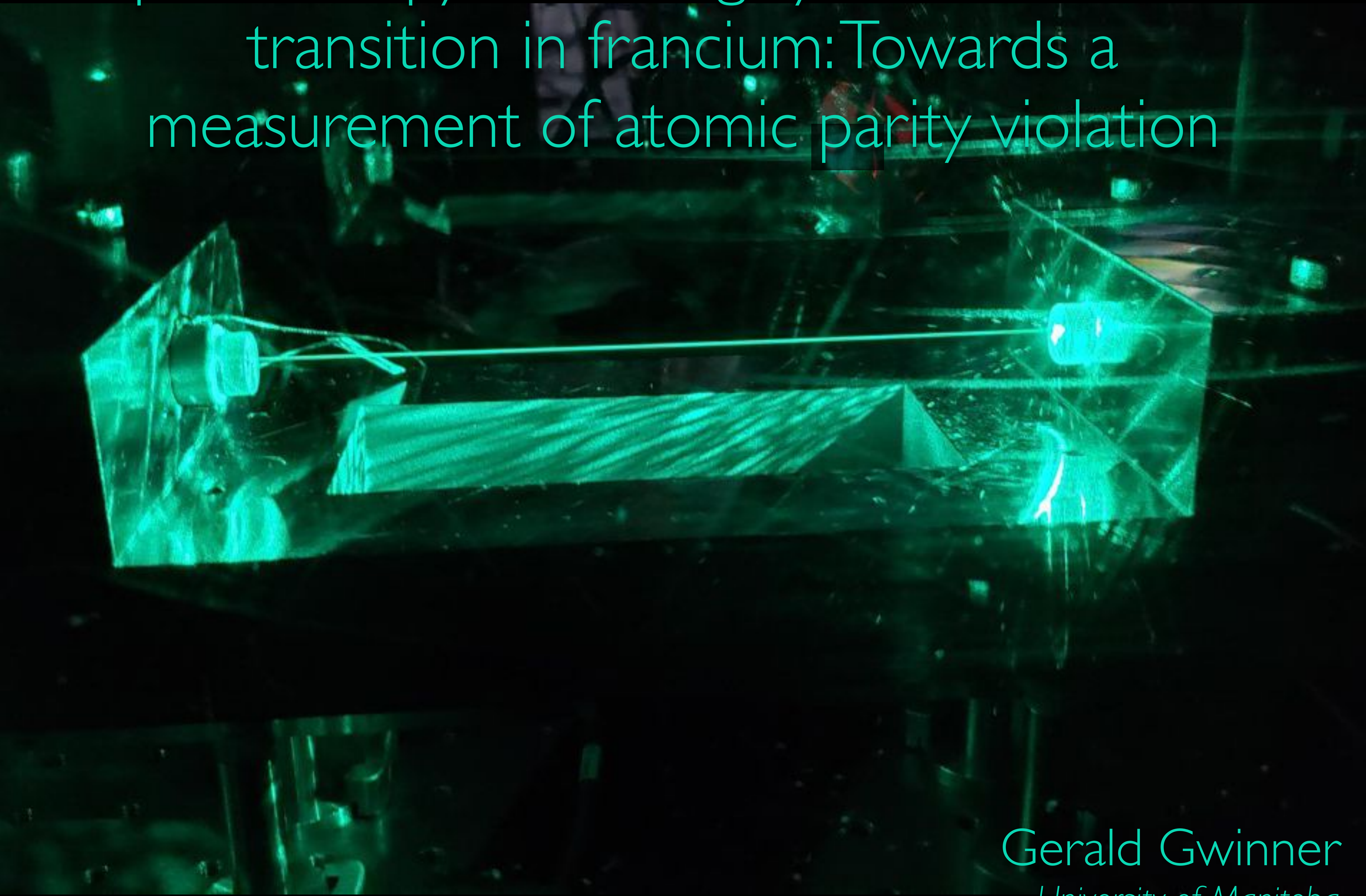
Spectroscopy of the highly forbidden 7s-8s transition in francium: Towards a measurement of atomic parity violation



Gerald Gwinner
University of Manitoba

Photo by PhD student Tim Hucko

Goals

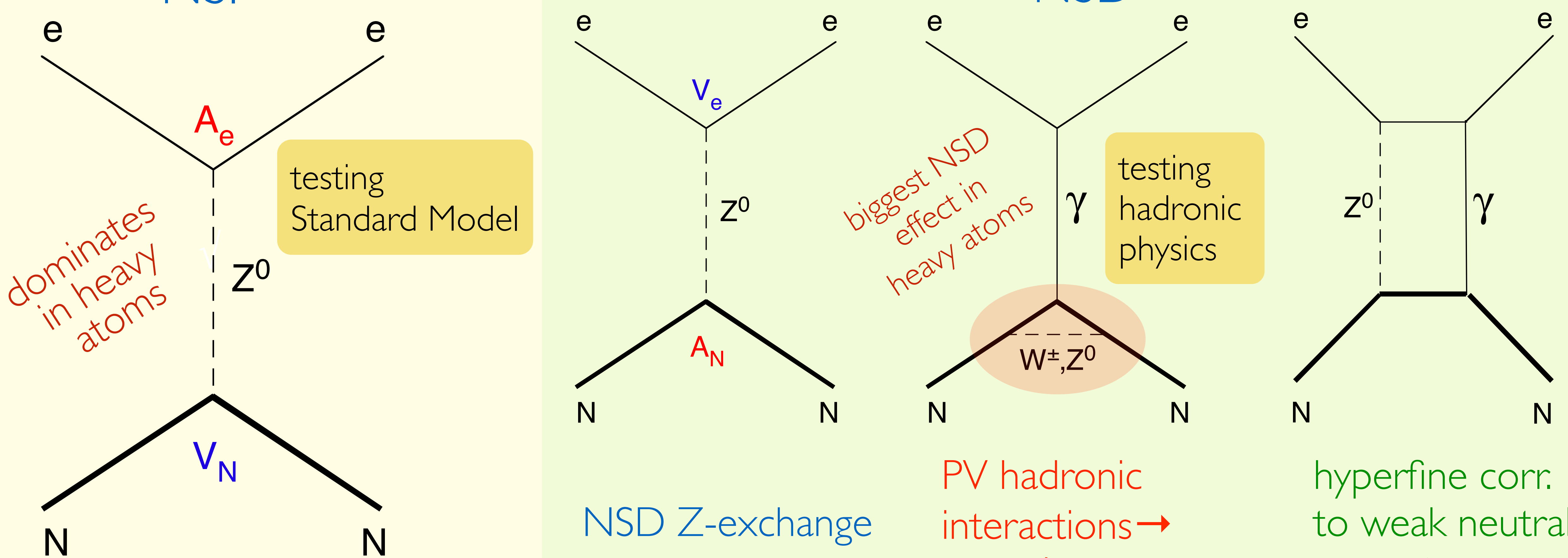
- **Long-term**
  - Atomic parity non-conservation (APV) measurements using the 7s-8s optical transition in laser-trapped francium
    - nuclear spin independent (Standard Model physics)
    - nuclear spin dependent (nuclear anapole moment)
- **Short-term**
  - spectroscopic investigations of 7s - 8s on critical path to APV
    - Stark-induced amplitudes (started Sept 2018, now precision)
    - relativistic and hyperfine-induced M1 amplitudes (started in Sept 2021)
    - $E1_{stark}$ - M1 interference
- **Timeline:** first observation of APV effect by end of 2024

Atomic Parity Violation

Z-boson exchange between atomic electrons and the quarks in the nucleus

Nuclear spin independent NSI

Nuclear spin dependent NSD



NSD Z-exchange

PV hadronic interactions → anapole moment

hyperfine corr. to weak neutral current

NSI: coherent over all nucleons (quarks):

Bouchiat & Bouchiat 1974, 1975

H_{pv} mixes electronic s & p states: $\langle n's|H_{pv}|np\rangle \propto Z^2N \approx Z^3$

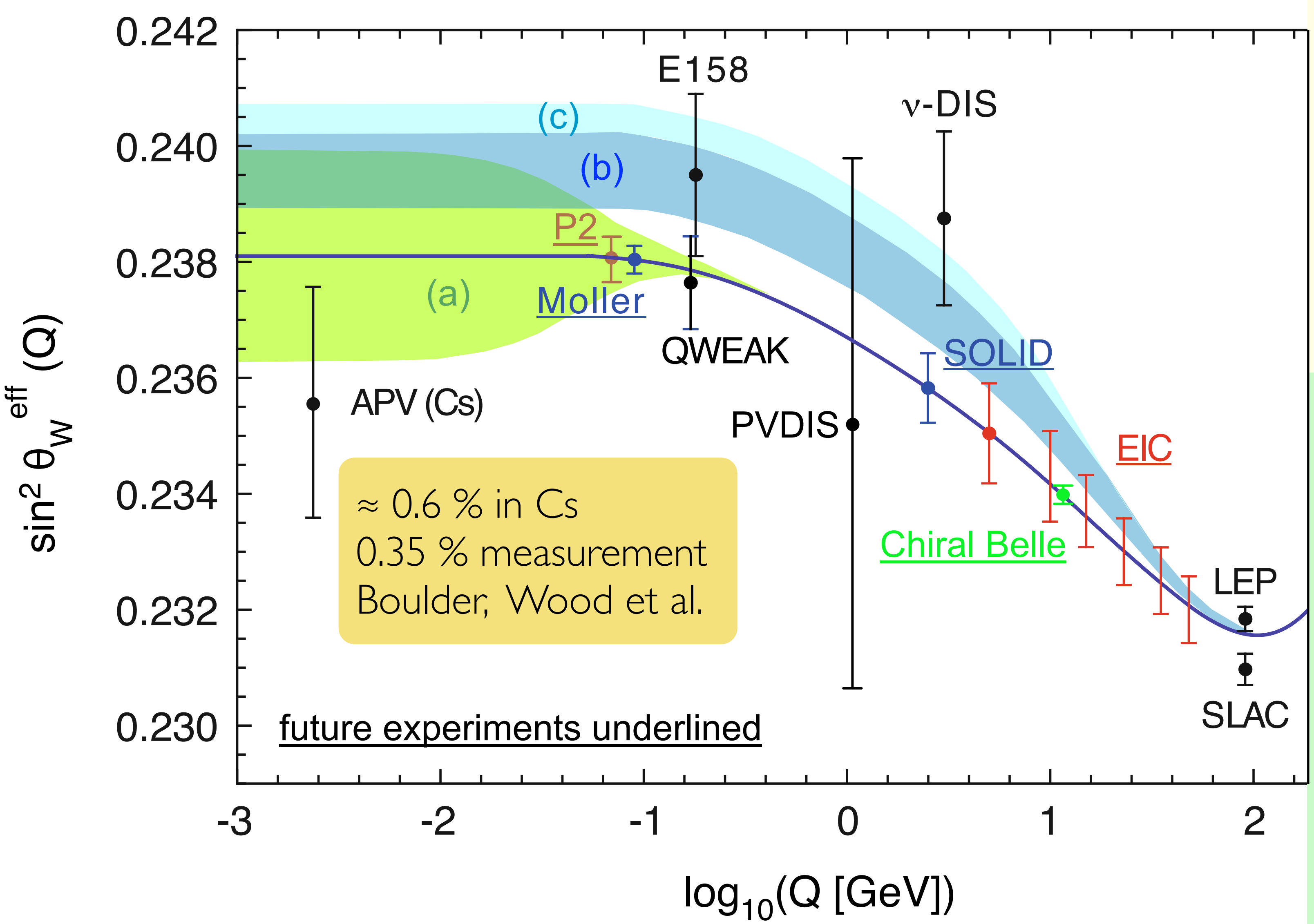
signature: drive $s \rightarrow s$ electric dipole ($E1$) transition

