Prospects for new atomic parity violation experiments

University of Manitoba

Particle & Atomic & Nuclear

CIPaAaNP 2018

Gerald Gwinner

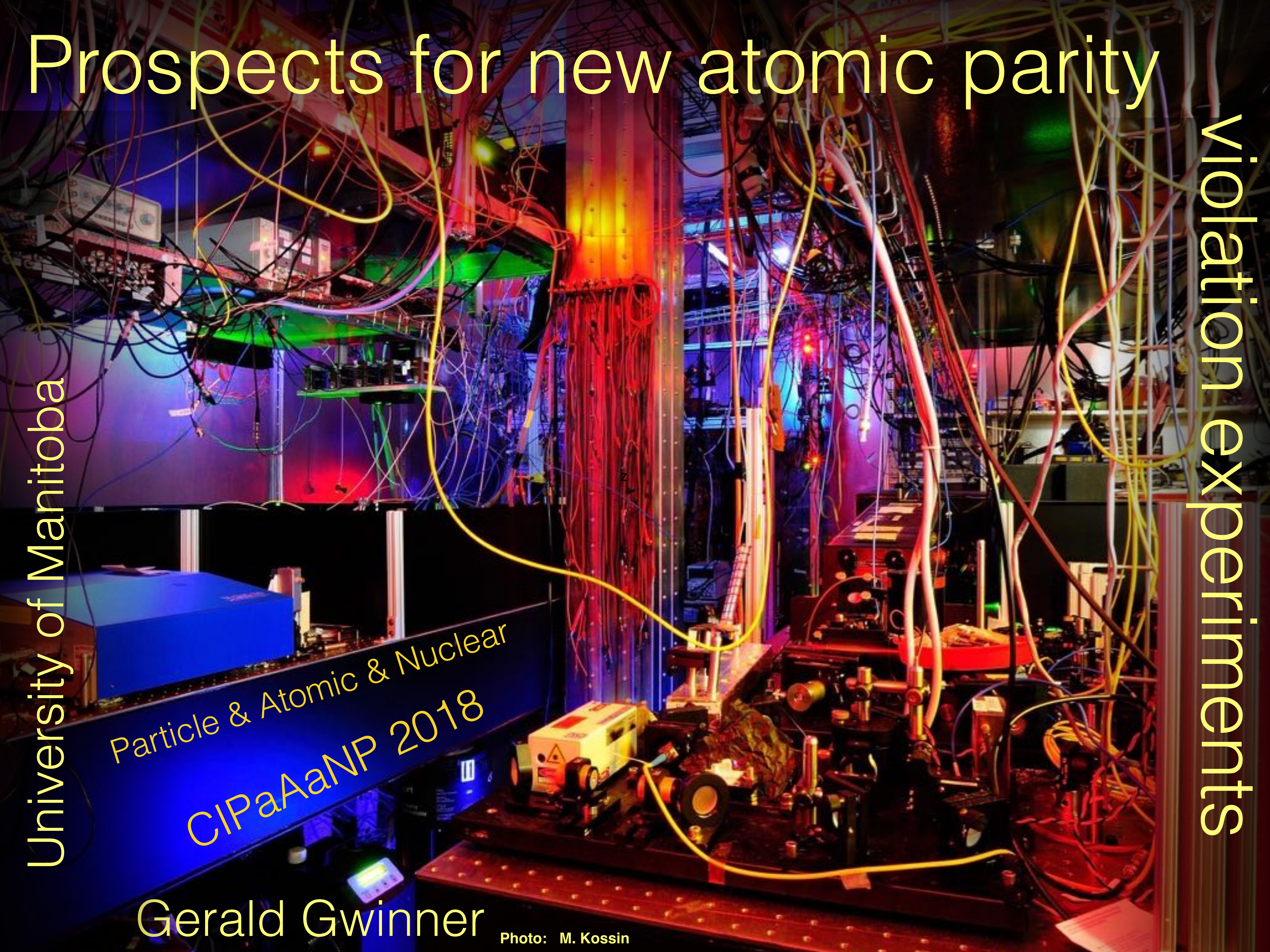
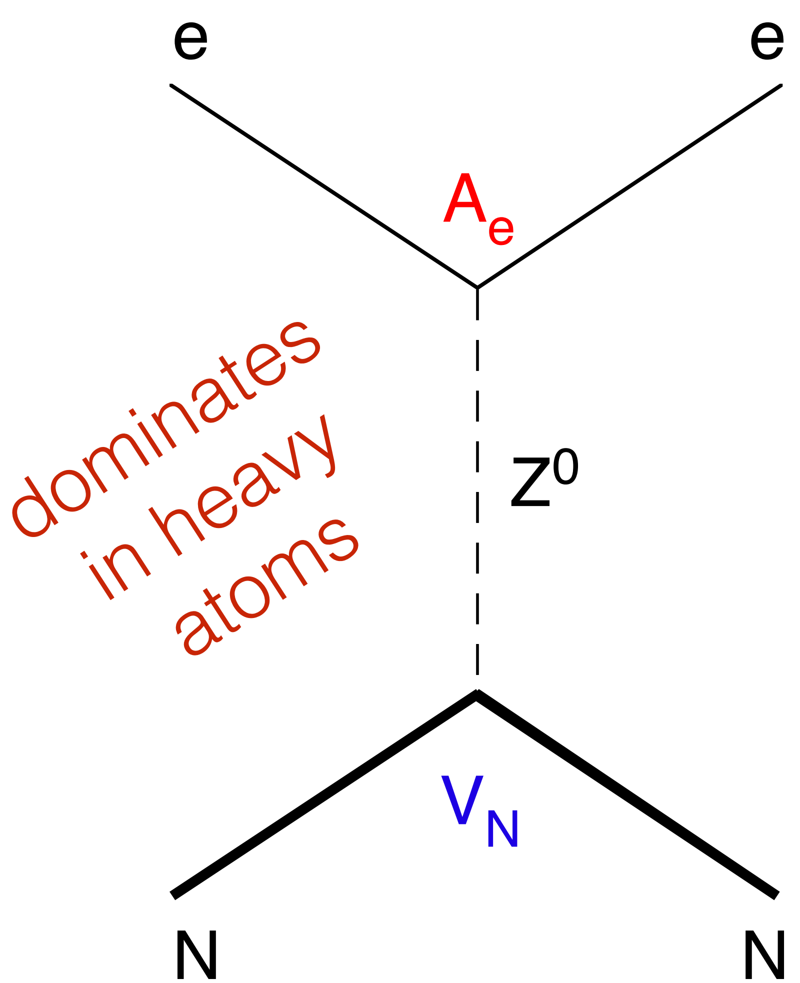


