Prospects for new atomic parity violation tests in francium

Gerald Gwinner University of Manitoba

Photo: M. Kossin

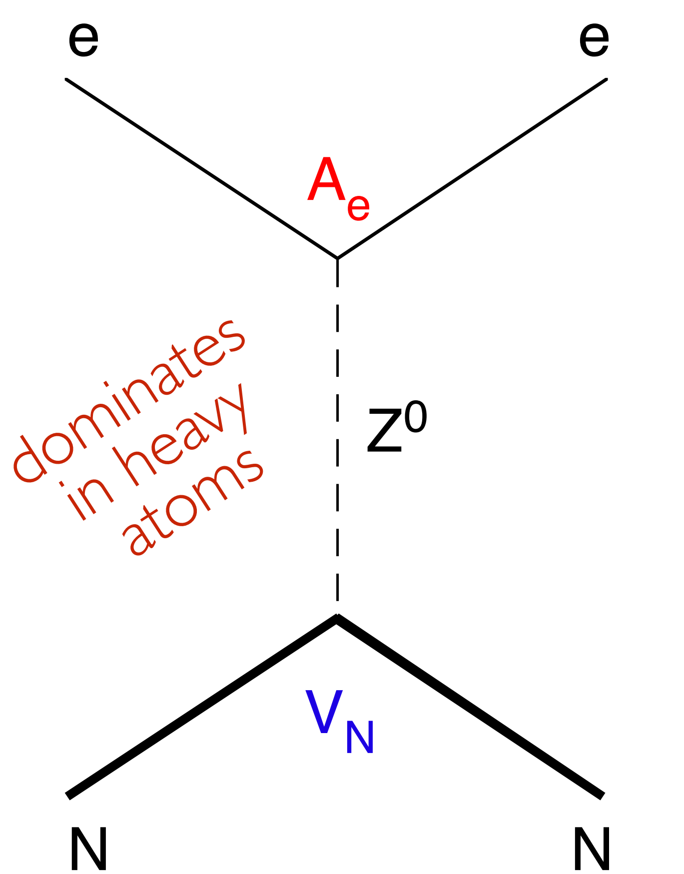
Goals

- 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, not discussed further today)
- Short-term
  - spectroscopic investigations of 7s - 8s on critical path to APV
    - Stark-induced amplitudes (started Sept 2018)
    - relativistic and hyperfine-induced M1 amplitudes (started in Sept 2021)

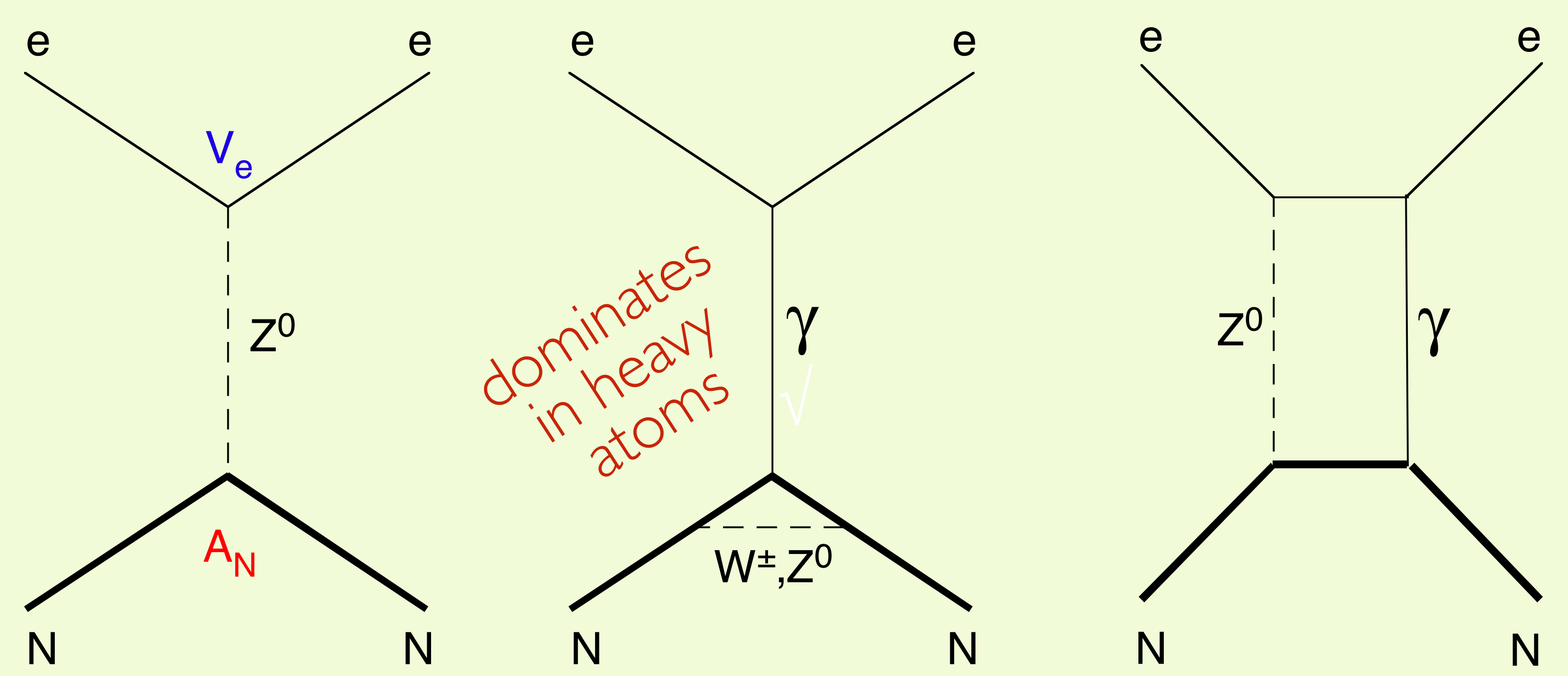
Atomic Parity Violation

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

Nuclear spin independent



Nuclear spin dependent



NSD Z-exchange

PV hadronic interactions → anapole moment

hyperfine corr. to weak neutral current

NSI: coherent over all nucleons (quarks):

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

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

Bouchiat & Bouchiat

1974, 1975

Let's build a NSI APV Hamiltonian for a pointlike nucleus

$H_{\mathrm{APV}}^{\mathrm{NSI}}$

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Fermi constant → generic strength of weak interaction

$$H_{\mathrm{APV}}^{\mathrm{NSI}} = \frac{G_F}{2\sqrt{2}}$$

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weak charge of the nucleus → how many nucleons + details of their weak interaction with electrons

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$\langle ns|\gamma_5|n'p\rangle$ depends on **details** of electron wavefunctions in nucleus $\propto Z^2$

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γ_5: $\propto Z^2$ Q_W: $\propto N$

APV $\propto Z^2 N \approx Z^3$
add'l relativistic enh. of for large Z

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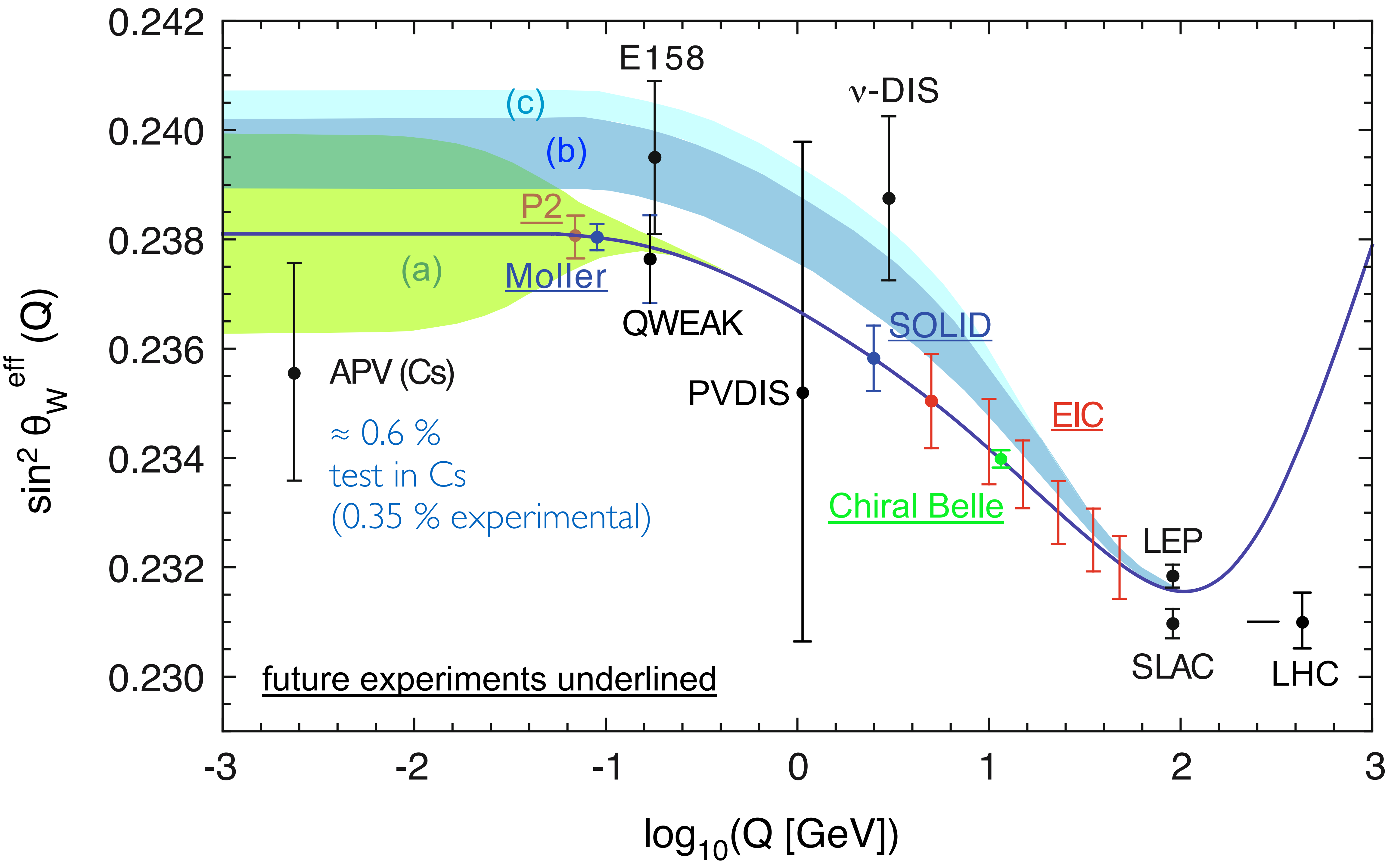
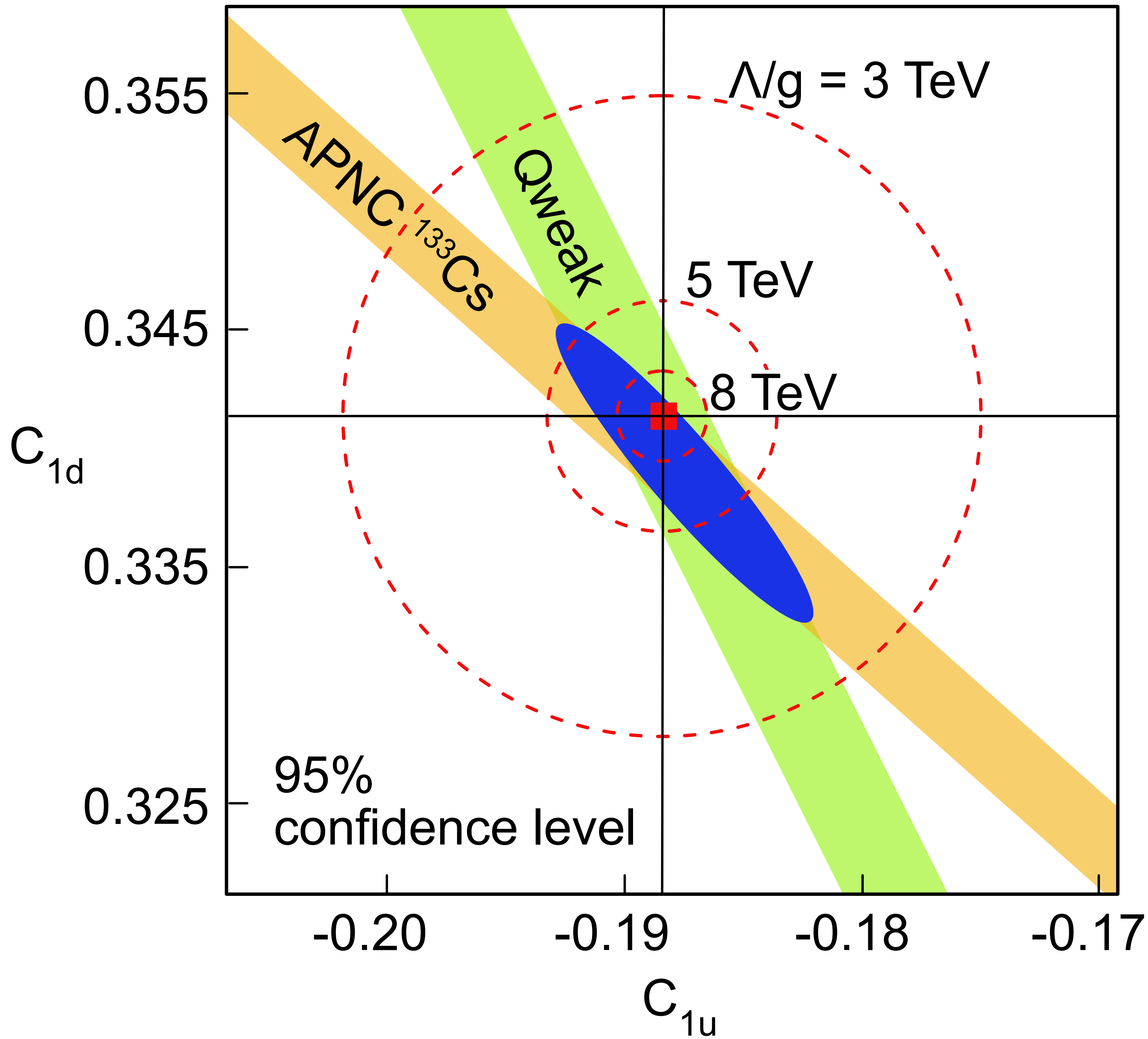
Electroweak tests