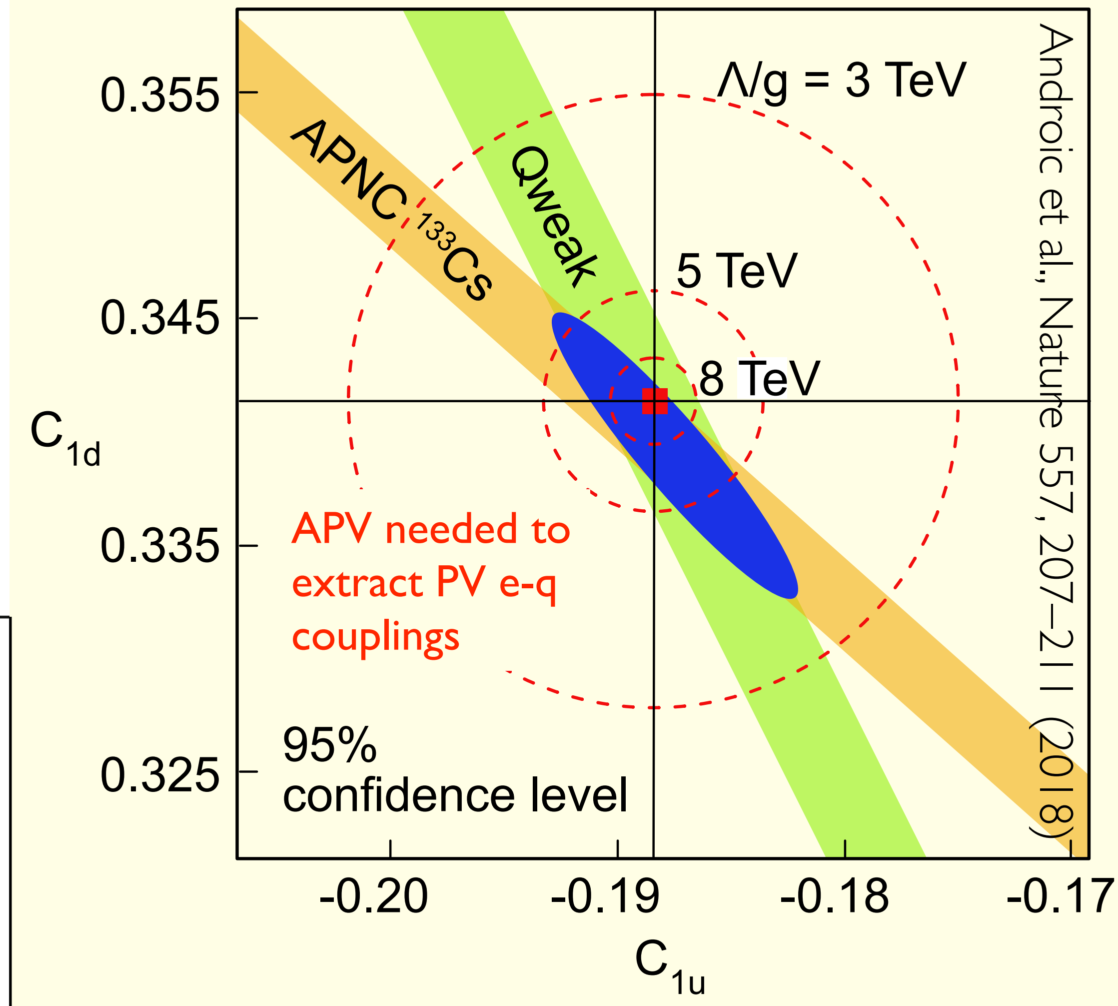
atomic theory to extract weak physics → heavy alkalis

≈ 18x larger in Fr than in Cs (incl. relativistic enhancement)

Atomic Parity Violation

- APV is a uniquely low-energy probe
  - sensitive to light dark boson scenarios

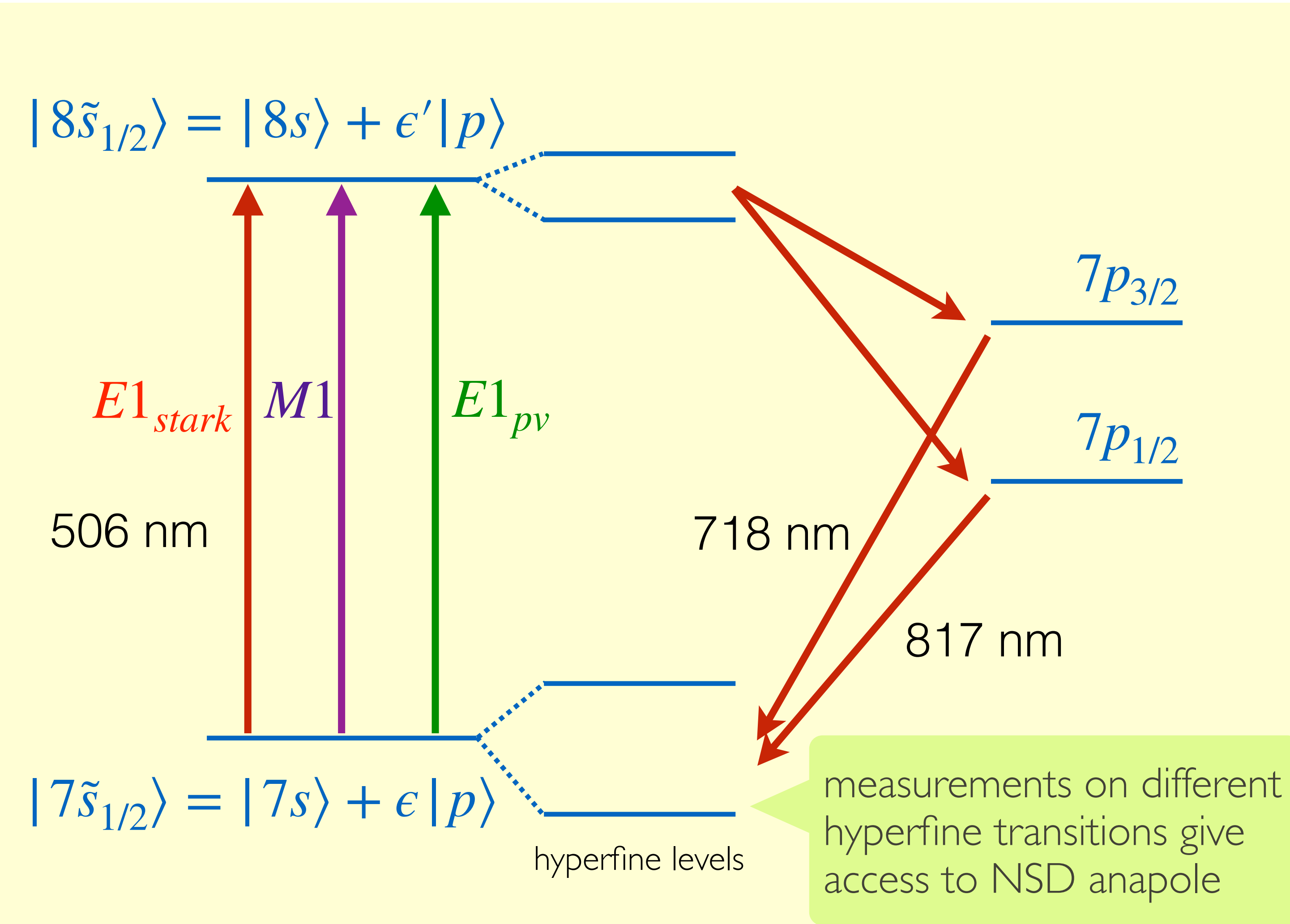




	precision	$\Delta \sin^2\bar{\theta}_W(0)$	Λ_{new} (expected)
APV Cs	0.58 %	0.0019	32.3 TeV
E158	14 %	0.0013	17.0 TeV
Qweak I	19 %	0.0030	17.0 TeV
Qweak final	4.5 %	0.0008	33 TeV
PVDIS	4.5 %	0.0050	7.6 TeV
SoLID	0.6 %	0.00057	22 TeV
MOLLER	2.3 %	0.00026	39 TeV
P2	2.0 %	0.00036	49 TeV
PVES ^{12}C	0.3 %	0.0007	49 TeV

Physics sensitivity from contact interaction
(LEP2 convention $g^2 = 4\pi$)
Frank Maas, CIPANP 2018 talk