Photo: M. Kossin

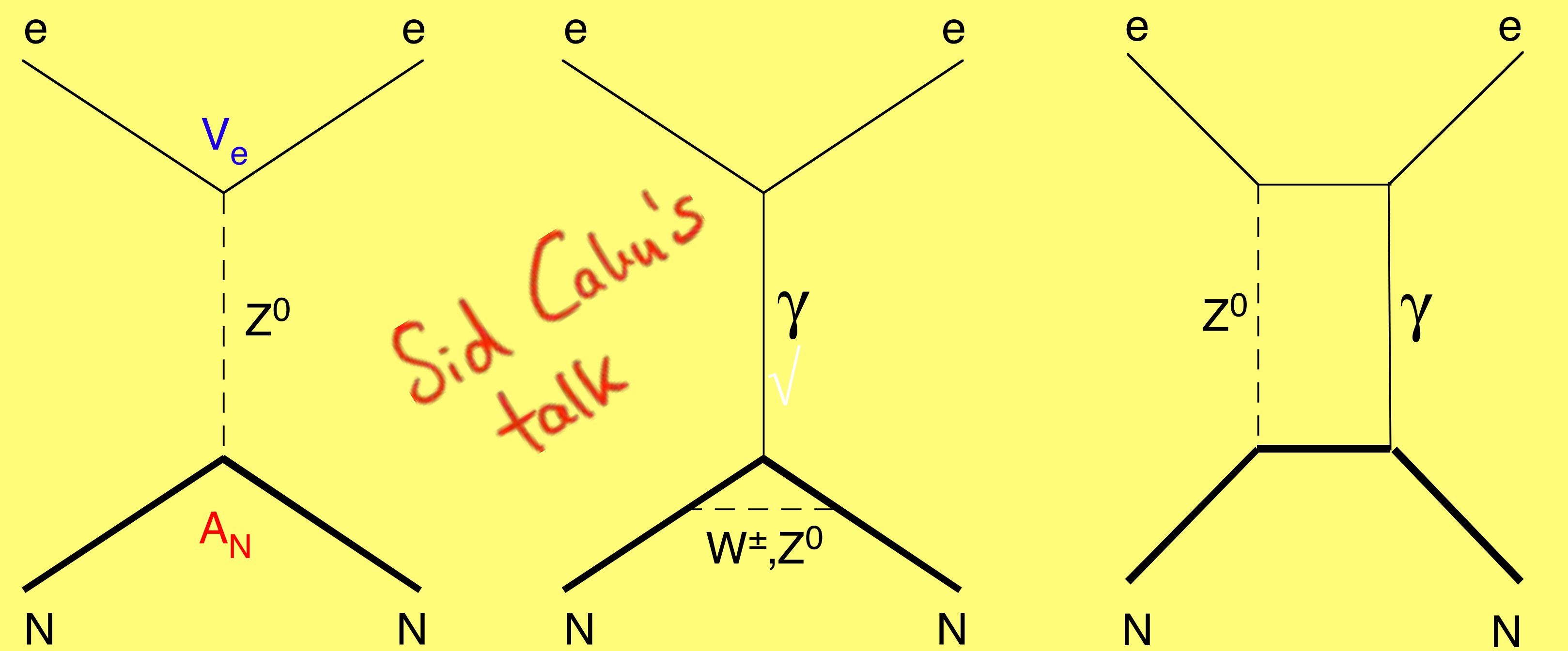
Atomic Parity Violation

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

Nuclear spin independent



Nuclear spin dependent



NSD Z-exchange

PV hadronic interactions ⇒ PV anapole moment of the nucleus

hyperfine correction to the weak neutral current

nuclear spin *independent* interaction: coherent over all nucleons

H_{PNC} mixes electronic *s* & *p* states

$< n's' \,|\, H_{PNC} \,|\, np > \;\propto\; Z^3$

Drive s → s E1 transition!

Cs: 6s → 7s osc. strength f ≈ 10^{-22}

use interference:

$$f \propto |\, A_{PC} + A_{PNC} \,|^2$$

$$\approx A_{PC}^2 + A_{PC}\, A_{PNC} \cos\varphi$$

The NSI APV Hamiltonian for a pointlike nucleus

$$H^{nsi}_{\mathrm{PNC}} = \frac{G}{\sqrt{2}} \frac{Q_W}{2} \gamma_5 \, \delta(\mathbf{r})$$

$$Q_W = 2(\kappa_{1p} Z + \kappa_{1n} N)$$

$$\kappa_{1p} = \frac{1}{2}(1 - 4\sin^2\theta_W), \kappa_{1n} = -\frac{1}{2}$$

↑ ≈ 0.02

$\rightarrow$ APV $\approx Q_W(n)$

The "nuclear weak charge" Q_W contains the weak interaction physics

$$< n'L' | H^{\mathrm{nsi}}_{\mathrm{PNC}} | nL > \quad = \frac{G}{\sqrt{2}} \frac{Q_w}{2} < n'L' | \delta(r) \vec{\sigma} \cdot \vec{p} | nL >$$

$$\propto < n'L' | \frac{d}{dr} | nL > |_{r=0} \qquad R_{nL} \approx r^L Z^{L+1/2}$$

