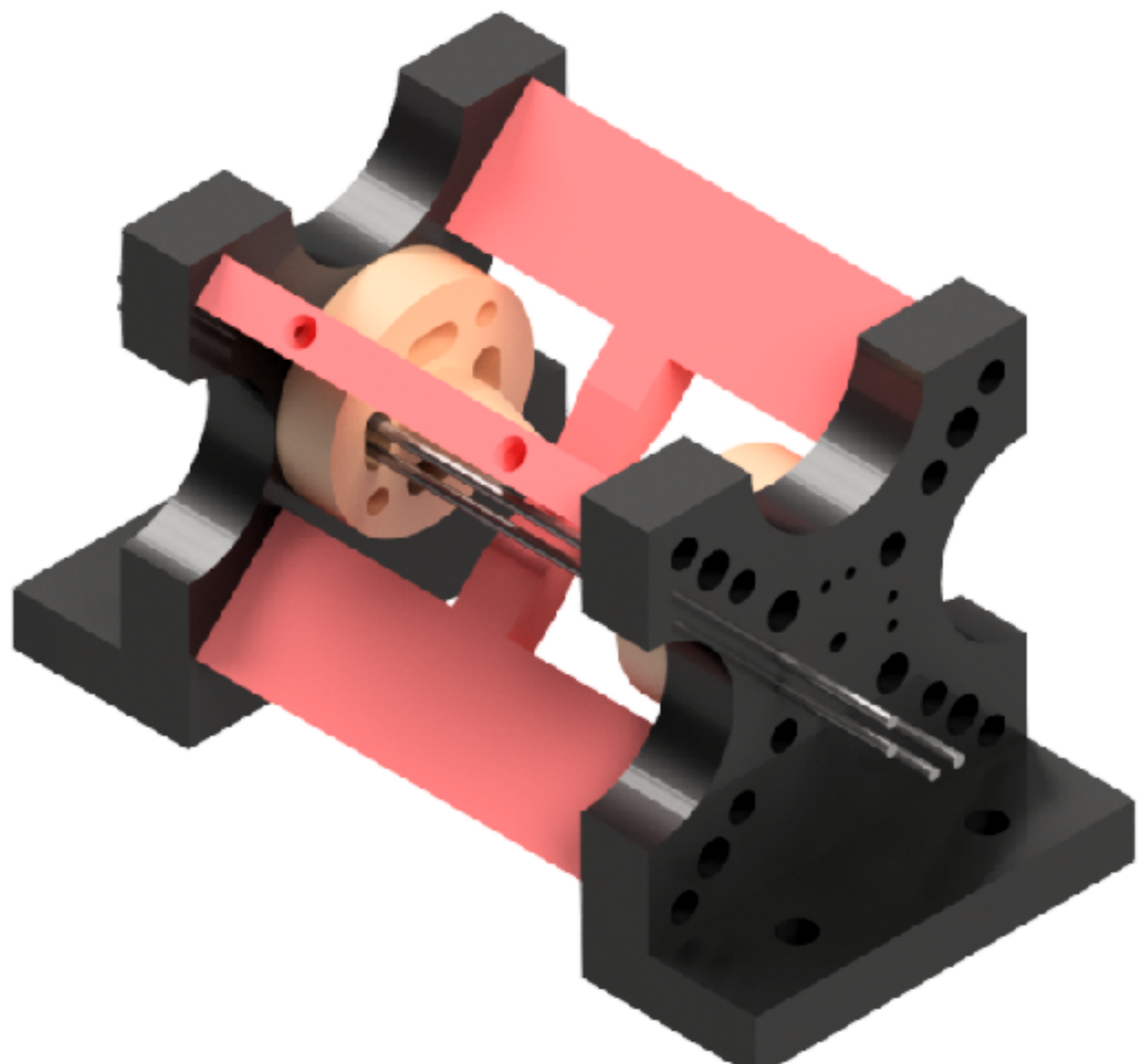
- nMQM constraint
- Radium-based molecular ions
- Parity nonconservation
- Optical clocks
- Quantum logic spectroscopy with Ra+
- Co-magnetometry with trapped Sr+
- Potential 225 Ra+ qubit
- Ra EDM measurement