Stark interference APV measurement



- faint transitions
- oscillator strengths
  - $f_{stark} \approx 10^{-10}$ (@ few kV/cm)
  - $f_{M1} \approx 10^{-13}$
  - $f_{pv} \approx 10^{-21}$ too weak for direct observation

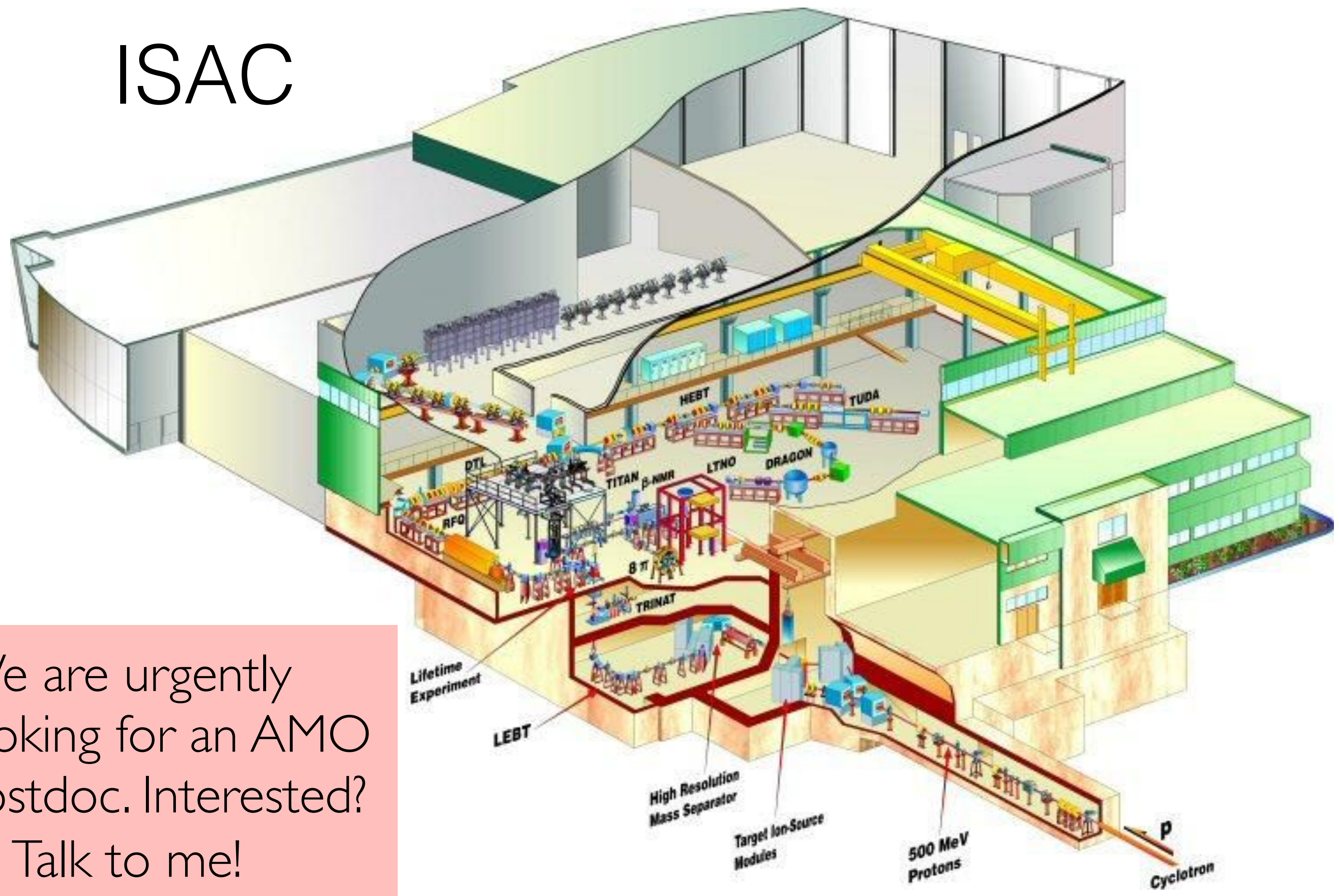
$$R_{7s\rightarrow 8s} \propto |E1_{stark} + M1 + E1_{pv}|^2$$

- observe **interference** between the Stark-induced and PV amplitudes ($f_{eff} \approx 10^{-16.5}$)
- IF term **changes sign** under parity transformations (e.g. electric field reversals)
  - modulation of decay fluorescence (in Fr $\approx 10^{-4}$) ➞ extract weak charge of Fr
- $M1$ always present ➞ study and understand $M1$ and $E1_{stark}$ in detail

A facility for experiments with francium

- Fr has not stable isotopes ➞ radioactive beam facility
- Boulder Cs used a massive atomic beam: 10^{13} s^{-1} cm^{-2}
- no existing RIB facility can do this, not even close
- key figure: Cs had 10^{10} "APV excitations" per second
- would need ≈ 10^6 - 10^7 Fr atoms stored in a neutral **atom trap** to yield similar signal ➞ can do this at TRIUMF/ISAC

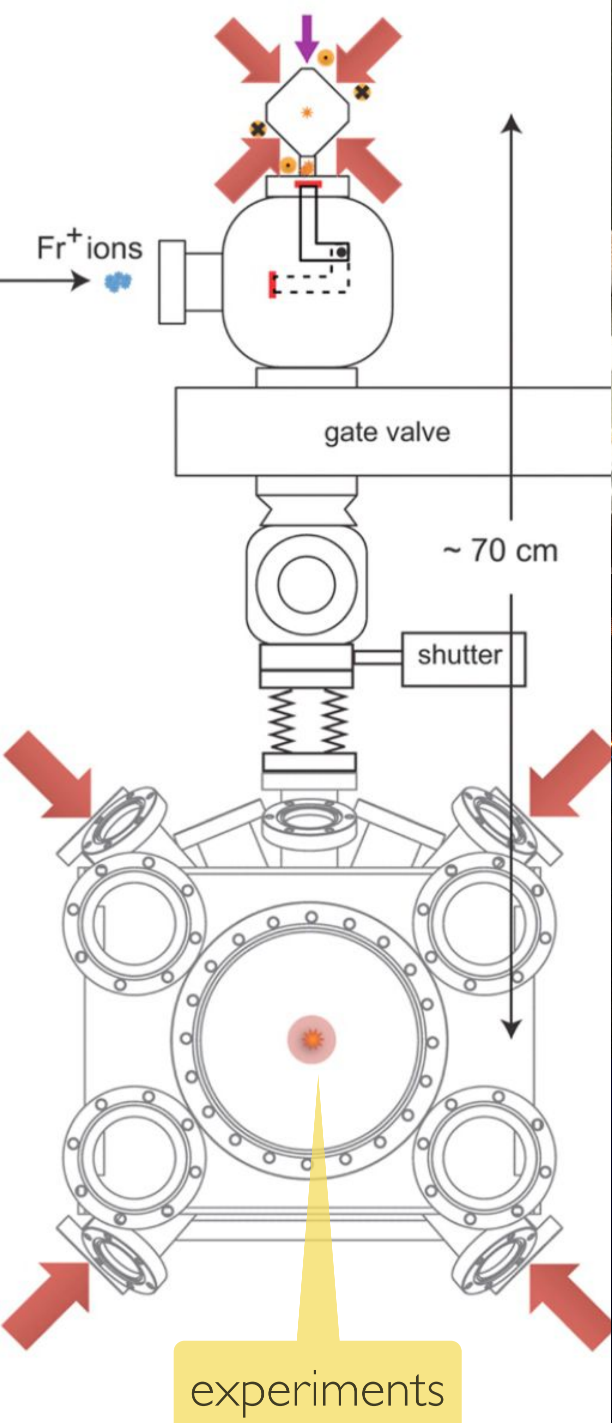
ISAC

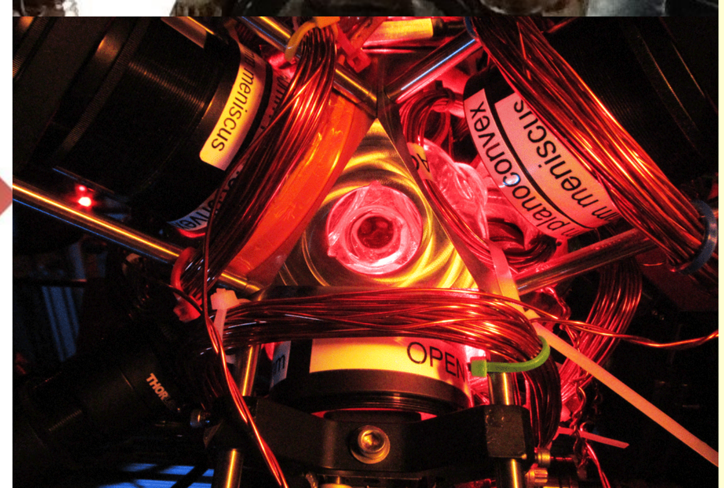


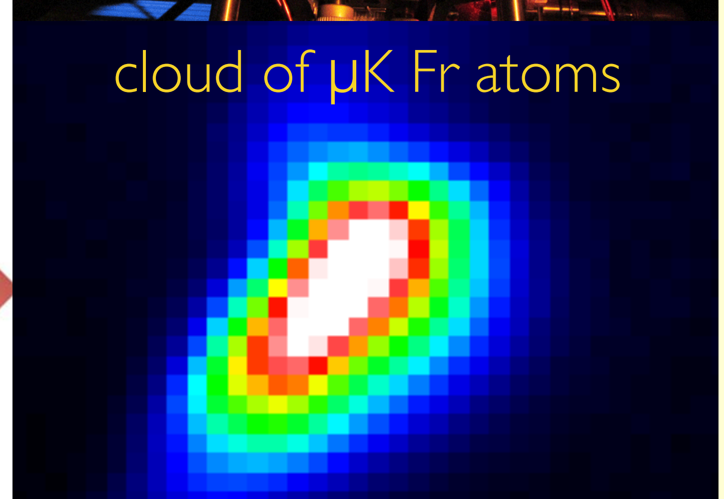
We are urgently looking for an AMO postdoc. Interested? ➞ Talk to me!