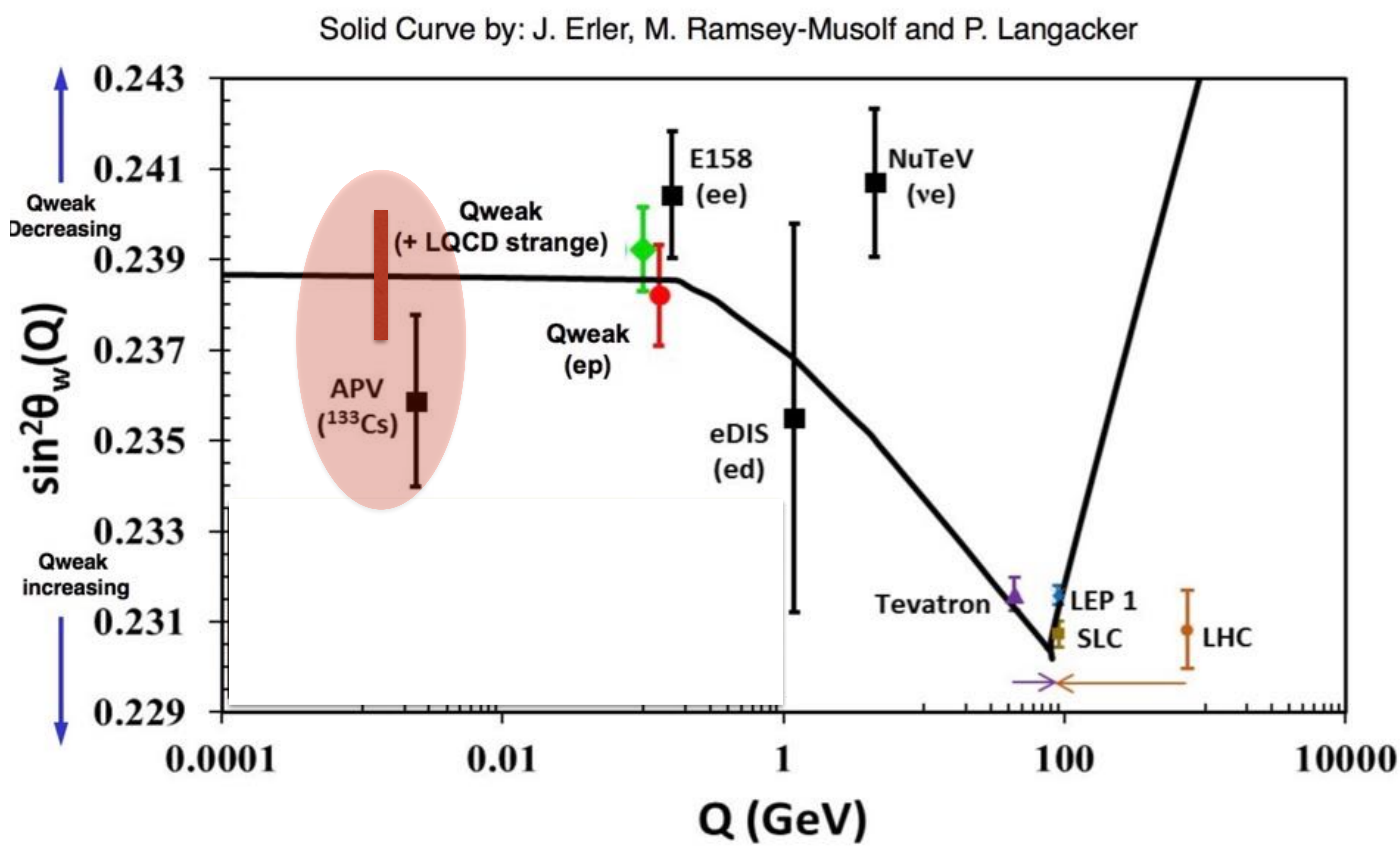
$\Rightarrow$ at $r = 0$ only R_{ns}, $\frac{d}{dr} R_{np}$ are finite

for offline ref

H_{PNC} mixes s and p states $\qquad < ns | H^{\mathrm{nsi}}_{\mathrm{PNC}} | n'p > \propto Z^3$