2.) Direct frequency comb QL spectroscopy

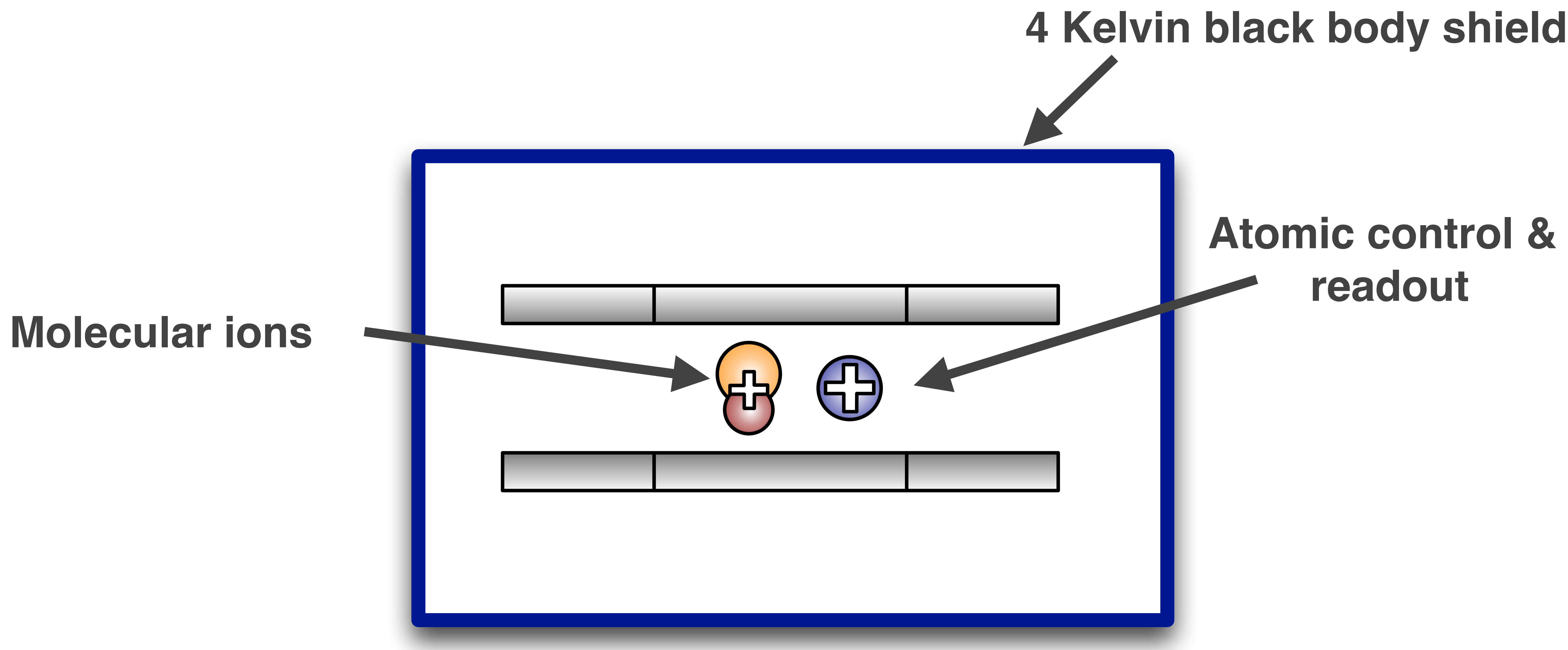




Spectroscopy candidates:

- Molecular ions
- Fe+
- Co+
- Towards He+

3.) Cryogenic molecular ion trap



rotational state readout:

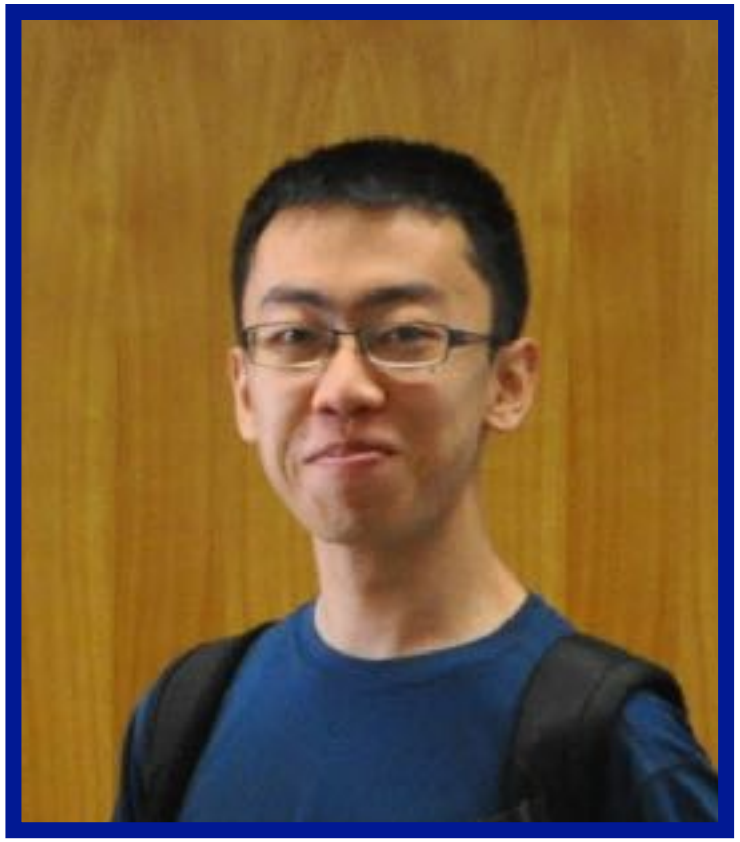
P. Schmidt *et al.*, *Nature* **530**, 457 (2016)

cryogenic ion trap:

Brandl *et al.*, arXiv:1607.04980 (2016)

1 K ~ 20 GHz

Acknowledgements



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