- The weak or Weinberg angle θ_W "runs" with momentum transfer
- APV is a unique test at very low momentum transfer



There is more to it

- Cs APV and Qweak constrain parity violating electron quark couplings together



Androic et al., Nature 557, 207–211 (2018)

Remarkable APV reach

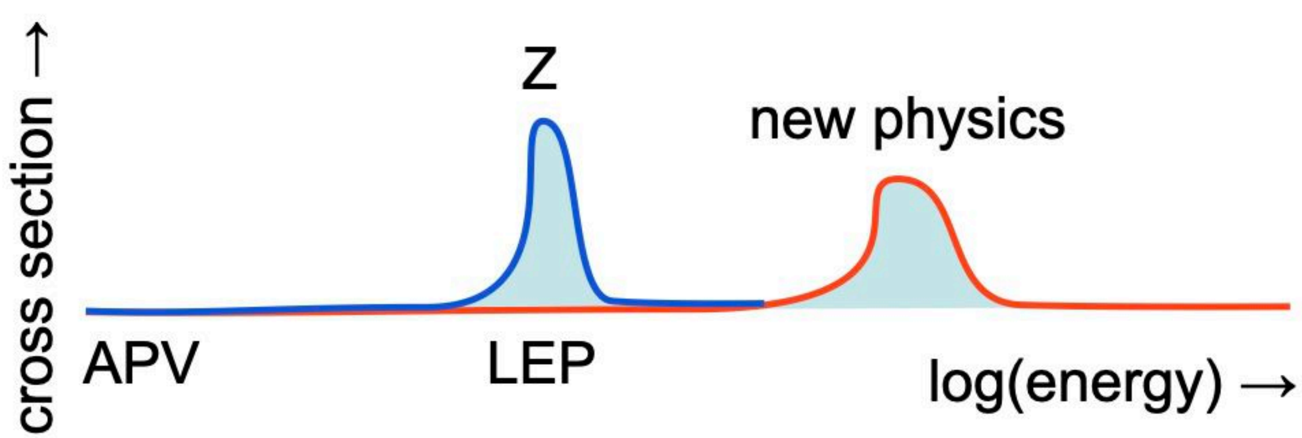
Physics sensitivity from contact interaction (LEP2 convention, $g^2 = 4pi$)

	precision	$\Delta \sin^2\overline{\theta}_W(0)$	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

Jens Erler

from Frank Maas' CIPANP 2018 talk

comparison to e.g. direct searches complicated



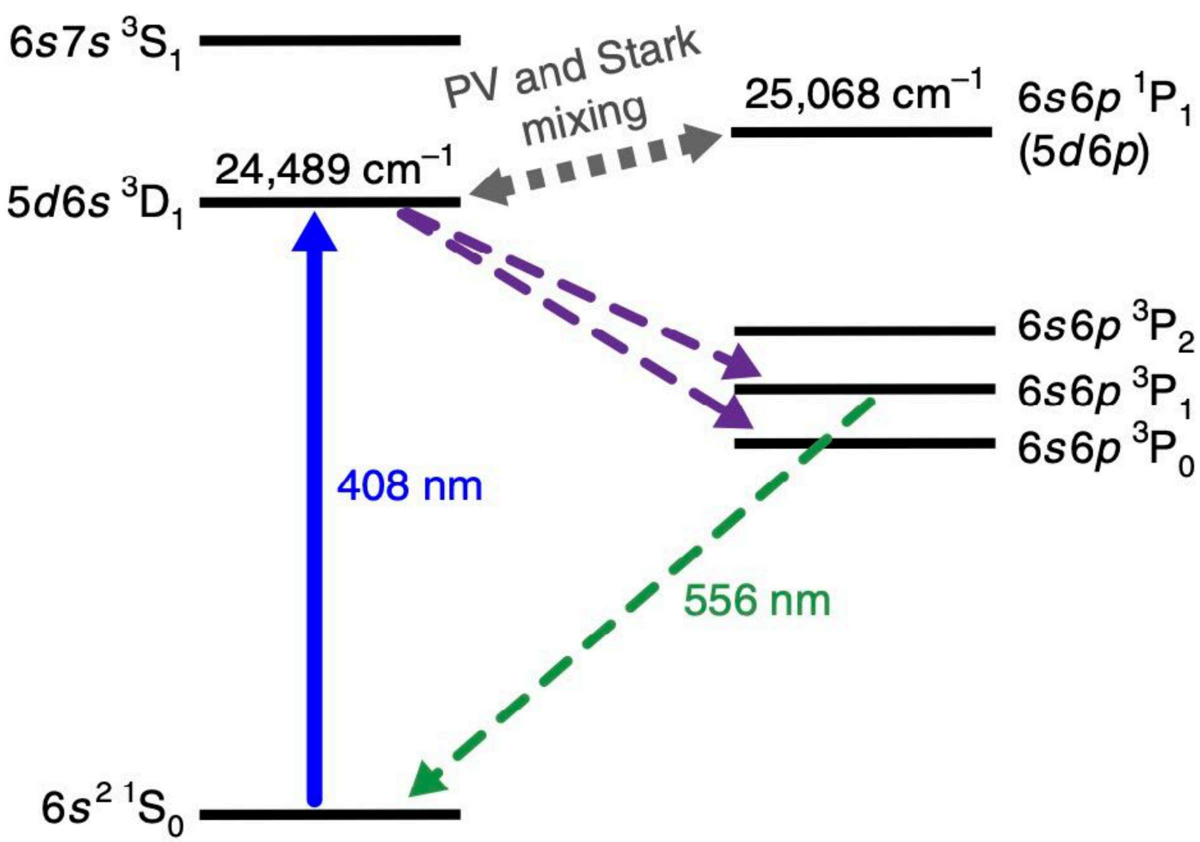
strong motivation to make progress on the APV front