Bouchiat, 1974

The Weinberg angle … does not do APV justice



Carlini/Gericke, Qweak presentations Aug 2017

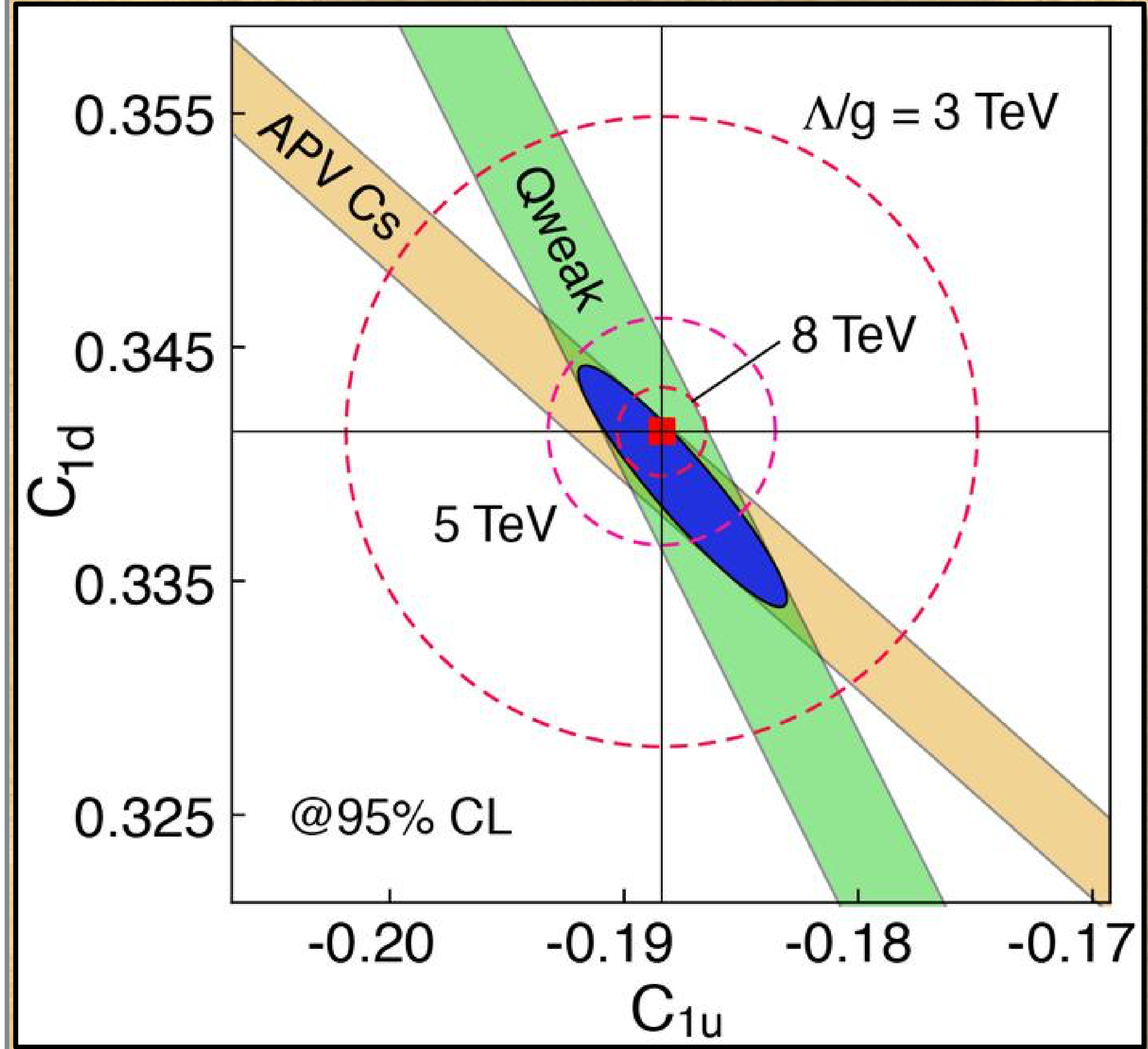
Limits on Semi-Leptonic PV Physics Beyond SM

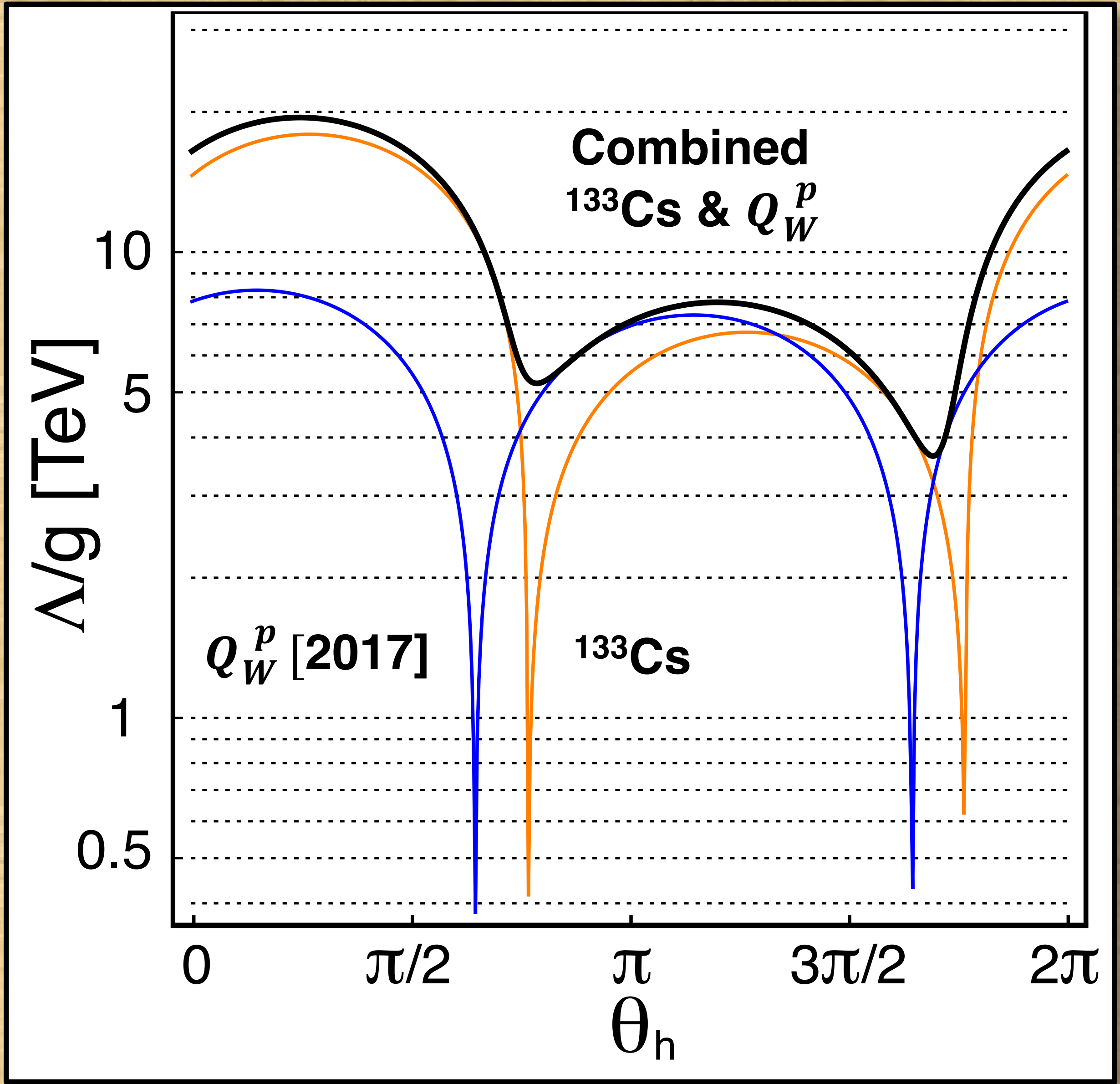
$$\mathcal{L}_{NP}^{PV} = -\frac{g^2}{\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h_V^q \bar{q}\gamma^\mu q$$