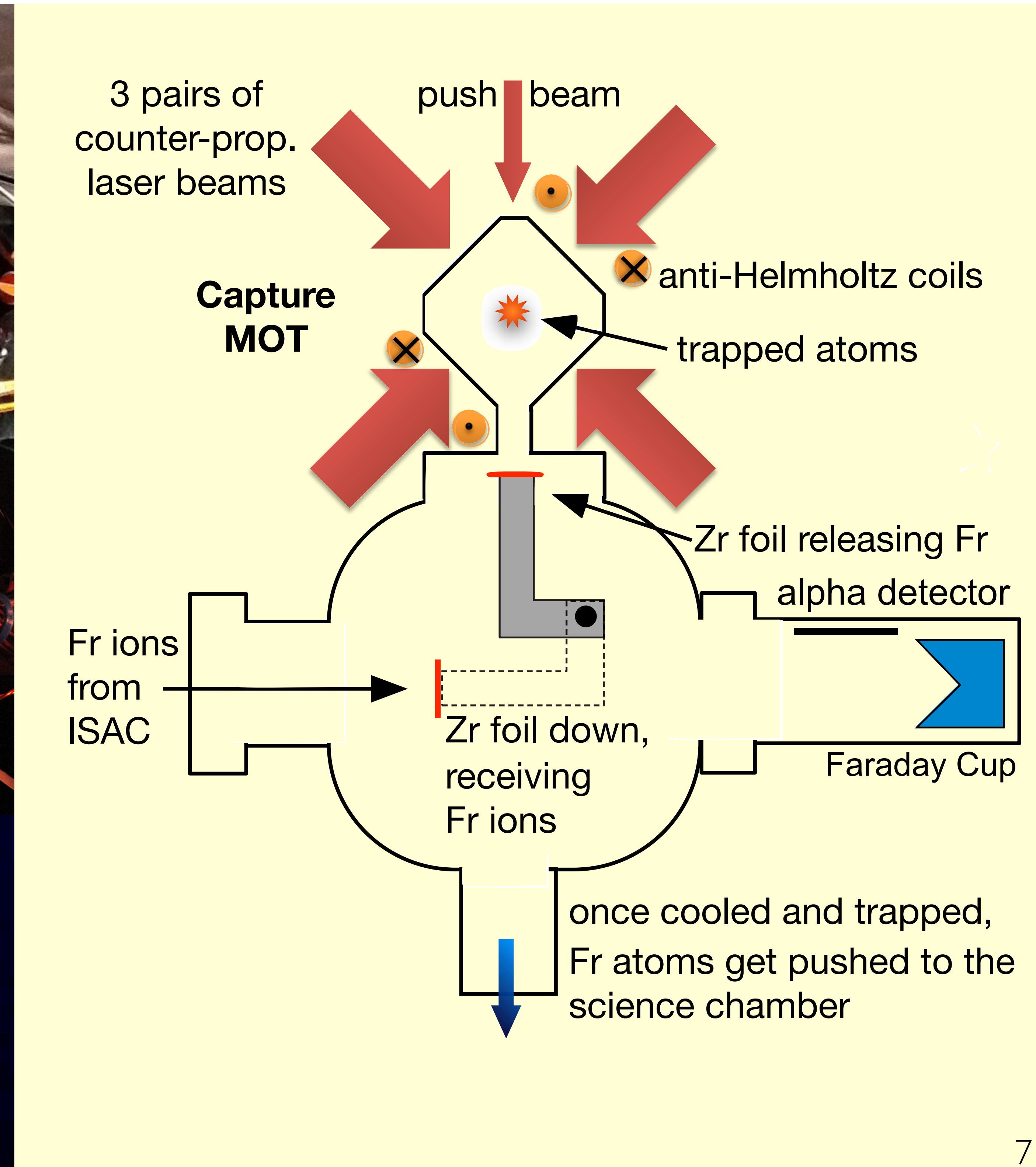
The Francium Trapping Facility at TRIUMF/ISAC