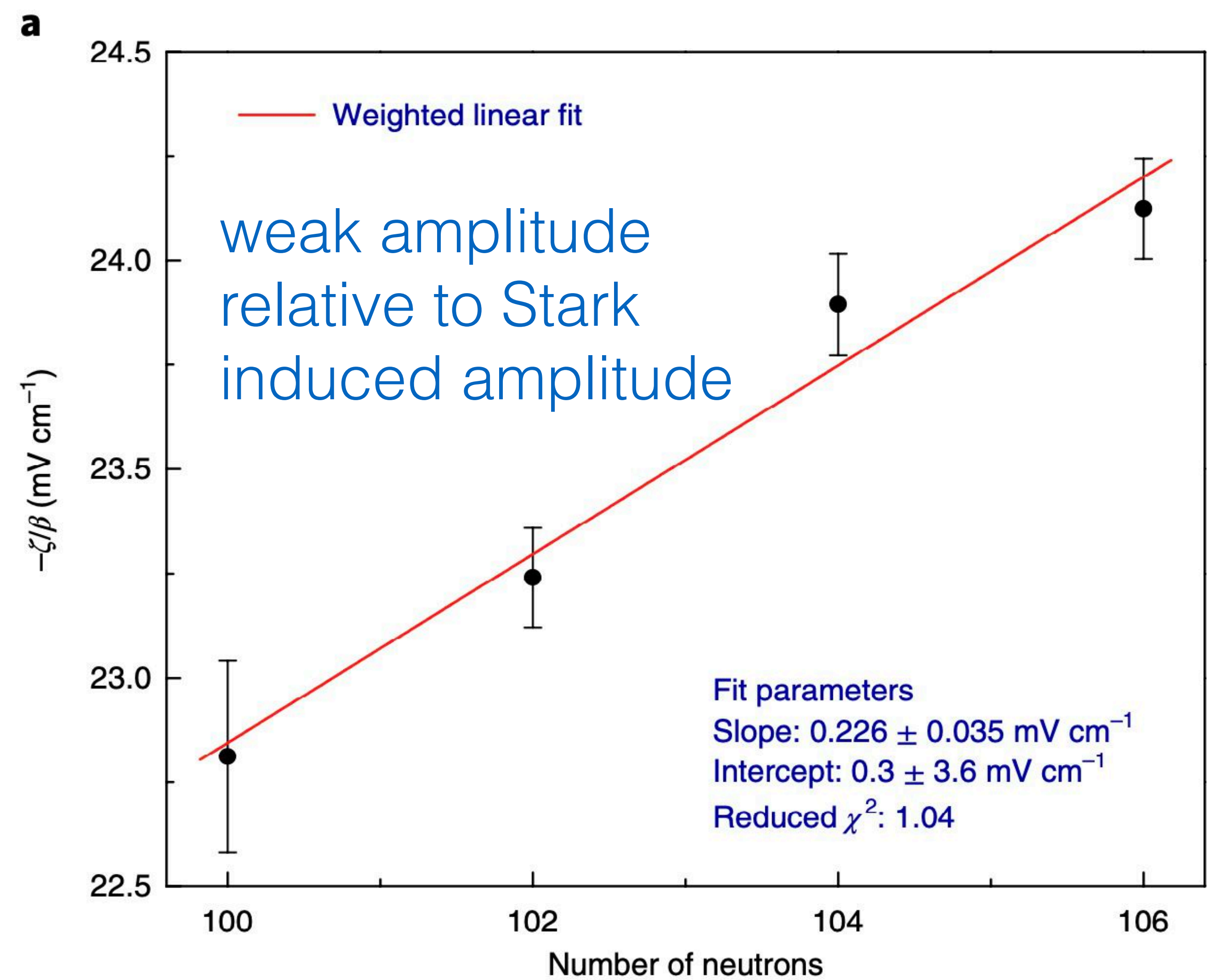
Finally, new results! Ytterbium by Mainz/Berkeley group

Antypas et al.

Nat. Phys. 15, 120 (2019)

First demonstration of dependence of nuclear weak charge on # of neutrons.



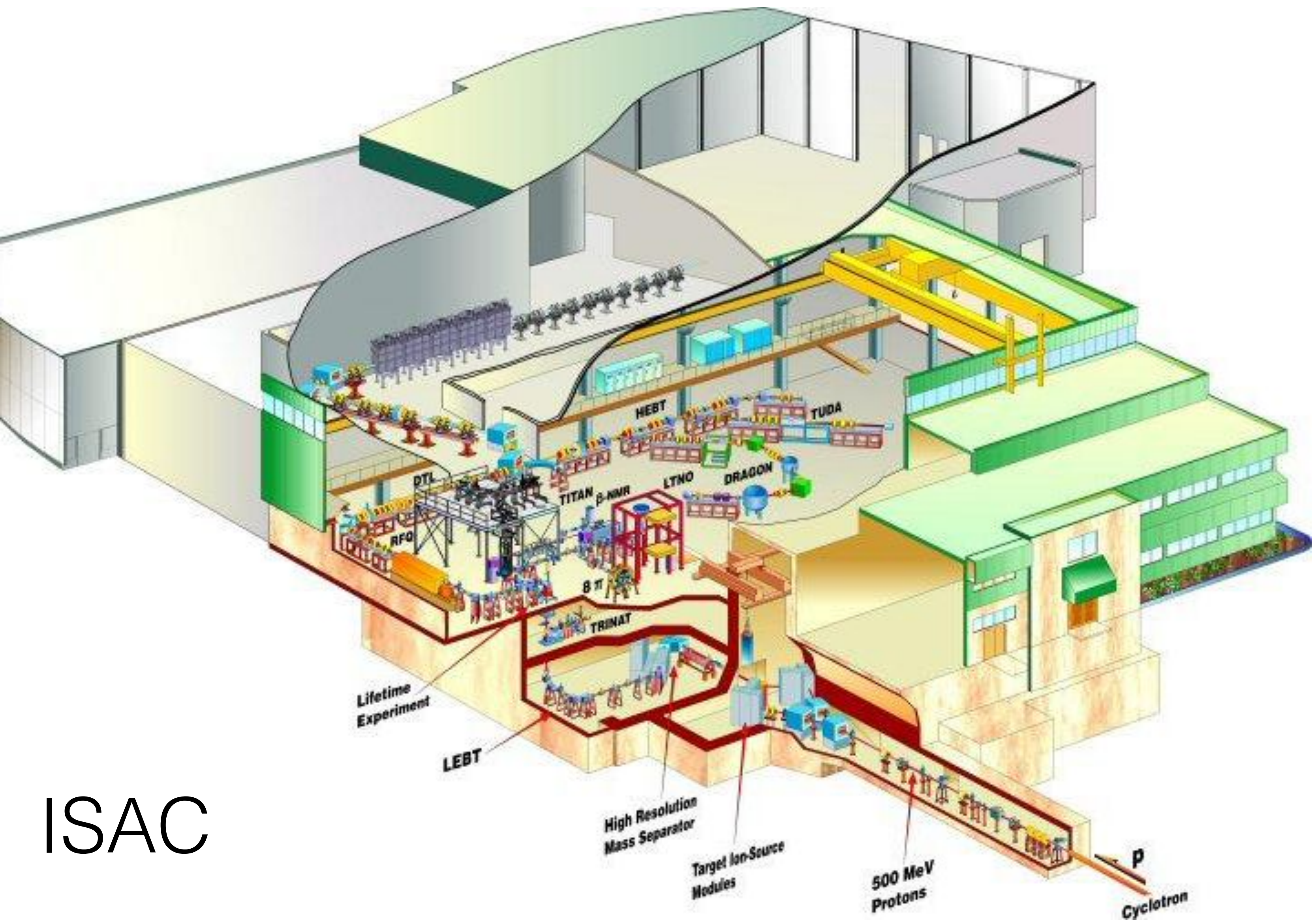


Experimental accuracy ≈ 0.5% in each isotope! Boulder Cs: 0.35%

But at this point, atomic theory not established at this level → alkalis still unique for interpretability

A facility for experiments with francium

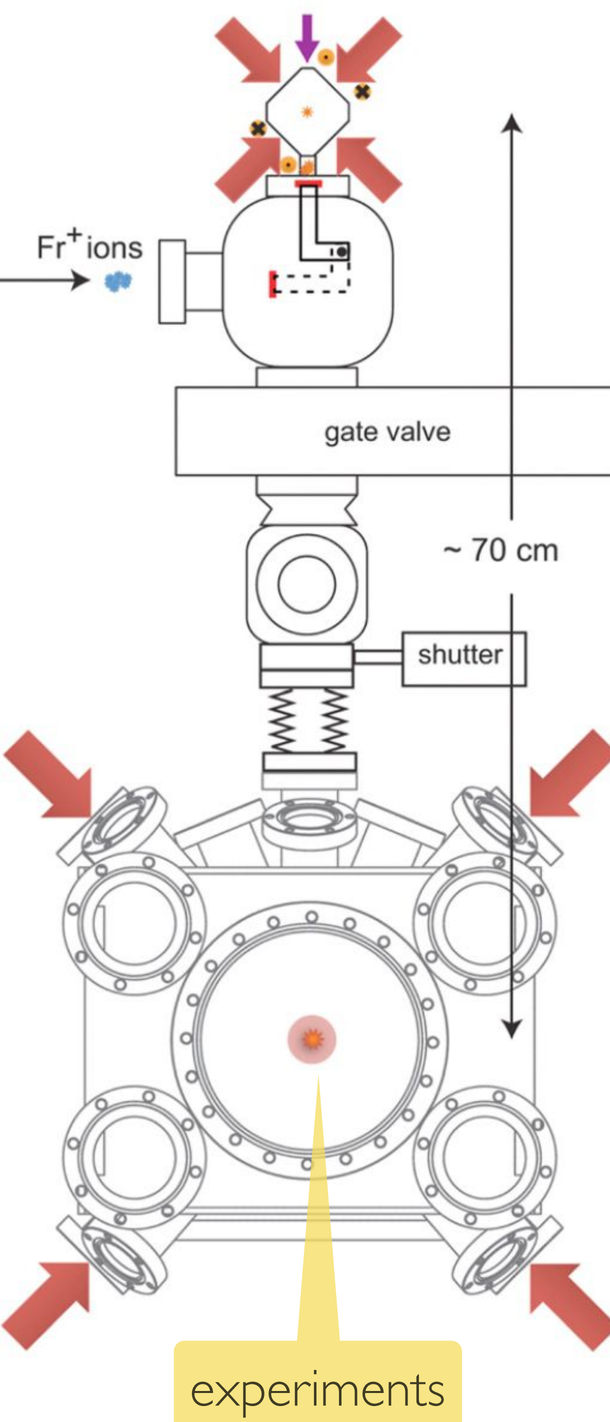
- Fr has not stable isotopes → need to work at a radioactive beam facility
- Boulder Cs experiment used a massive atomic beam: 10^{13} s^{-1} cm^{-2}
- No existing RIB facility can do this, not even close
- Key figure: Cs had 10^{10} APV excitations per second
- Would only need ≈ 10^6 - 10^7 Fr atoms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