$$h_V^u = \cos\theta_h \qquad h_V^d = \sin\theta_h$$

$$Q_W^p = -2(2C_{1u} + C_{1d})$$

New Physics Ruled Out @95% CL Below Mass Scale of Λ/g

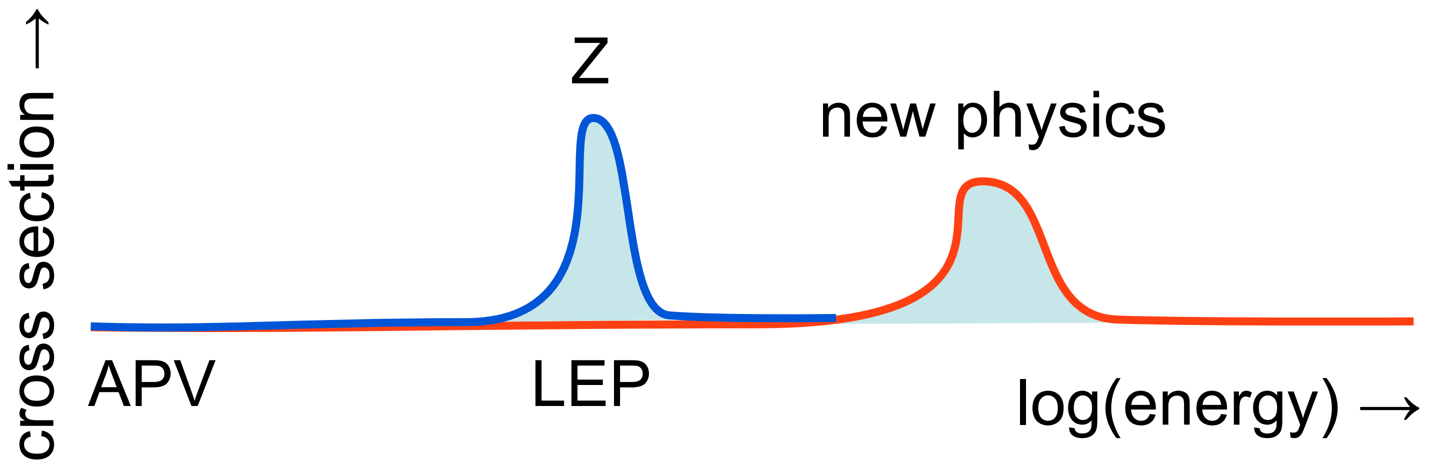




SM is red square. Dashed contours indicate value of Λ/g = 3, 5, and 8 TeV.
(^{133}Cs APV, from PDG – Flambaum)

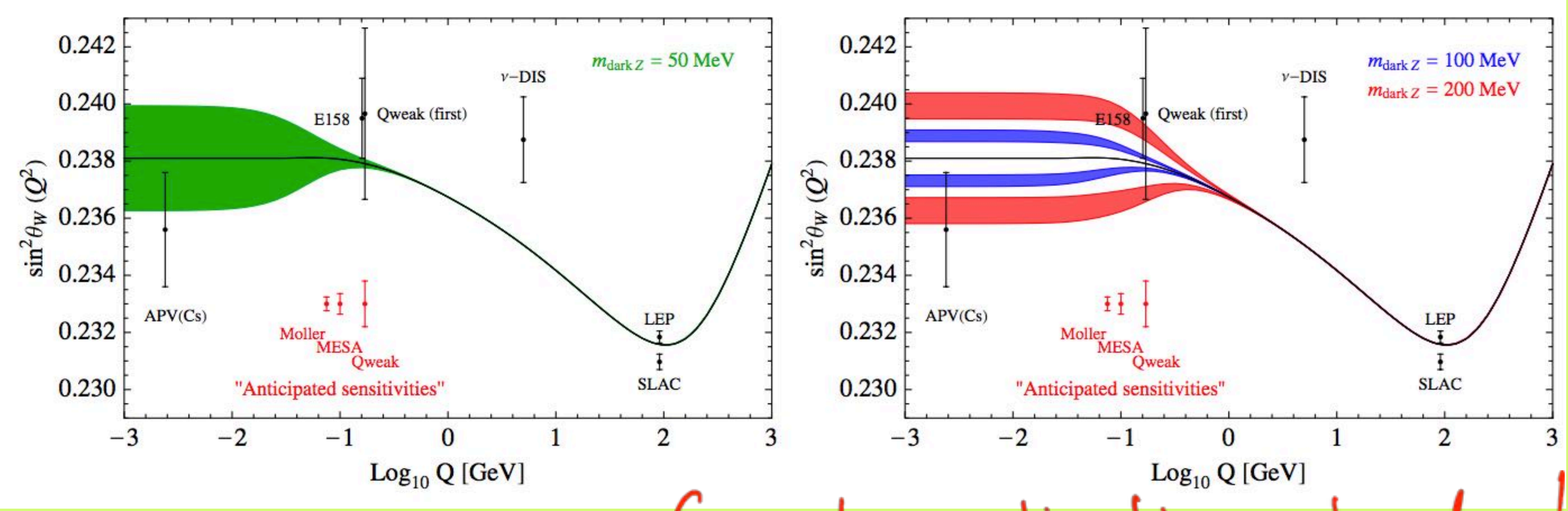
θ_h is "flavor mixing angle" in Lagrangian $\mathcal{L}_{NP}^{PV}$ for new physics at value Λ/g mapped around boundary of experimental limits.