part 1: online capture trap

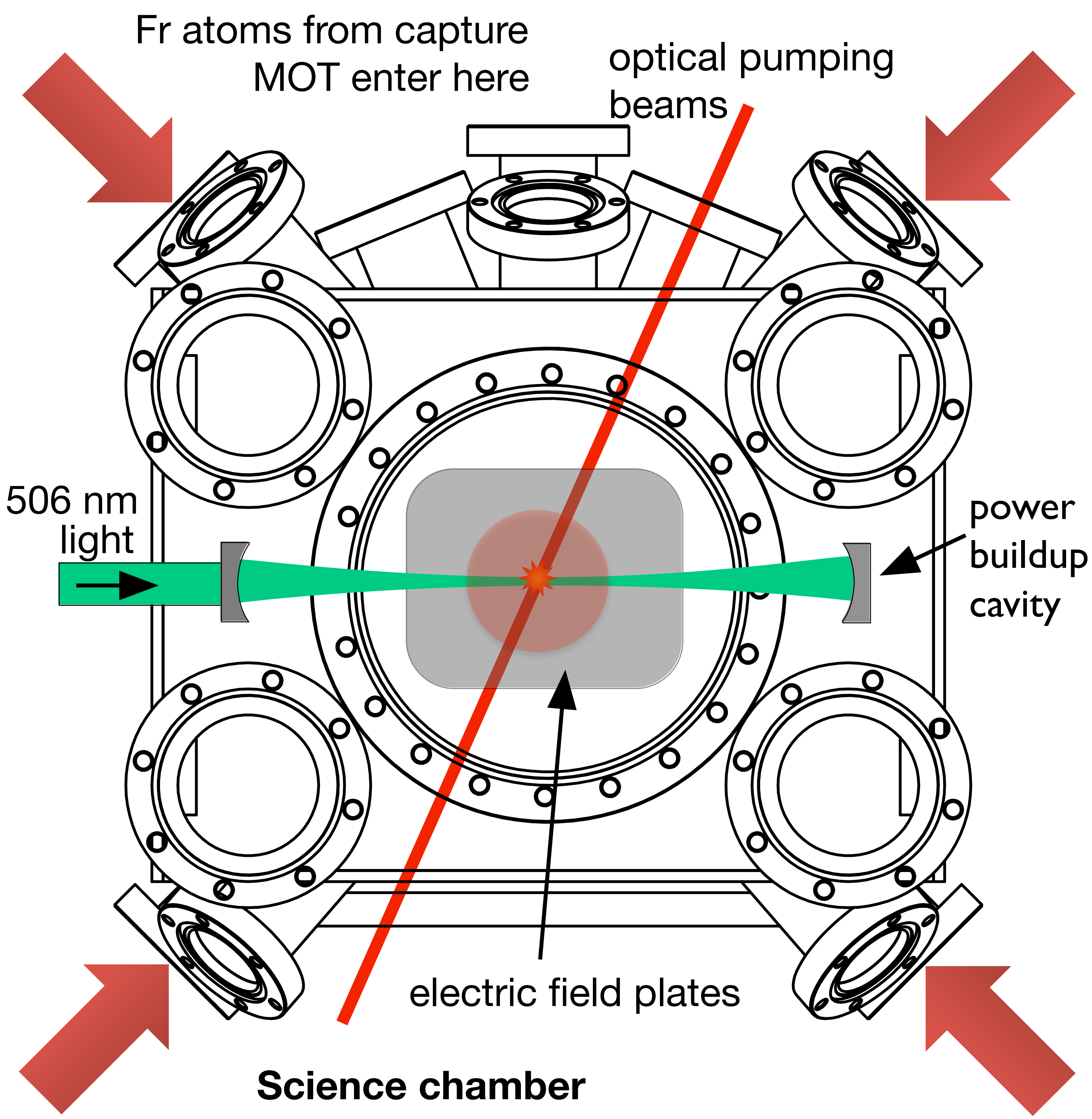


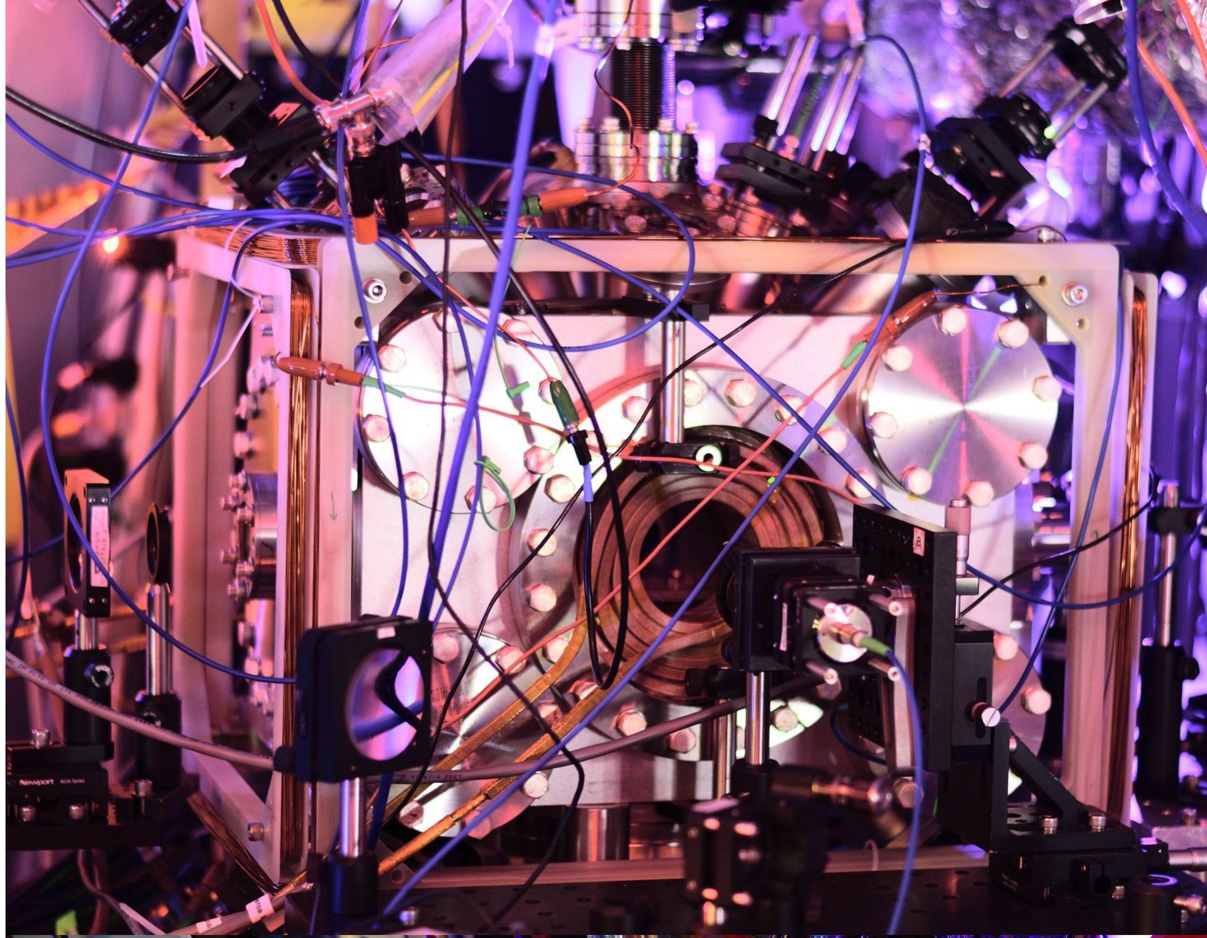


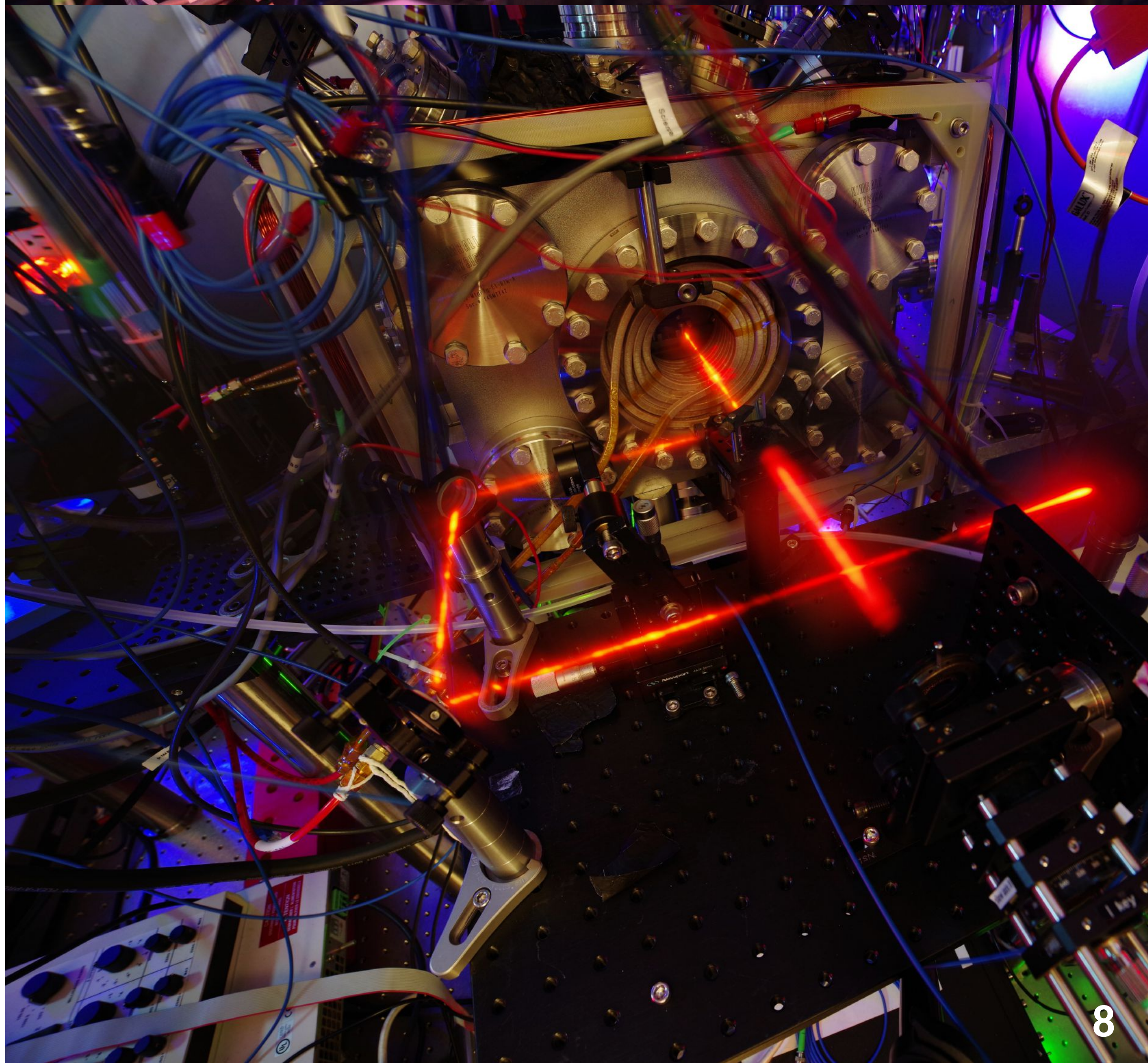




Part 2: Science chamber



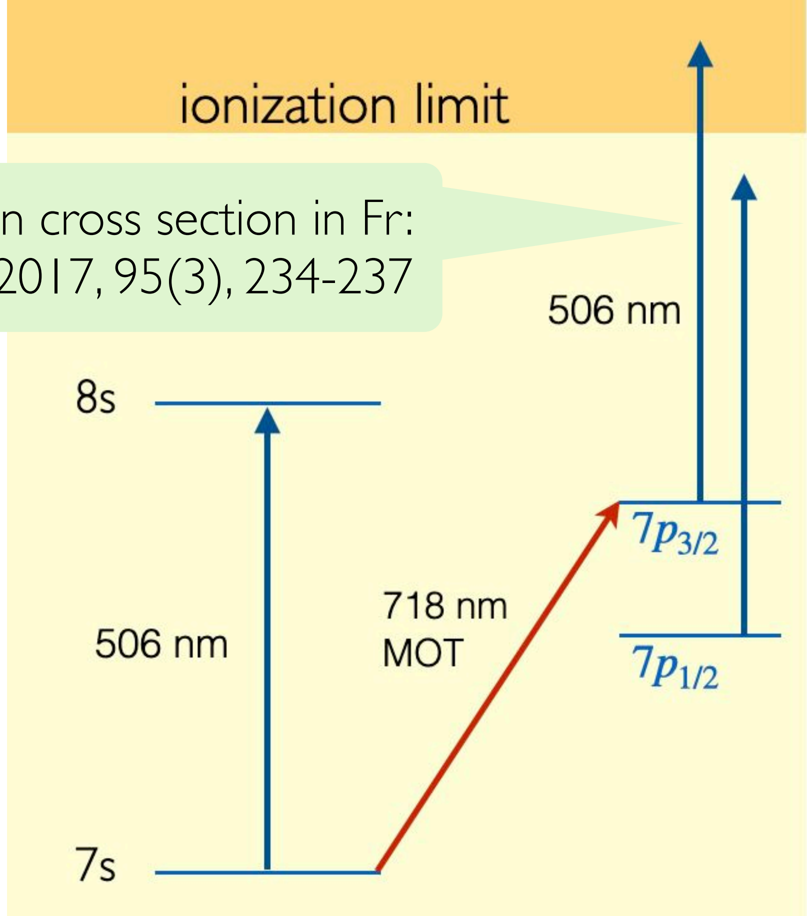


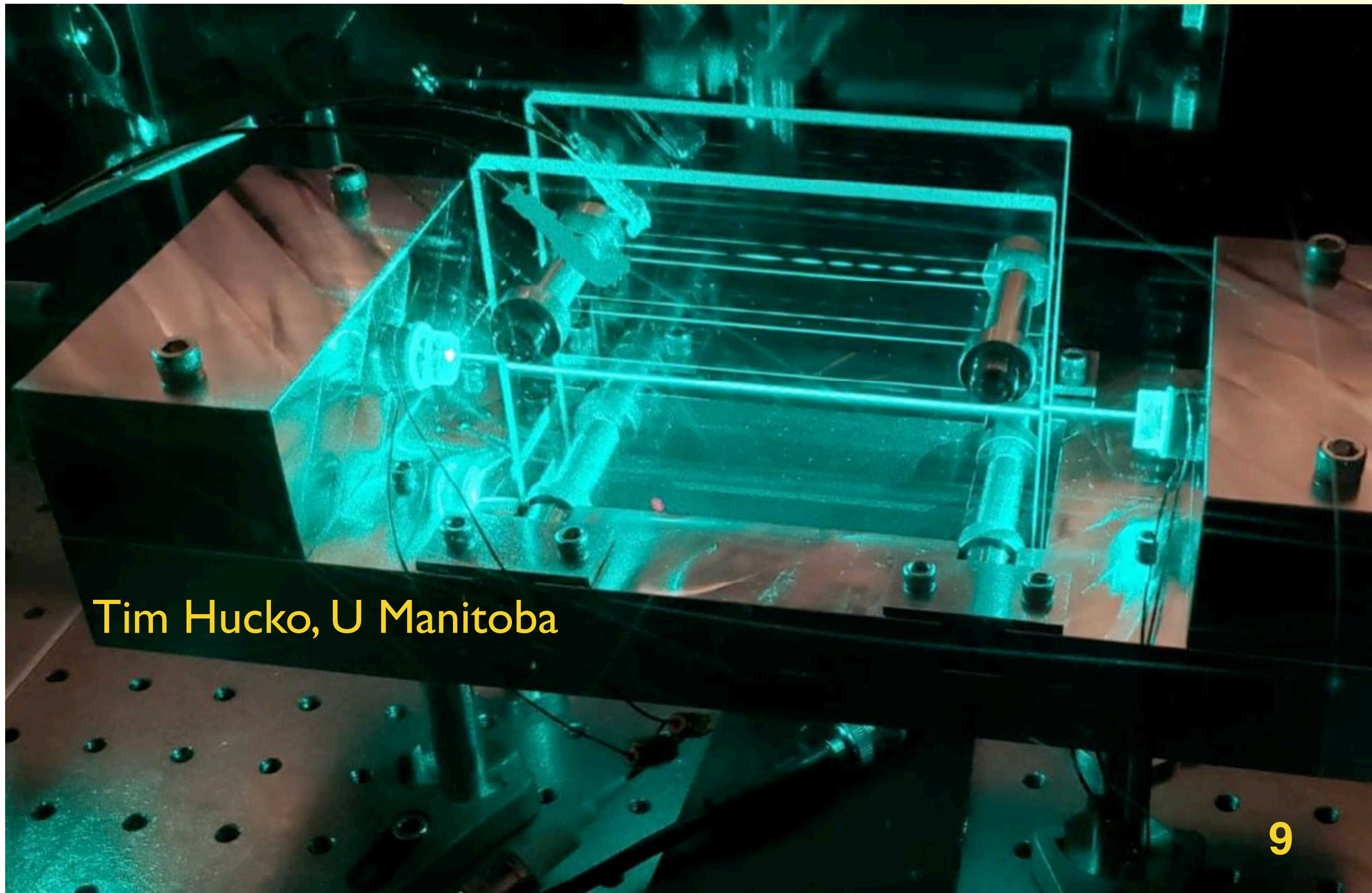


7s-8s spectroscopy: Apparatus

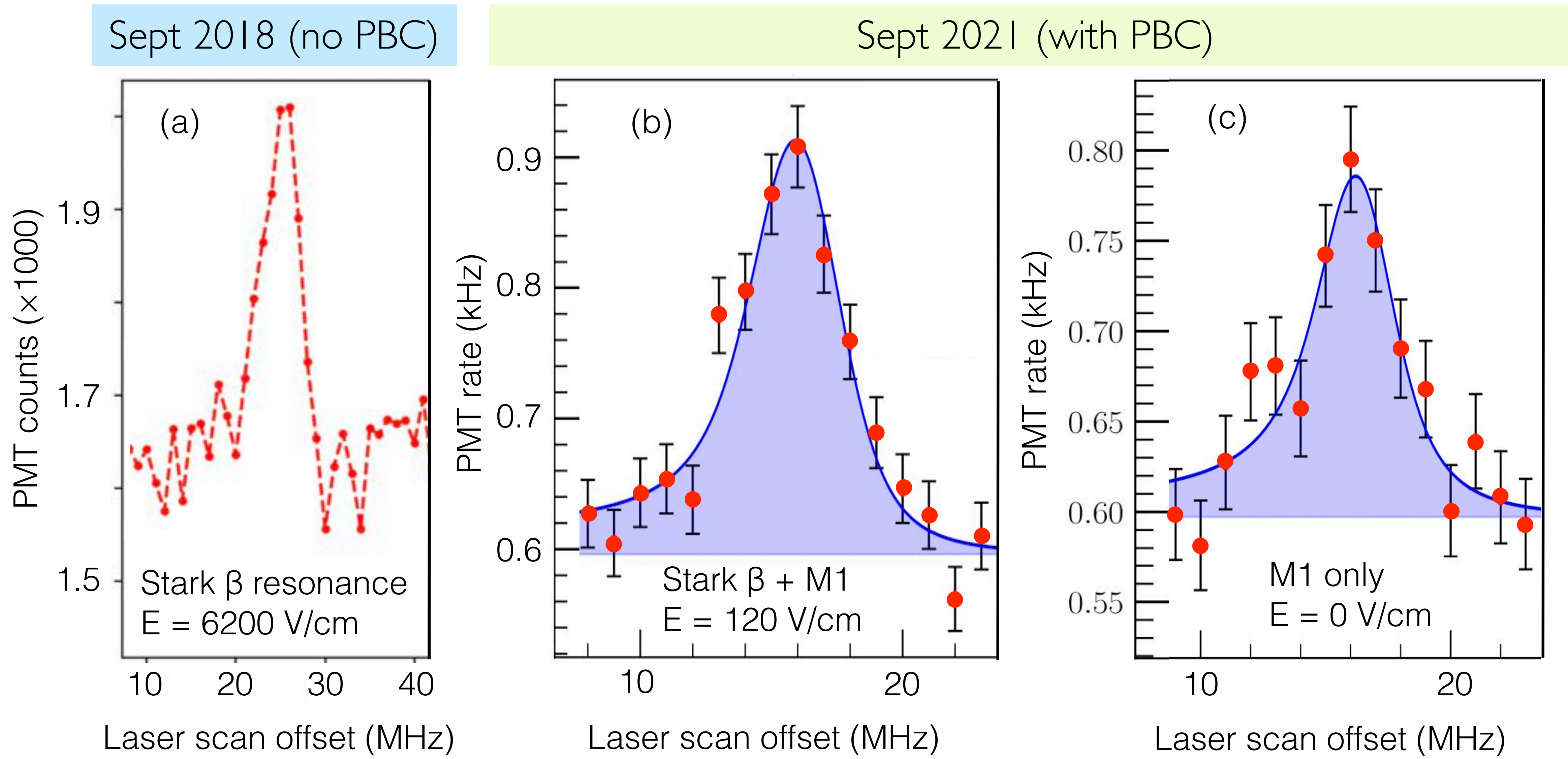
- E_{stark}: transparent electric field plates compatible with MOT
- $M1$: impossible with a power buildup cavity, very challenging
  - inside UHV chamber on ISAC beamline, not optics table
  - achieved **4000×** enhancement
    - higher intensities lead to photo-ionization of Fr