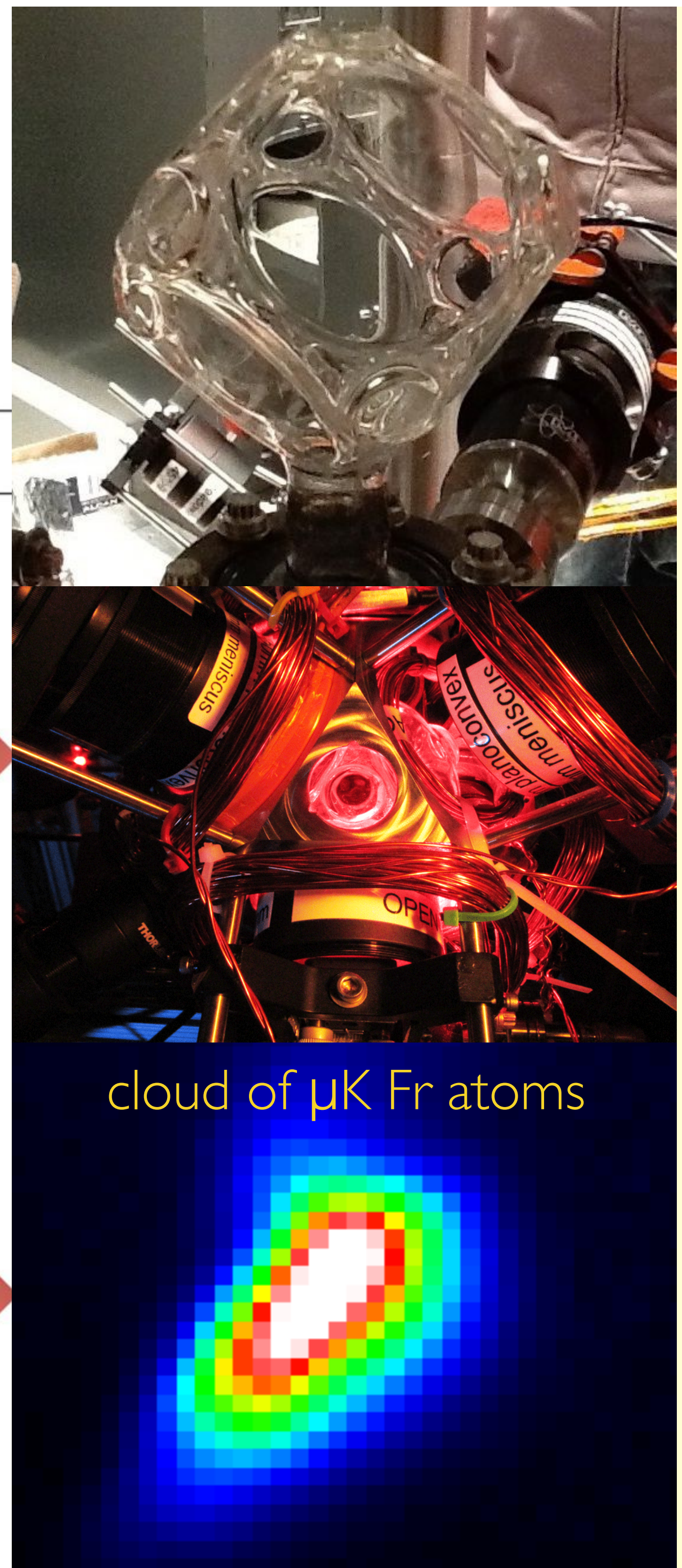


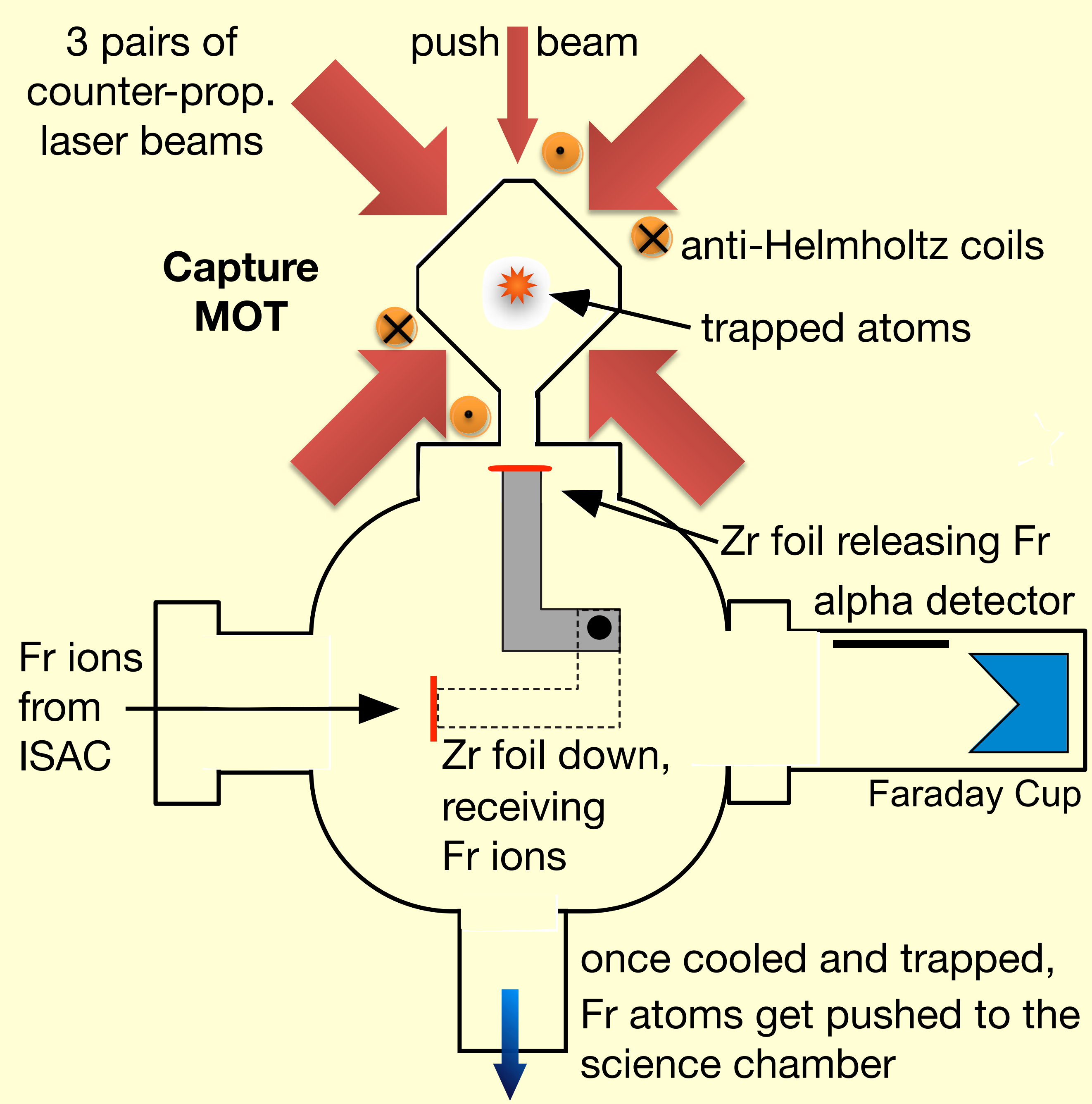
ISAC

The Francium Trapping Facility at TRIUMF/ISAC

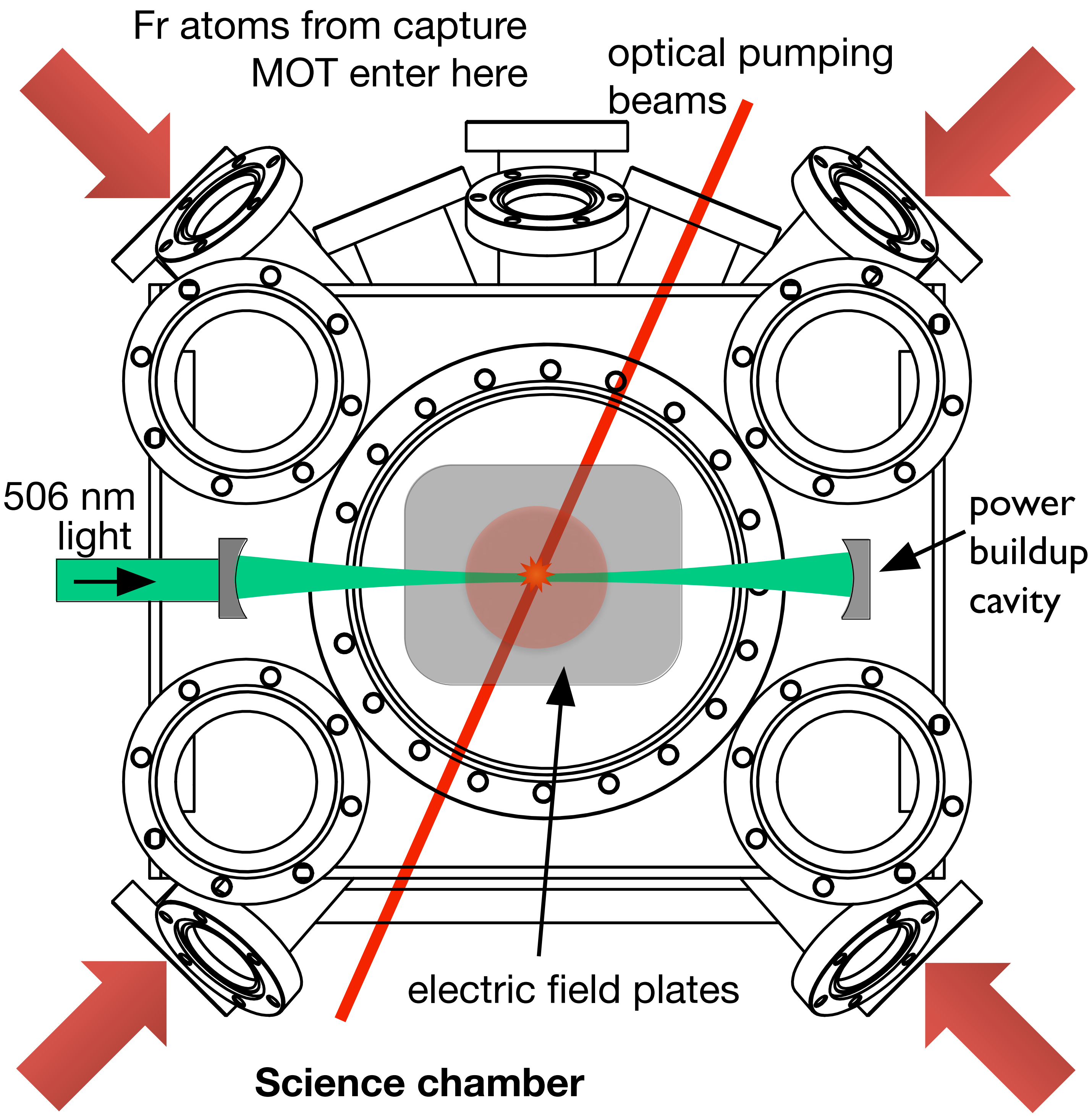
part 1: online capture trap