Why are low-energy experiments such as APV relatively sensitive to new physics at higher energy scales? My poor-man's explanation:



APV complementary to other low and high energy tests

Parity violation from dark bosons [Davoudiasl PRD 89, 095006 (2014)]



Enough motivation already!

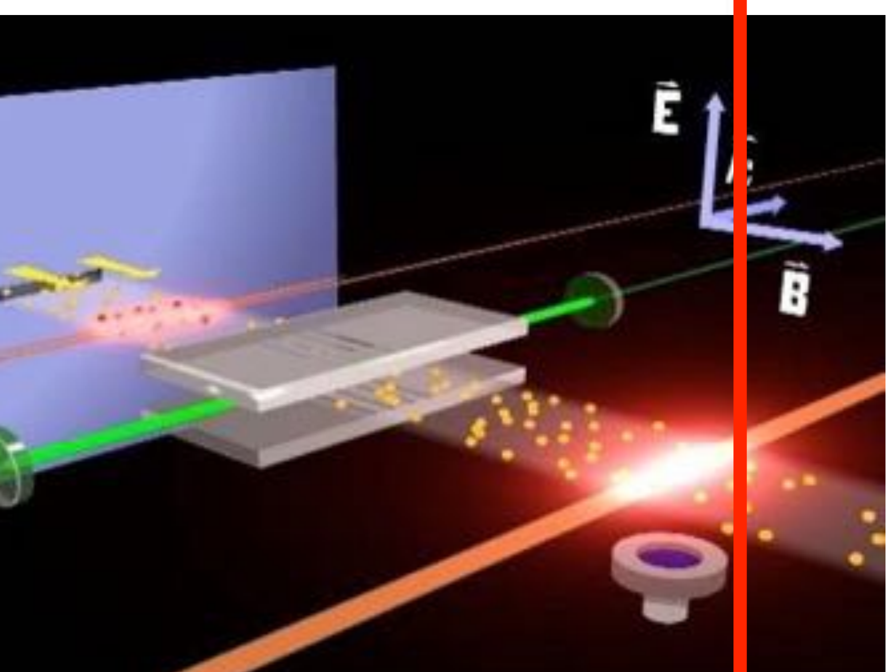
Good news: An outstanding experiment in Cs (Wood, 1996)

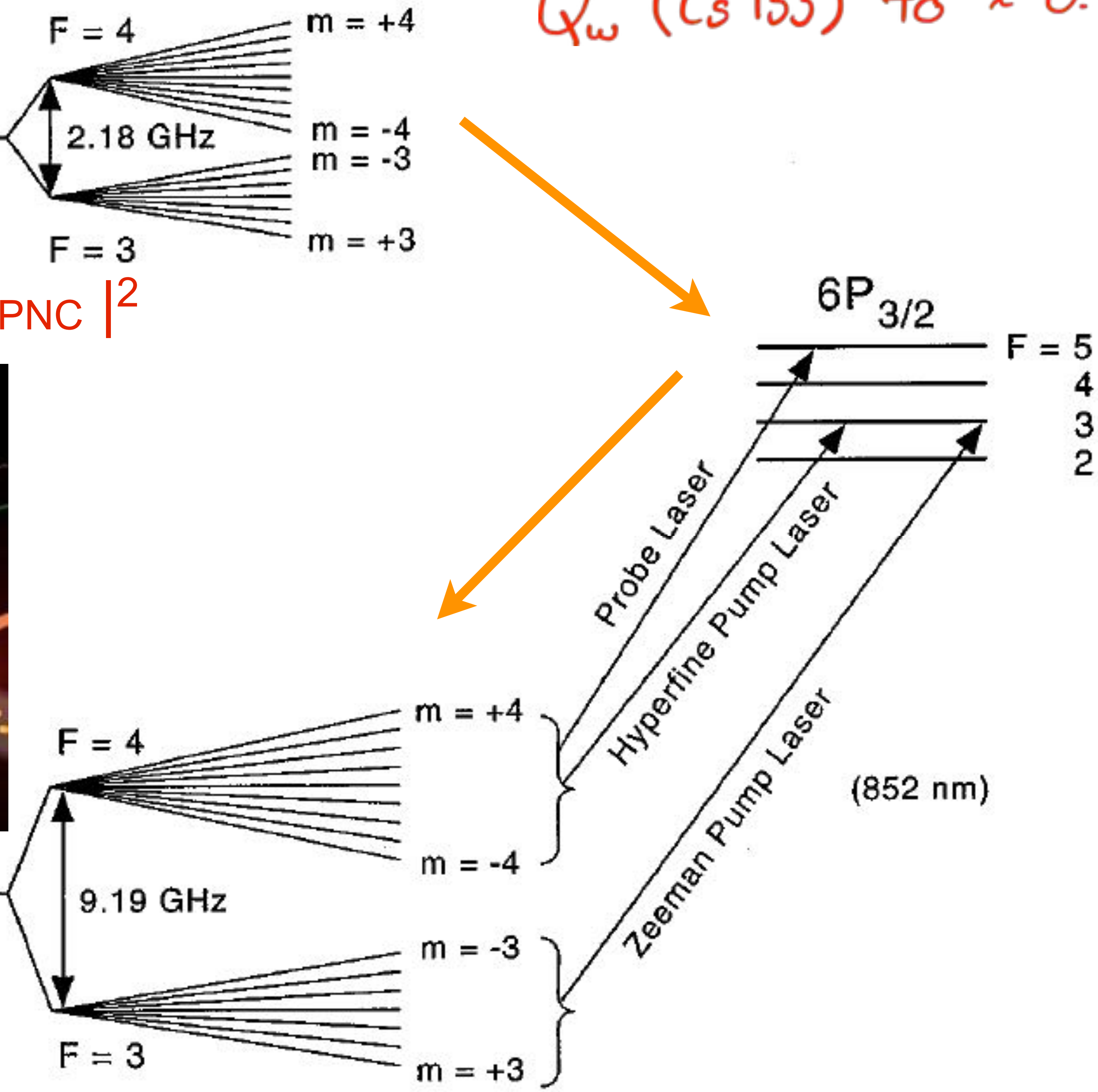
Bad news: The Cs experiment has been towering