  - MOT beams and PBC @ 506 nm cannot be on at the same time → photo-ionization
    - interleave MOT and PBC every 3-5 ms
    - miraculously (to us) PBC able to maintain lock!
    - → 10s of kW/cm² of 506 nm light available for spectroscopy

measured 7p3/2 photo-ionization cross section in Fr:
Collister *et al.* 2017, Can J Phys, 2017, 95(3), 234-237





7s-8s spectroscopy: Results



$$R \propto \beta^2 E^2 + M1_{rel}^2 \pm M1_{hf}^2$$

β predicted by Safronova et al. (much higher confidence than $M1_{rel}$)

very hard to calculate

$\Delta F = \mp 1$

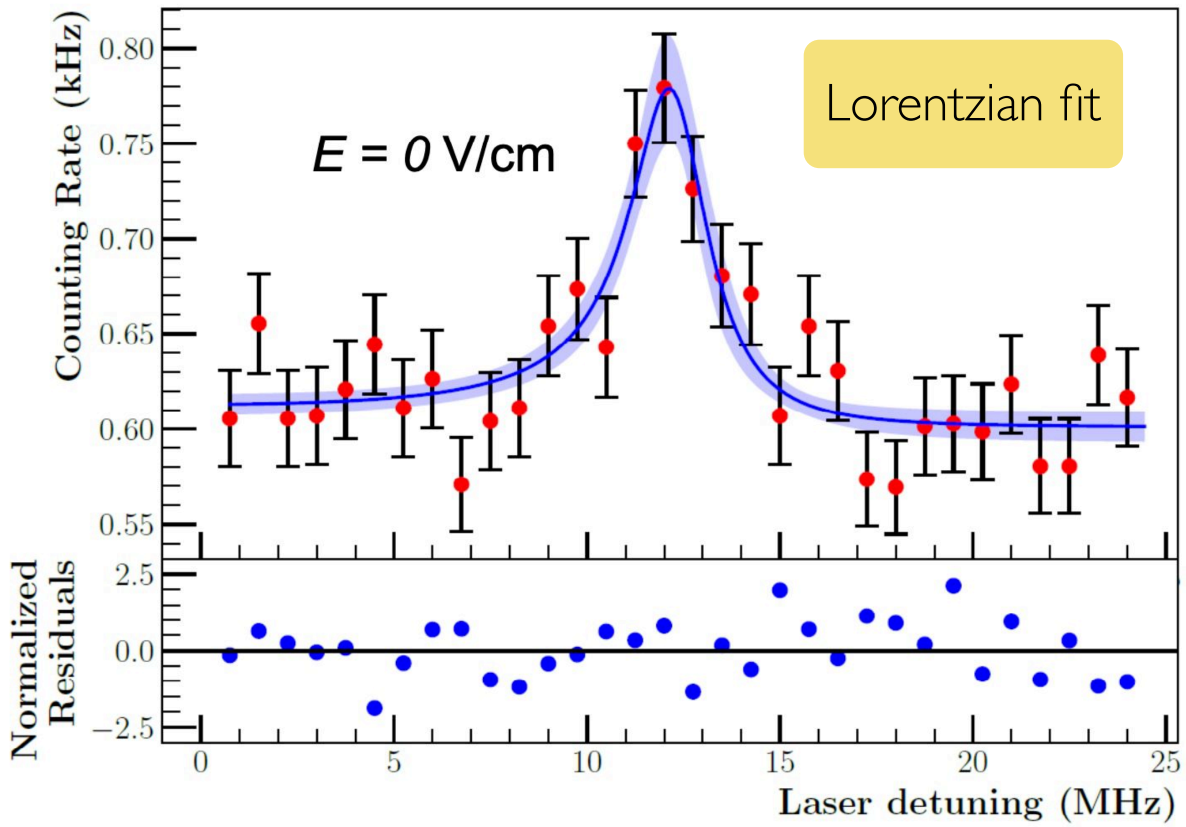
$M1_{hf}$ calculable from known hyperfine splitting