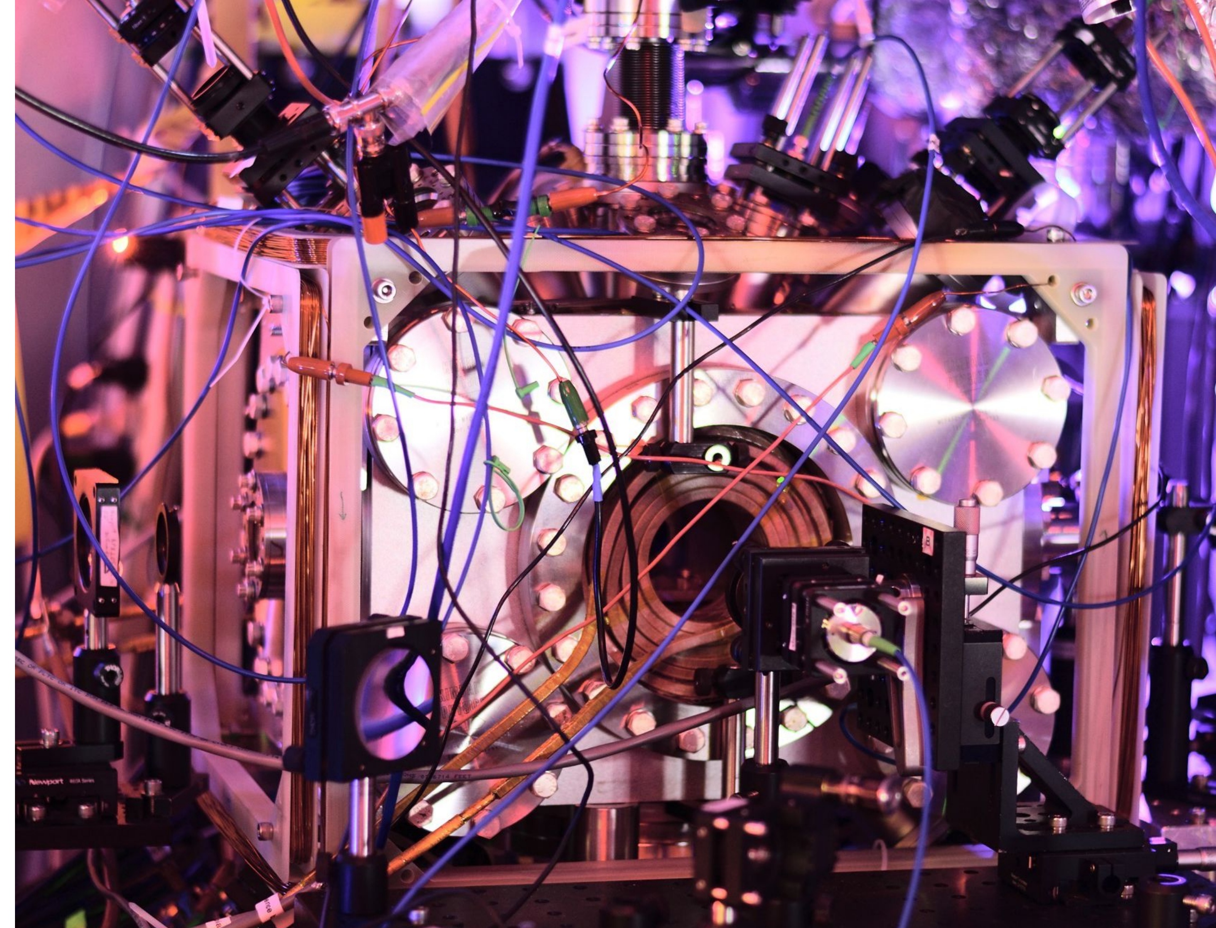


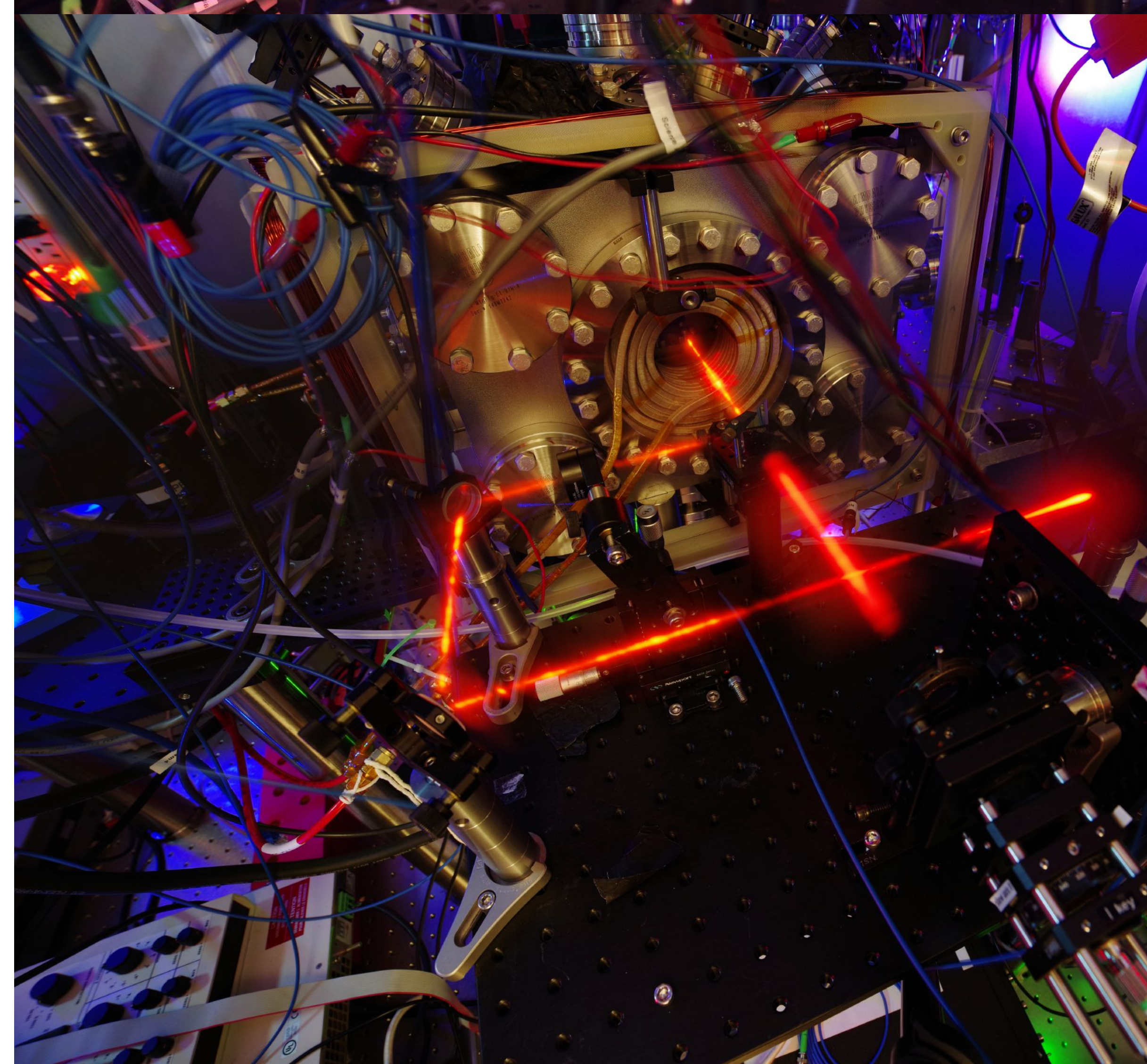


Part 2: Science chamber



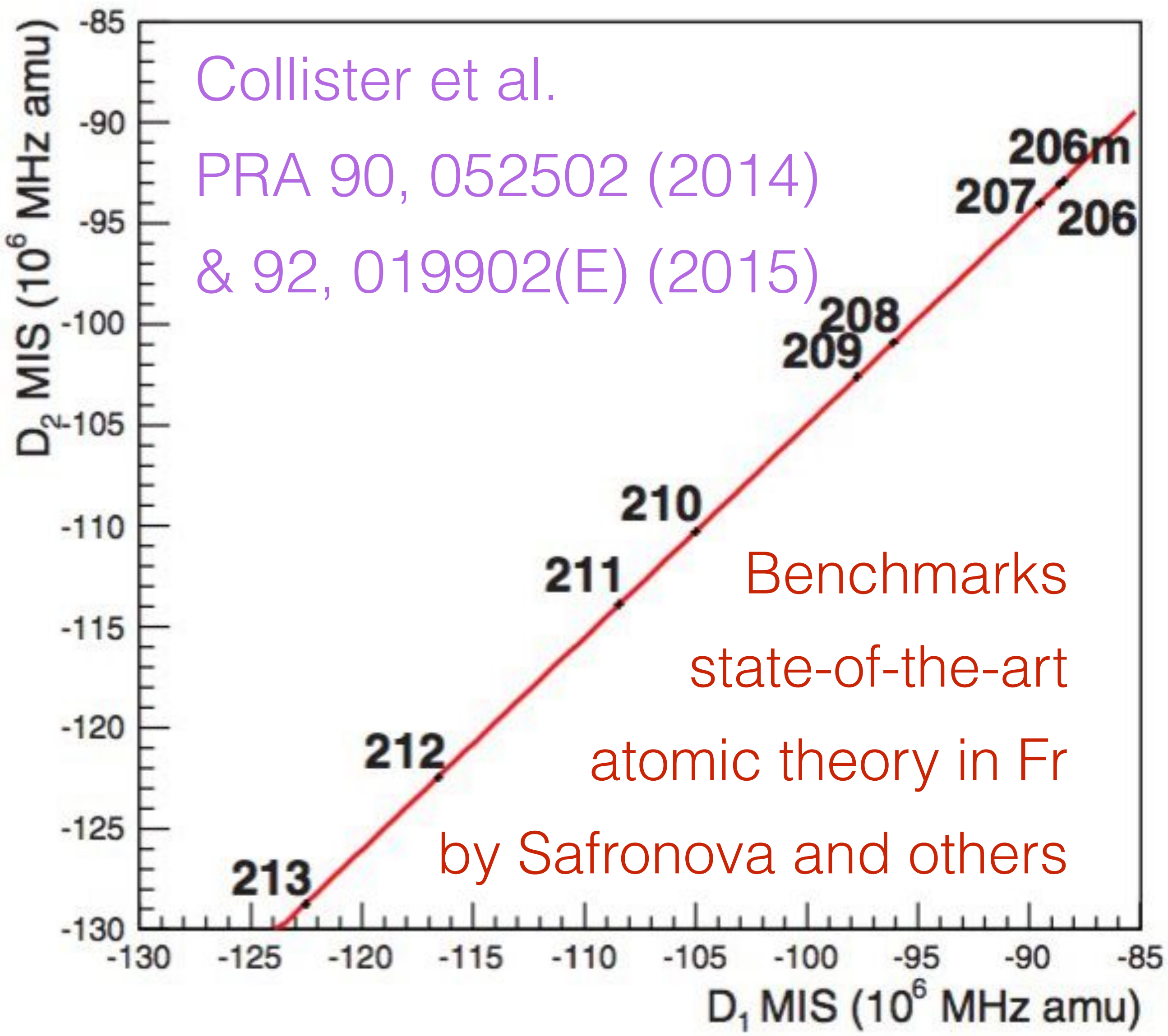
Science chamber

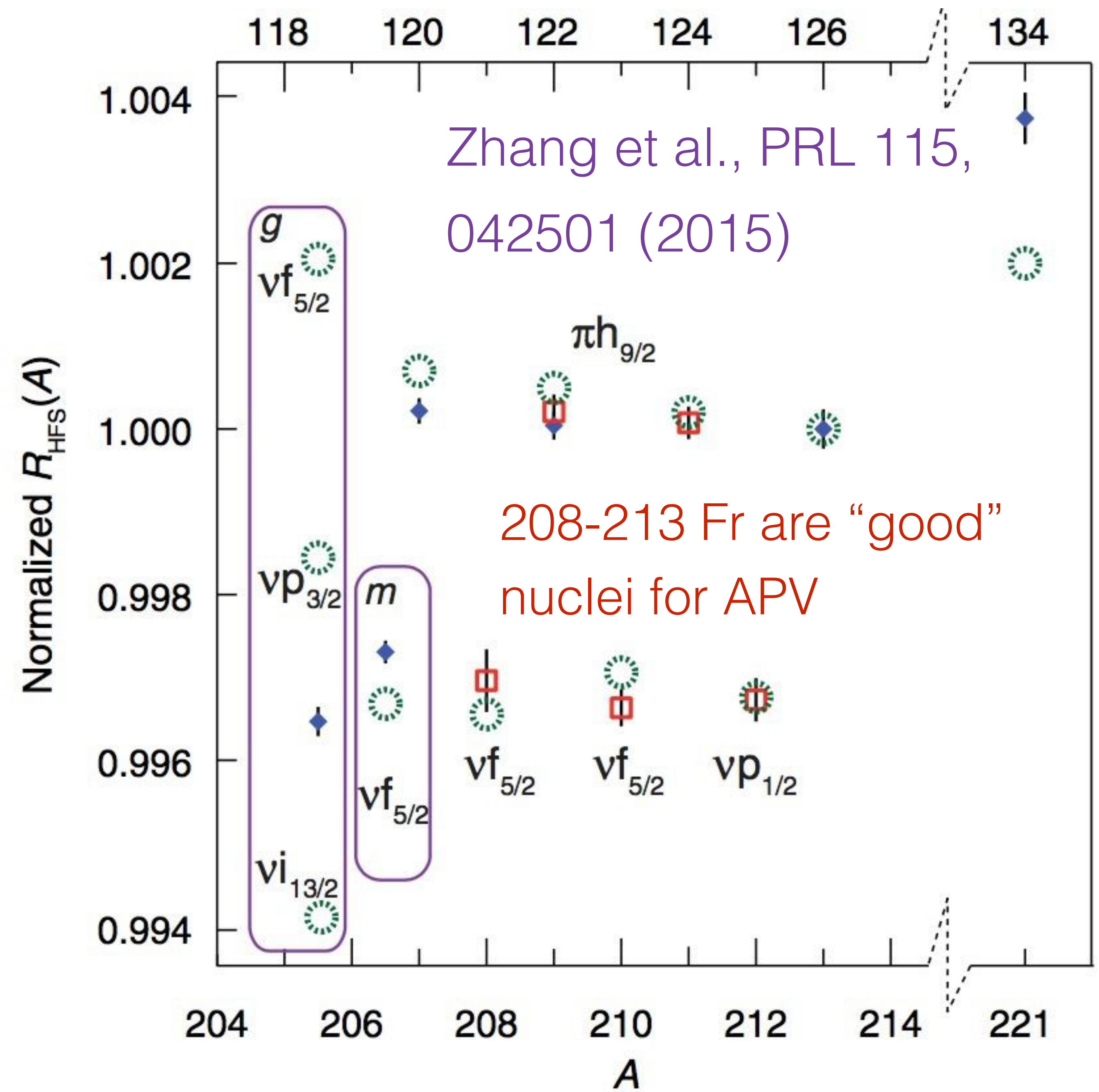