Q_w (Cs 133) to ≈ 0.5%

$$\overline{|7s\rangle} = |7s + \epsilon p\rangle$$

$| E1_{Stark} + M1 + E1_{PNC} |^2$



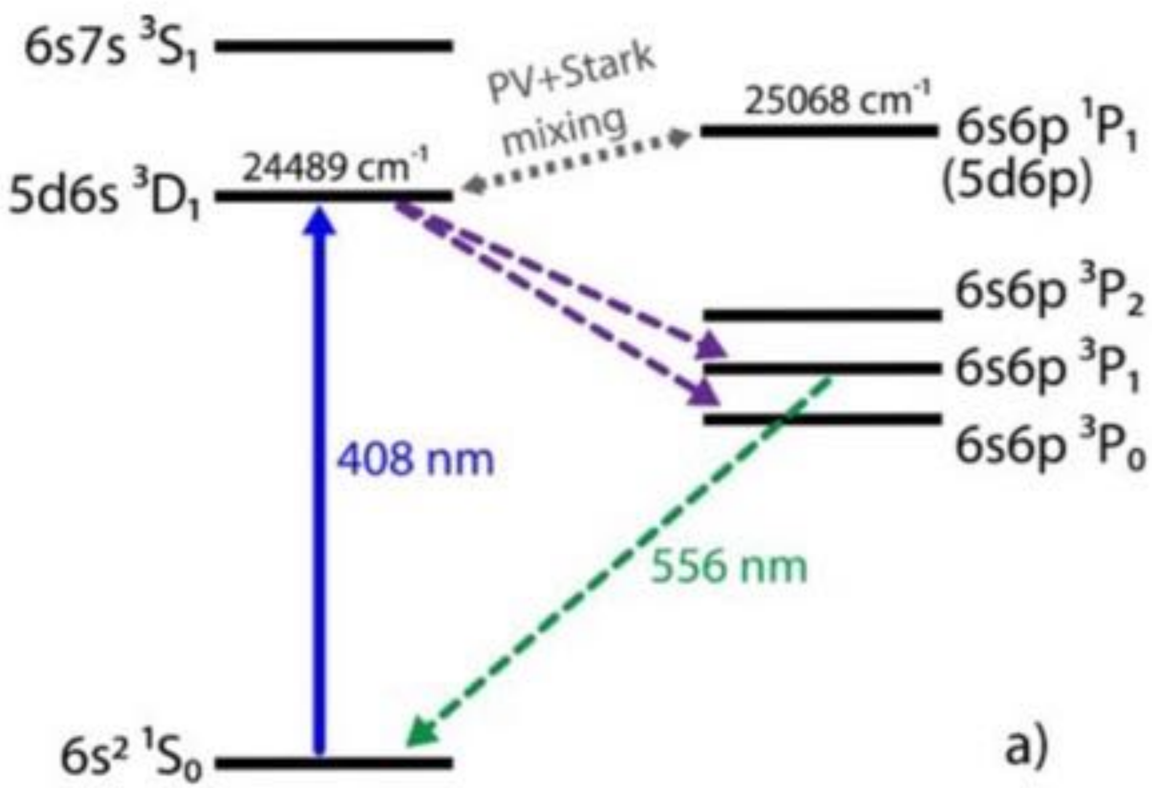


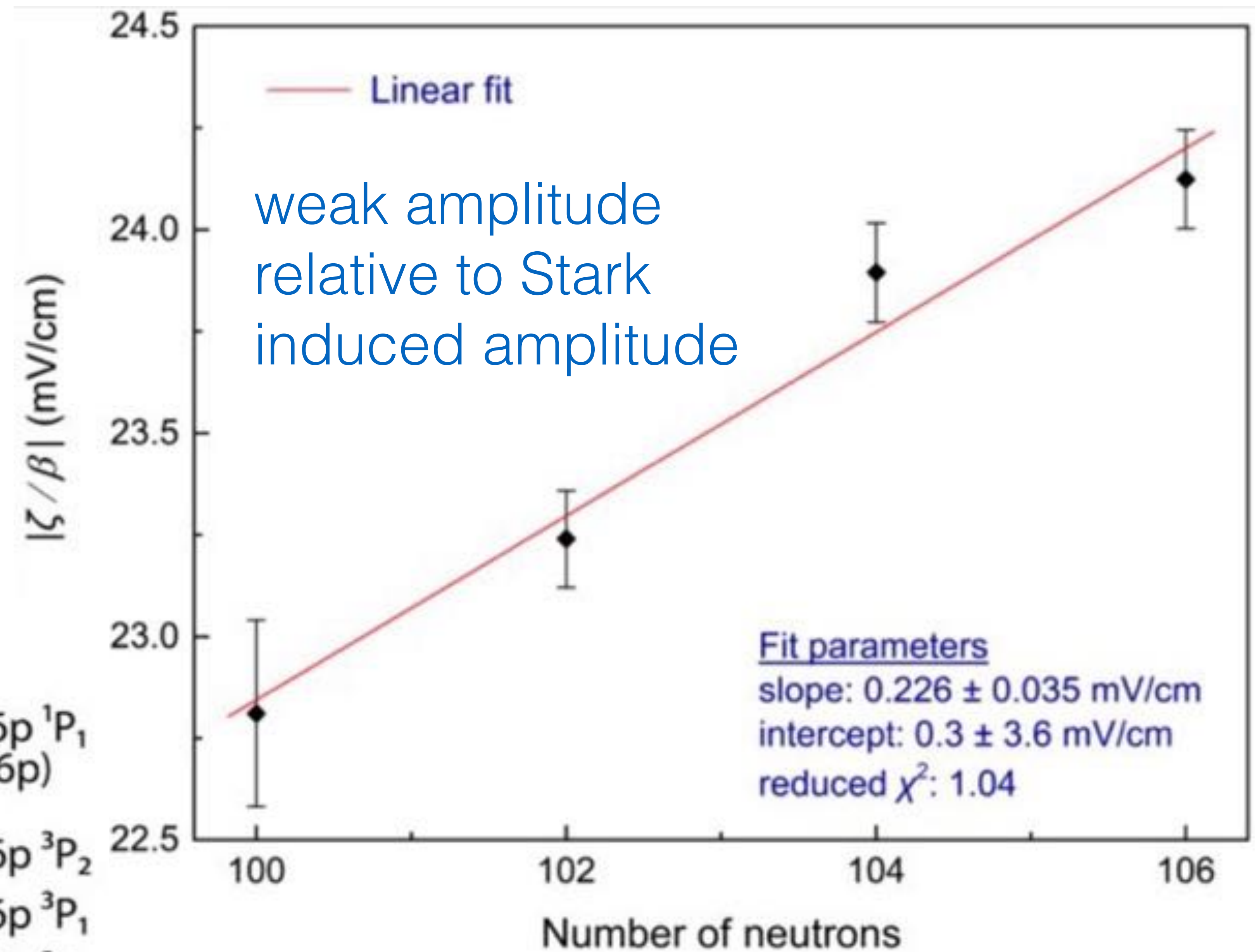
$$\overline{|6s\rangle} = |6s + \epsilon p\rangle$$