for a standing wave (as in our PBC) $E1_{stark} - M1$ interference is absent

- only had time for $\Delta F = -1$ transition

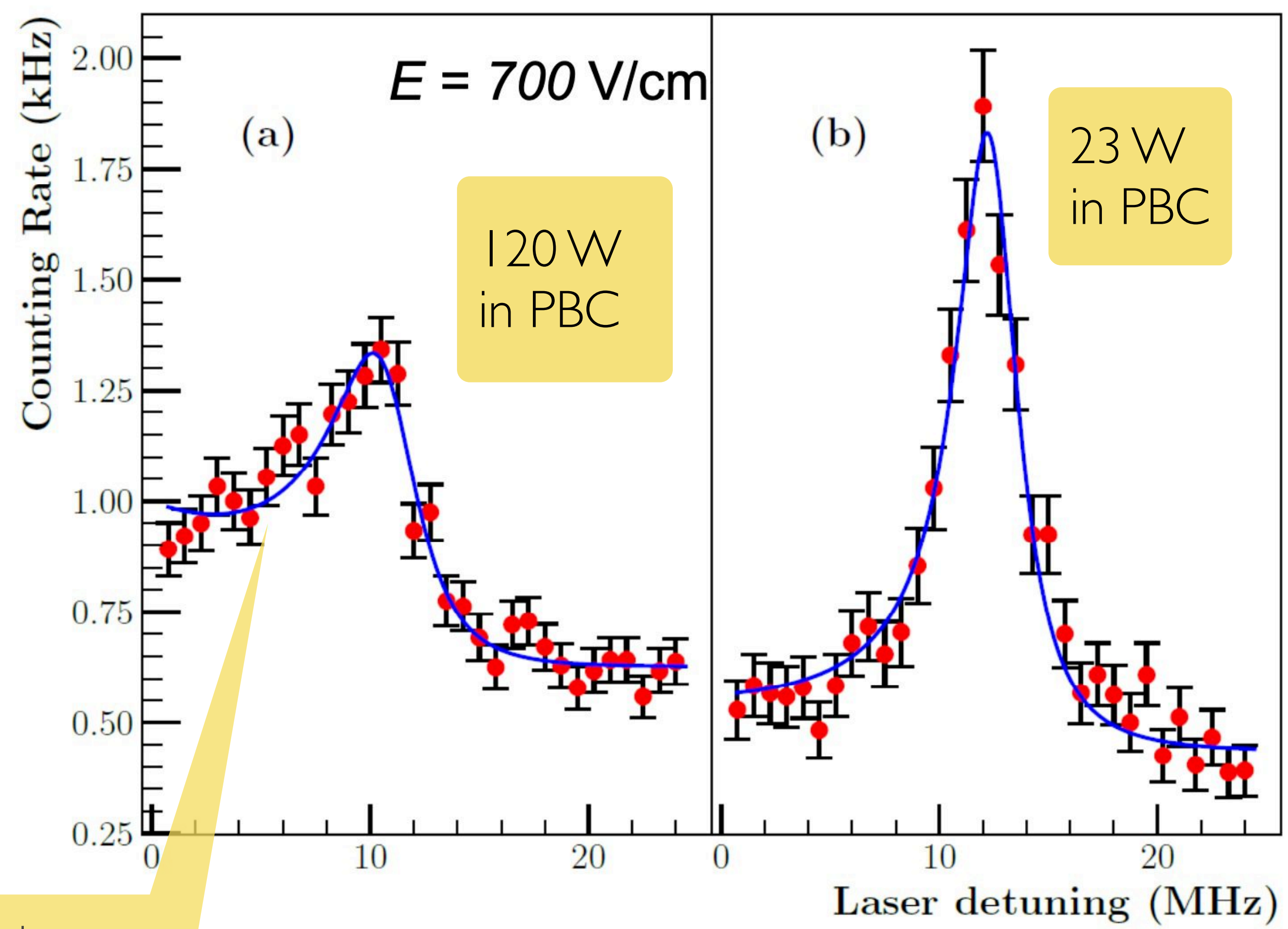
7s-8s spectroscopy: Results (again)

- Investigations of resonance strength as a function of applied electric field



all with ^{211}Fr and around 10^5 trapped atoms

- at higher fields, we have too much light → hyperfine pumping → saturation
- observed saturation and broadening consistent

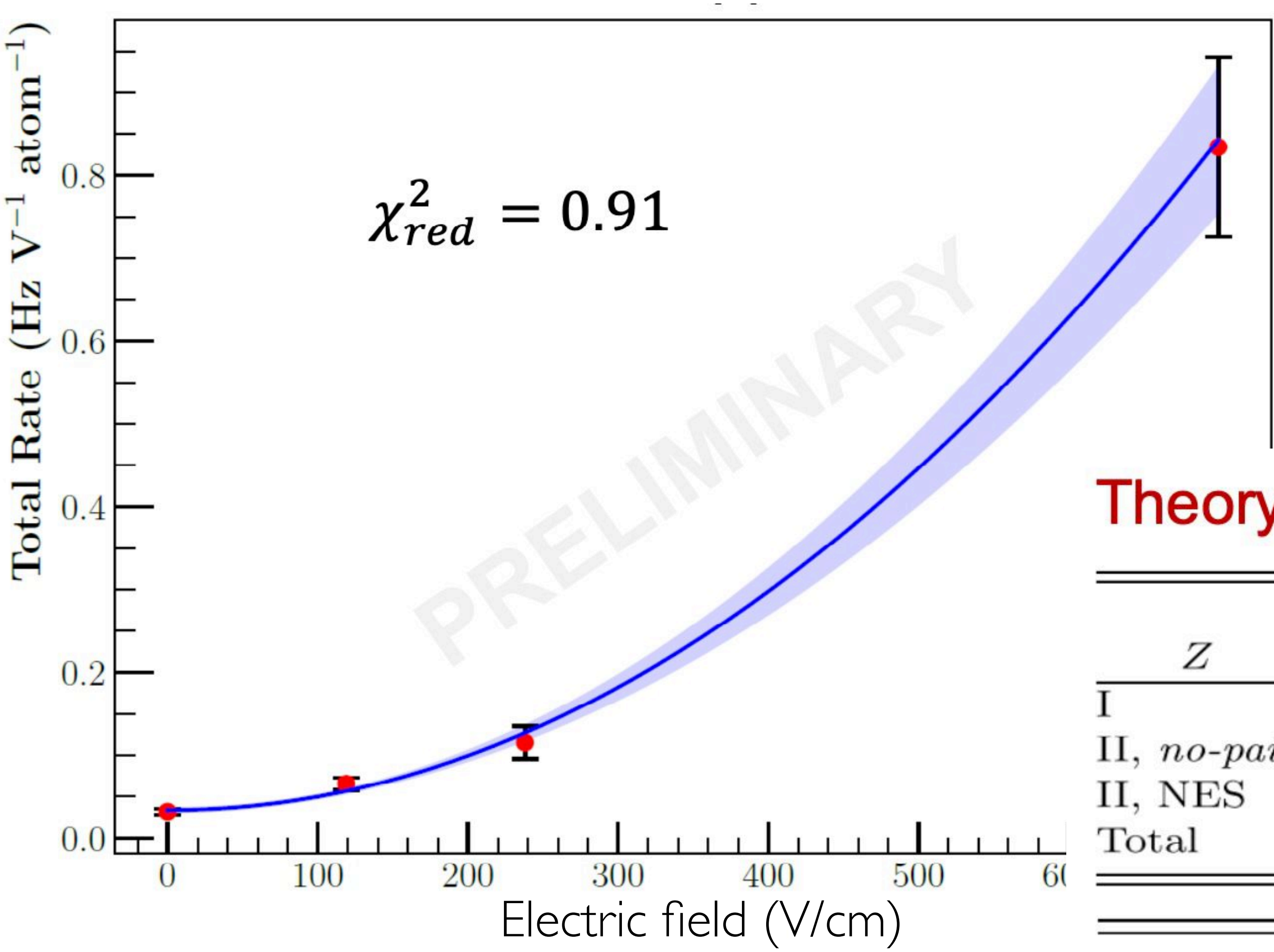


asymmetry to due MOT decay during scan

analysis and plots by T. Hucko

7s-8s spectroscopy: Results (and again)

- Investigations of resonance strength as a function of applied electric field



analysis and plots by T. Hucko

Theory Calculations for M_{rel} $(\times 10^{-5}\ \mu_B)$

Z	Li 3	Na 11	K 19	Rb 37	Cs 55	Fr 87
I	0.91	1.16	1.15	1.38	1.51	2.09
II, *no-pair*	0.12	0.03	-0.08	-1.86	-10.69	-116
II, NES	0.02	0.13	0.20	0.31	0.40	0.64
Total	1.05	1.06	1.27	-0.17	-8.78	-113

			Tran	DF	DF [16]	RPA	RPA [16]	MBPT3
Fr	NBr	$8s-7s$	-2.559		177.1		139.9
	Br	$8s-7s$	-3.000	-2.49	174.4	176.5	137.4

[1] Savukov *et al. Phys. Rev. Lett.* 83, 2914, 1999 (table I)
[2] Safronova *et al. Phys. Rev. A* 95, 042507, 2017(table VI)
β taken from Safronova *et al. Phys. Rev. A* 60, 4476,1999 (table IX)

- plan for fall 2022 beamtime
  - measure both $\Delta F = \pm 1$
  - get precise experimental values for $M_{\rm rel}$ and β
  - not enough signal!