Warm-up exercises with allowed transitions

7s-7p1/2 (D1) isotope shifts in light Fr isotopes

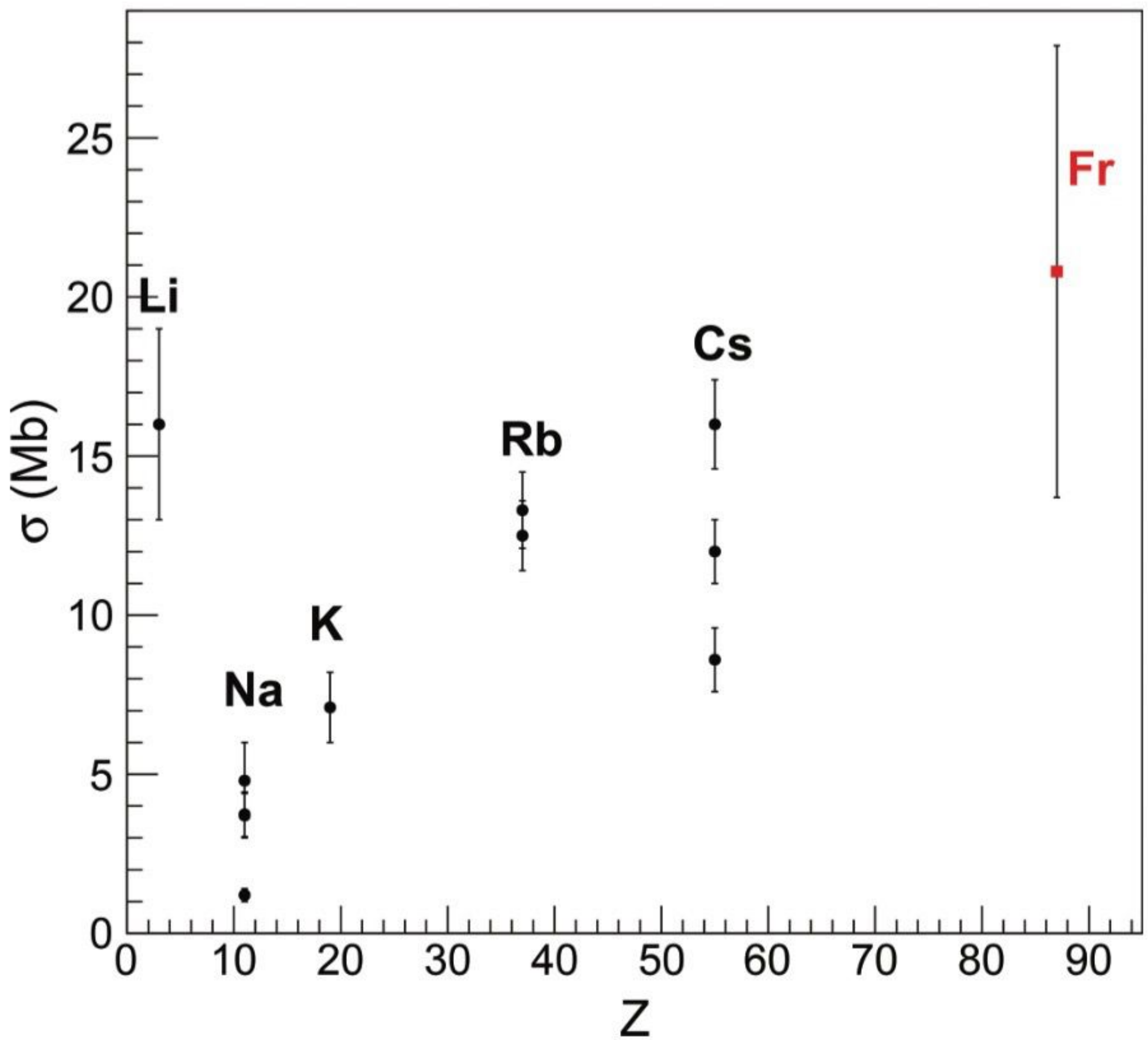


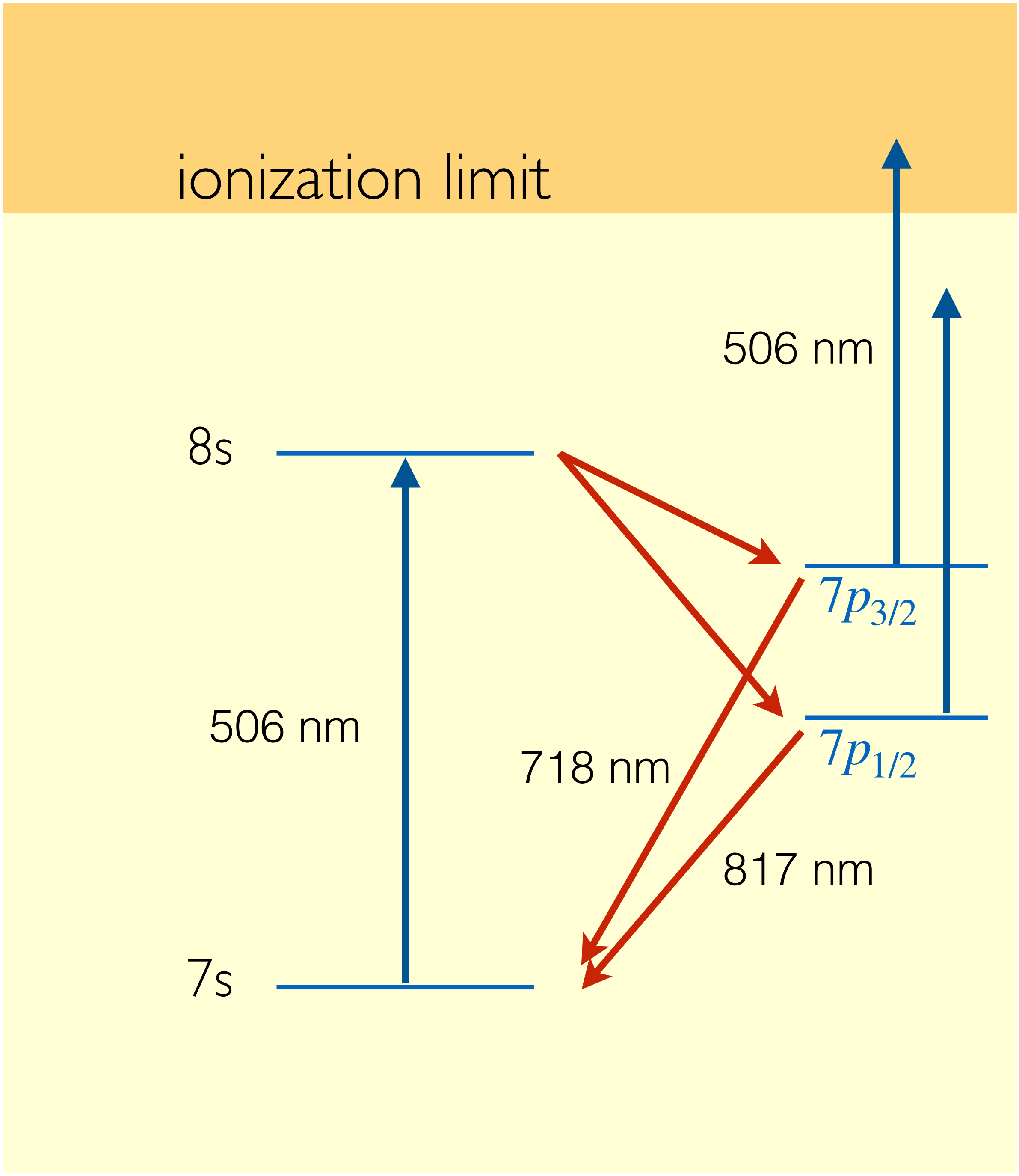


- also Kalita *et al.* Phys. Rev. A 97, 042507 (2018)

Hyperfine anomaly (Bohr Weisskopf effect) in light Fr isotopes

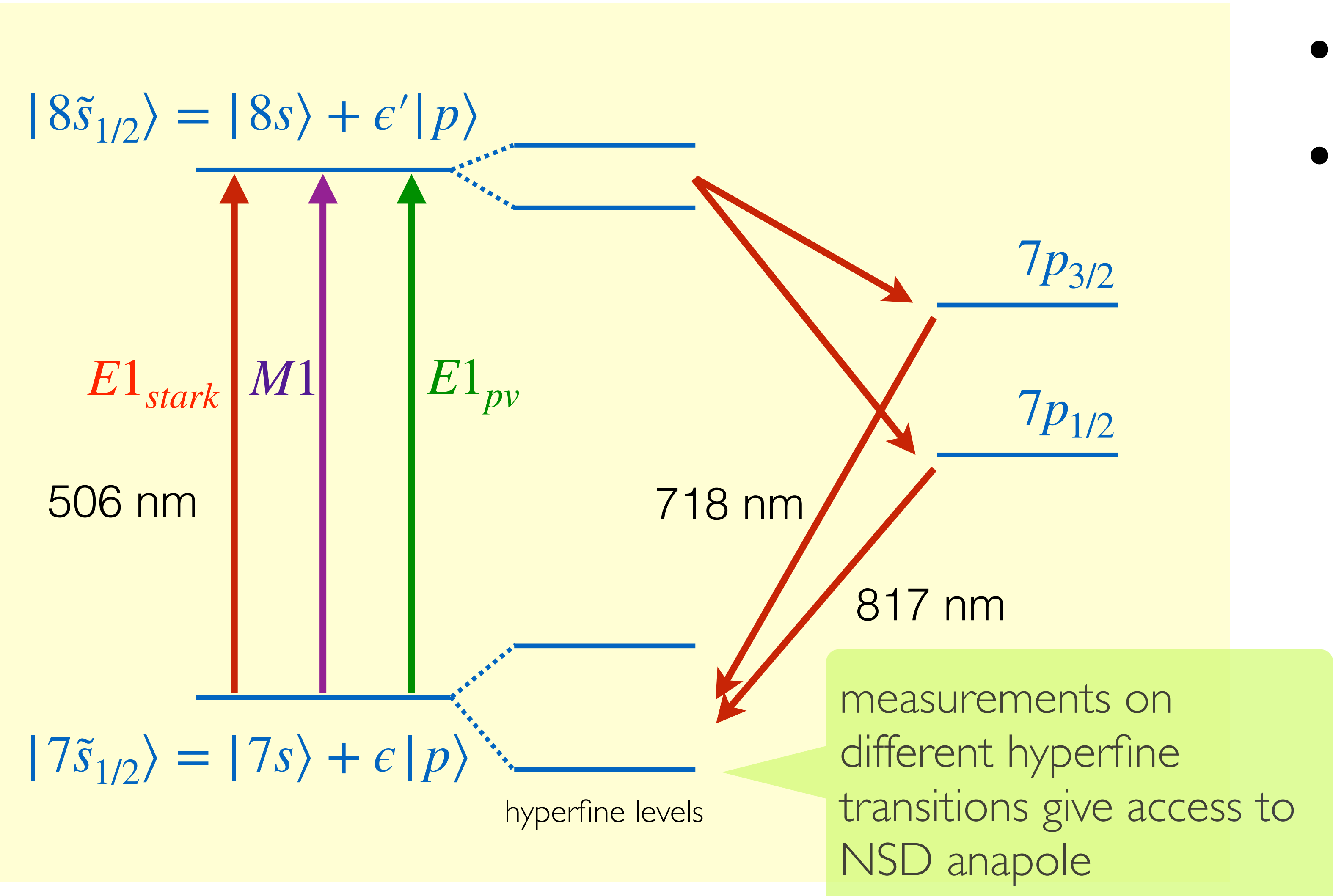
7p3/2 photoionization: Crucial for APV





Francium 7p3/2 photoionization
Collister et al. 2017, Can J Phys, 2017, 95(3), 234-237
Important for APV to know this (roughly)

APV measurement in francium



- 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

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

- Observe **interference** between the Stark-induced and PV amplitudes ($f_{eff} \approx 10^{-17}$)
- Interference terms **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

7s - 8s — Disentangling the amplitudes

electric field, parallel to light polarization

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

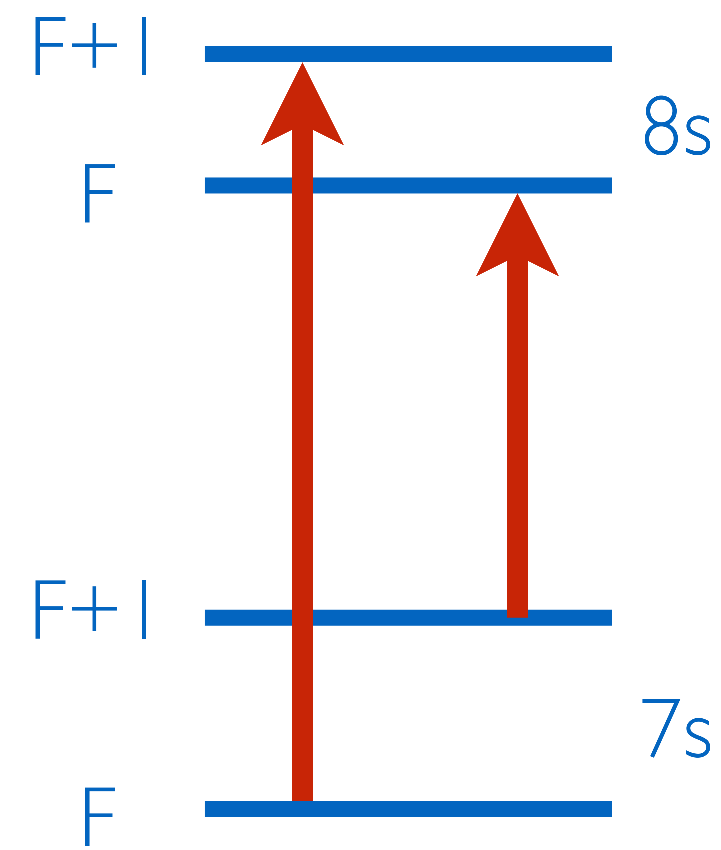
light intensity

$$|\alpha E_{\parallel} + (\beta E_{\perp} + M1_{rel} \pm M1_{hf} + E1_{pv})\langle F'm'|\vec{\sigma}|Fm\rangle|^2\ I$$

$\Delta F = 0$ only

present on $\Delta F = \pm 1$

- to extract $E1_{pv}$
  - have to know $\beta, M1_{rel}, M1_{hf}$ to sub-% precision
  - not possible to just measure their values
    - # of atoms, light intensity, detection efficiency cannot be determined at that level



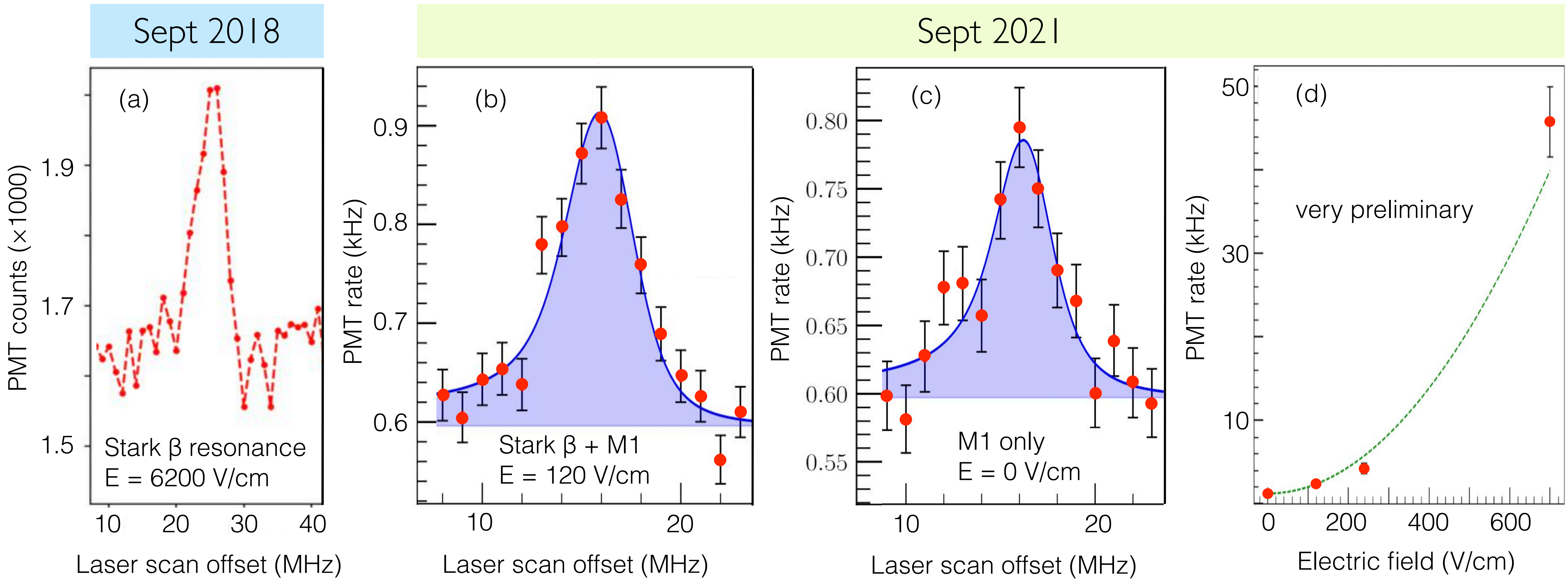
Hyperfine M1 to the rescue

- the vector transition polarizability β can be calculated with state-of-the-art atomic theory reasonably well
- the relativistic magnetic dipole amplitude $M1_{rel}$ is extremely difficult to predict
- but the hyperfine induced magnetic dipole amplitude $M1_{hf}$ can be straightforwardly determined from the known hyperfine splittings
- in a suitable series of measurements, all the other amplitudes can be calibrated against it.