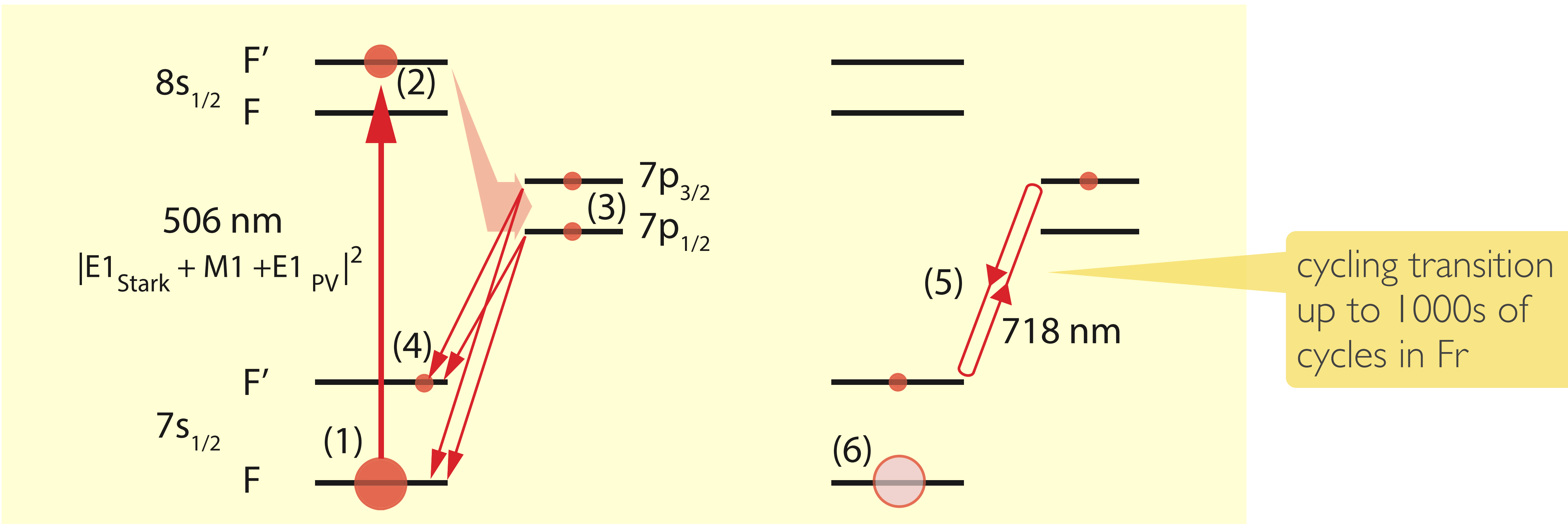
$|M/\beta| = 143 \pm 11$ V/cm

$|M_{rel}| = 130 \pm 10 \times 10^{-5}\ \mu_B$

preliminary

7s-8s: Boosting the signal

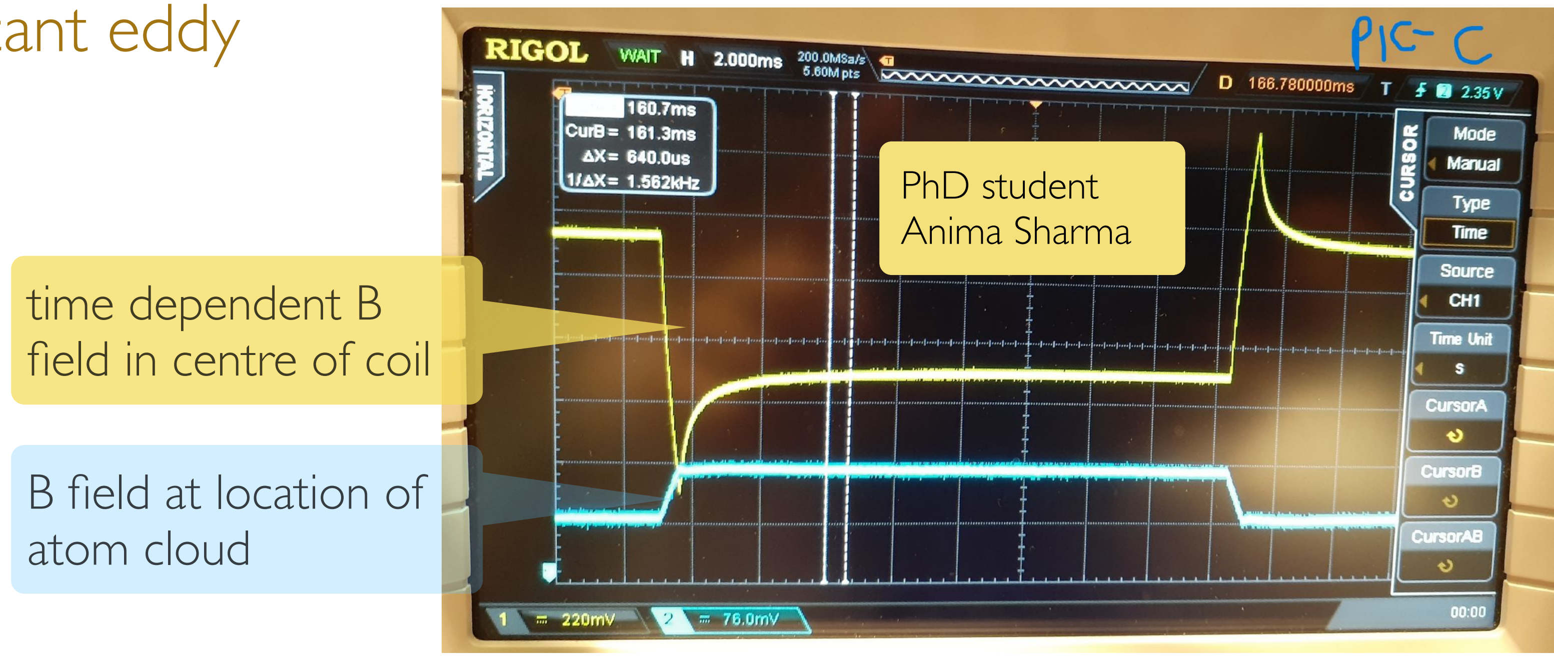
- so far: detect decay fluorescence at 817 nm ($7p_{1/2} \rightarrow 7s$)
  - pro: background free (MOT is at 718 nm on $7s \rightarrow 7p_{3/2}$)
  - con: efficiency ≈ 1/4000 (PMT 10% QE, lens solid angle, filters, ...)
- Our planned answer: "burst detection"



- June 2022: validated this method with Rb MOT in our apparatus
  - MOT seems not (or minimally) affected by driving the cycling transition for ≈ 400 μs with a counter-propagating probe beam while MOT off
  - can enhance signal by another factor ≈ 2000× in Fr → **million-fold since 2018!**

And then?

- PBC and burst detection → optimal signal rate per atom
- to measure APV → will need to up the MOT to probably $\gtrsim 5 \times 10^6$ atoms
- Stark-PV IF requires specific $|F, m_F\rangle$ states
  - atoms in magneto-optical trap largely (but not entirely) unpolarized
  - need to **optically pump** the atoms in $m_F = \pm F$ stretched states
  - new level of magnetic field control
  - ≈10 msec cycle: trap - optically pump - excite 7s-8s - burst detect - re-trap
  - switch quadrupole MOT coils and homogenous holding fields on and off **sub-msec**
  - chamber geometry leads to significant eddy current problems (coils external)
  - use 200 kHz bandwidth bipolar power supplies (Matsusada)
  - active coil current shaping to counter location-dependent eddy fields



The FrPNC team

A. Gorelov, A. Teigelhöfer, J. Behr — TRIUMF

T. Hucko, A. Sharma, G. Gwinner — U Manitoba

L. Orozco — U Maryland

E. Gomez — San Luis Potosi

S. Aubin — William & Mary

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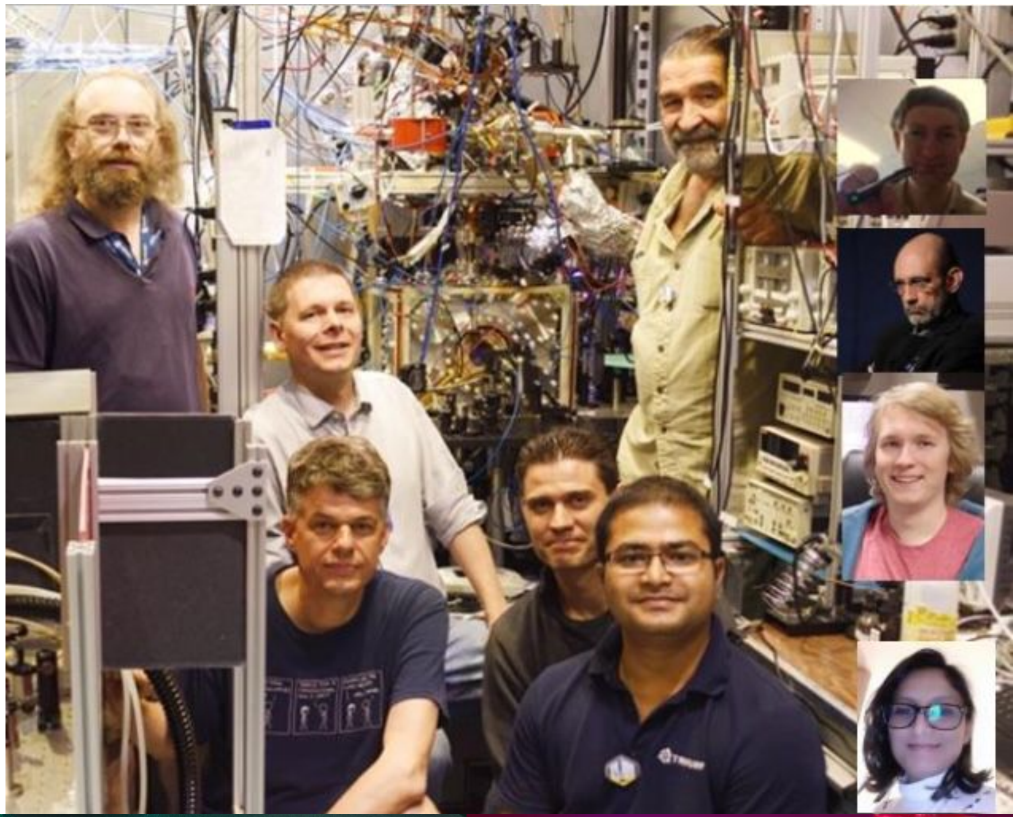
U Manitoba, U Maryland



Joining in 2022:

J. Lassen and S. Malbrunot-Ettenauer (TRIUMF)

new PD, new grad student

Alumni:

M. Kossin (MSc, 2016-21, U Manitoba)

M. Kalita (PD 2016-21, TRIUMF)

M. Pearson (2011-21, TRIUMF)

DeHart (MSc 2018, U Manitoba)

J. Zhang (PhD 2015, U Maryland)

R. Collister (Phd 2015, U Manitoba)

M. Tandecki (PD 2011-14, TRIUMF)