details in the next talk by Tim Hucko

Recent progress: $M1$ and E_{stark}

- Measured combined $M1 + E_{stark}$ signal as a function of electric field



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

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

very hard to calculate

$\Delta F = \mp 1$

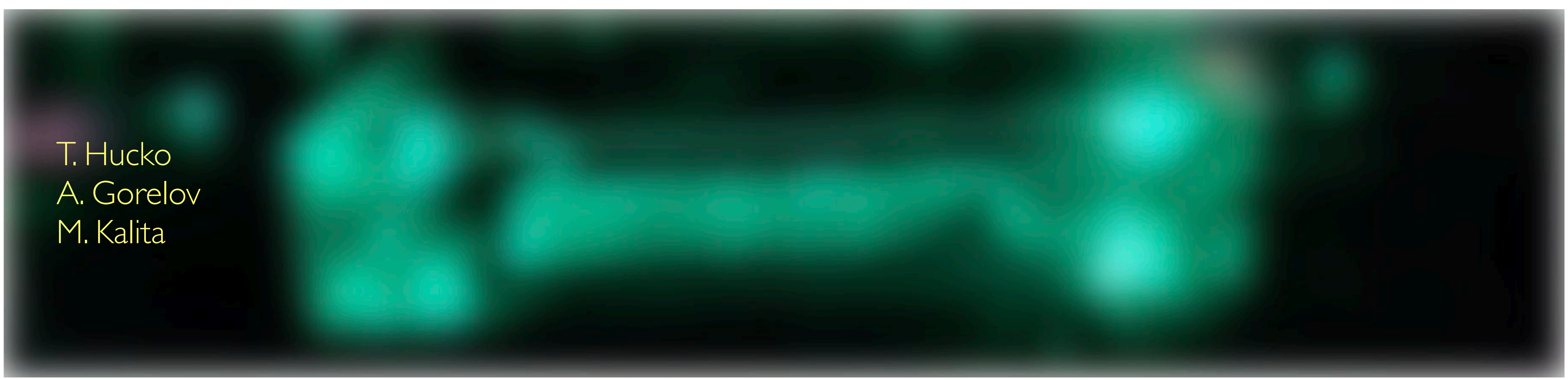
$M1_{hf}$ calculable from known hyperfine splitting

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

- extract $M1_{rel}$ to $\lesssim 10\,\%$ (evaluation in progress)
  - better than the tension between experiment and theory in cesium

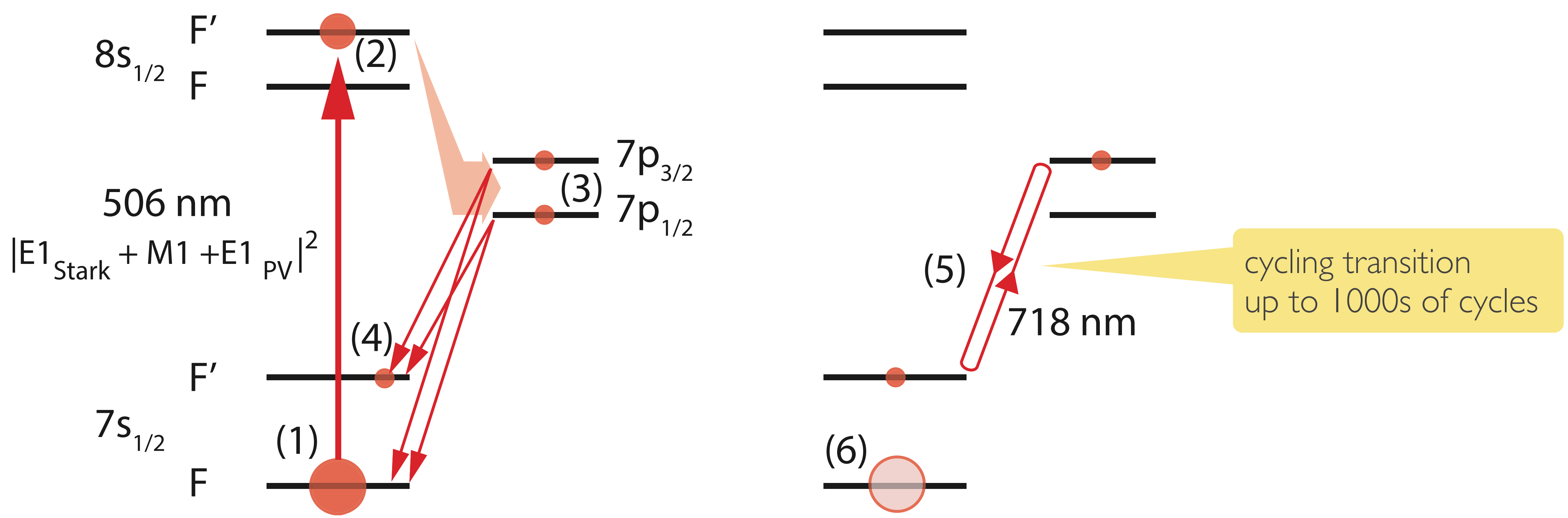
Recent progress: technical

- September 2018
  - 100 mW of 506 nm light and 10^5 trapped atoms
  - sufficient to detect β-type Stark-induced E1 at high field (≈ 6 kV/cm)
  - no chance to observe M1
- 2019-2021: development of UHV-compatible power buildup cavity (PBC)
  - hard! (e.g. vibrational environment on beamline)
  - reached ≈ **4000×** power buildup
    - close to theoretical limit, can't use more due to Fr photo-ionization
  - very robust now, lock holds mirror distance at picometer level
  - lock survives periodic 5 msec light on-off cycles!



What's next ?

- precision measurement of $M1_{rel}, M1_{hf}, \beta$ (sub-%)
  - need more signal → improve detection efficiency of currently ≈ 1/2000
  - difficult to improve light collection solid angle
  - best bet is "burst detection"



- development started, some good challenges ahead
- goal1000× more signal (together with PBC: million-fold improvement over 2018)
  - enough to get us signal wise to APV era

but signal is not everything!

And then?

- Beyond the $M1$ the β calibration, we need to do **interference** experiments
  - 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

5-10 ms	< 500 µs	3 ms	< 500 µs	5-10 ms
trap on quadrupole field (8 G/cm)	quadrupole off homogeneous field on (few G)	optical pumping measurement burst detection	quadrupole on homogeneous field off	re-trapping quadrupole field (8 G/cm)
trap lasers on PBC off		trap lasers off PBC on		trap lasers on PBC off

- chamber geometry leads to significant eddy current problems
- use 200 kHz bw bipolar power supplies (Matsusada)
- active coil current shaping to counter location-dependent eddy fields
- challenging → optically pumped atoms ready for 2023 campaign

time dependent B field in centre of coil

B field at location of atom cloud

after-next talk by Anima Sharma

Outlook

- 2023 with optically pumped atoms
  - measure ratio of the scalar to vector Stark transition polarizabilities α/β
  - observe $E1_{stark} - M1$ interference (PBC removed)
- 2024
  - attempt to see $E1_{stark} - E_{pv}$ interference (APV effect)

after-next talk by Anima Sharma

but 2022 is already half over

The FrPNC team

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

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

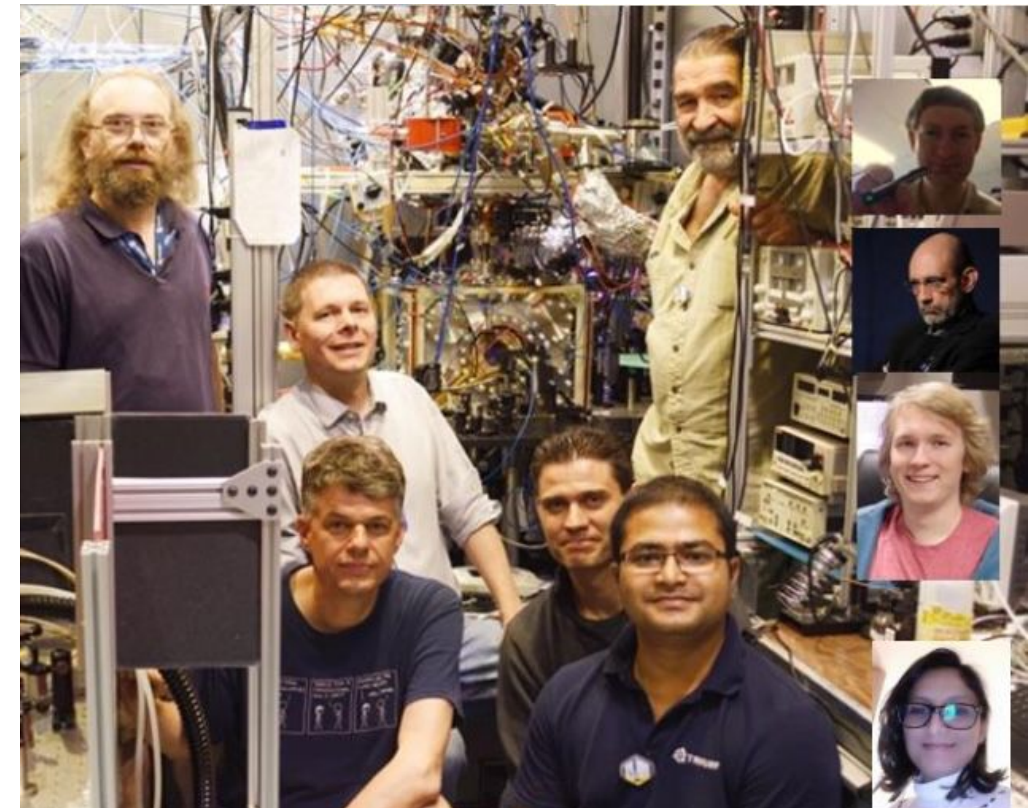
L. Orozco — U Maryland

E. Gomez — San Luis Potosi

S. Aubin — William & Mary

Funding:

NSERC, NRC/TRIUMF,
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. 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)