Finally, new stuff is happening! Mainz/Berkeley group

Antypas et al.
arXiv:1804.05747

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.

Why Cs? Not particularly heavy...

It's the heaviest, stable 'simple atom'

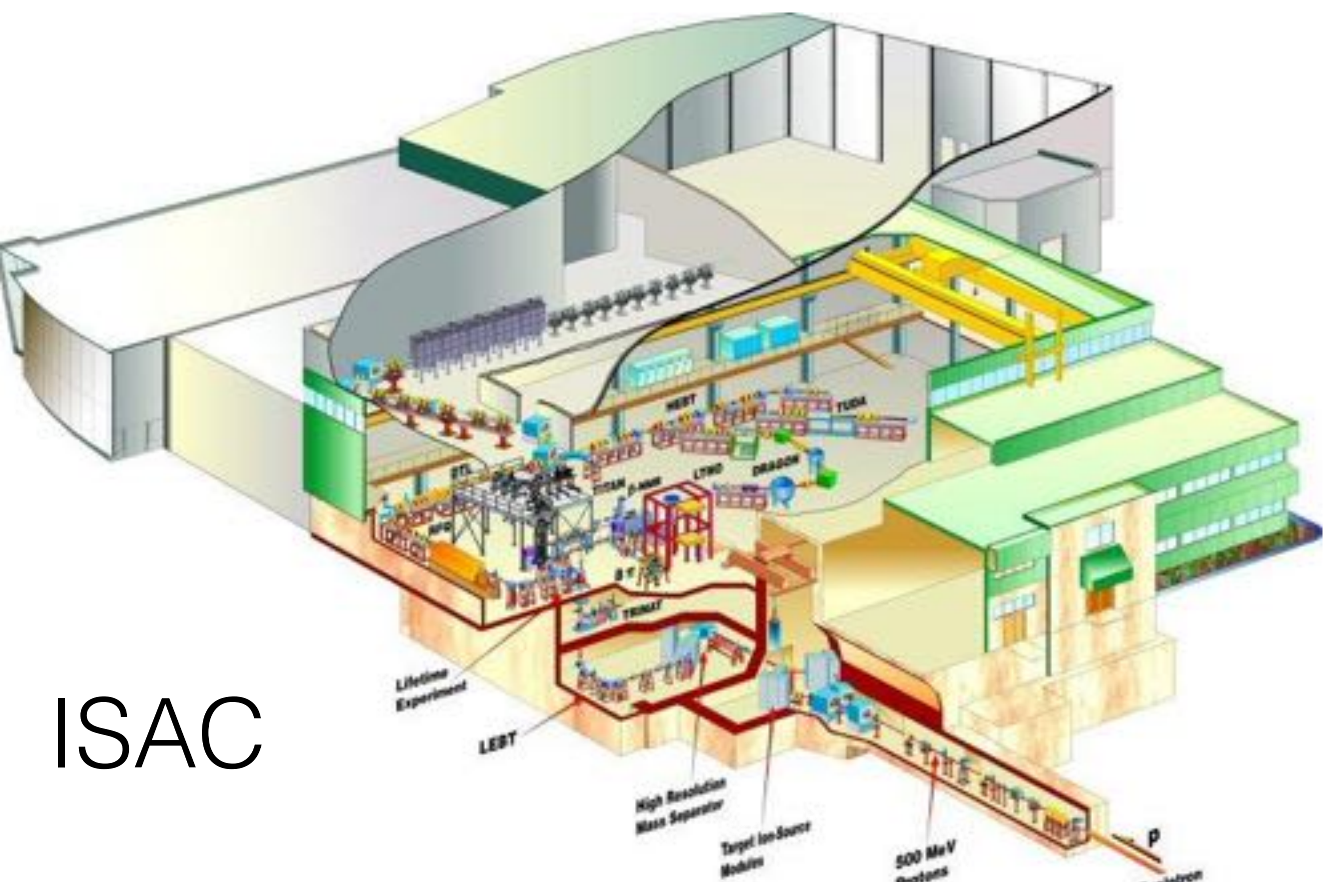
Precise experiments in Tl (and Bi, Pb) have been limited by their more complicated atomic structure

Use francium (Z=87)

atomic structure (theory) understood at the same level as in Cs

APNC effect 18 x larger!

Problem: no stable isotope

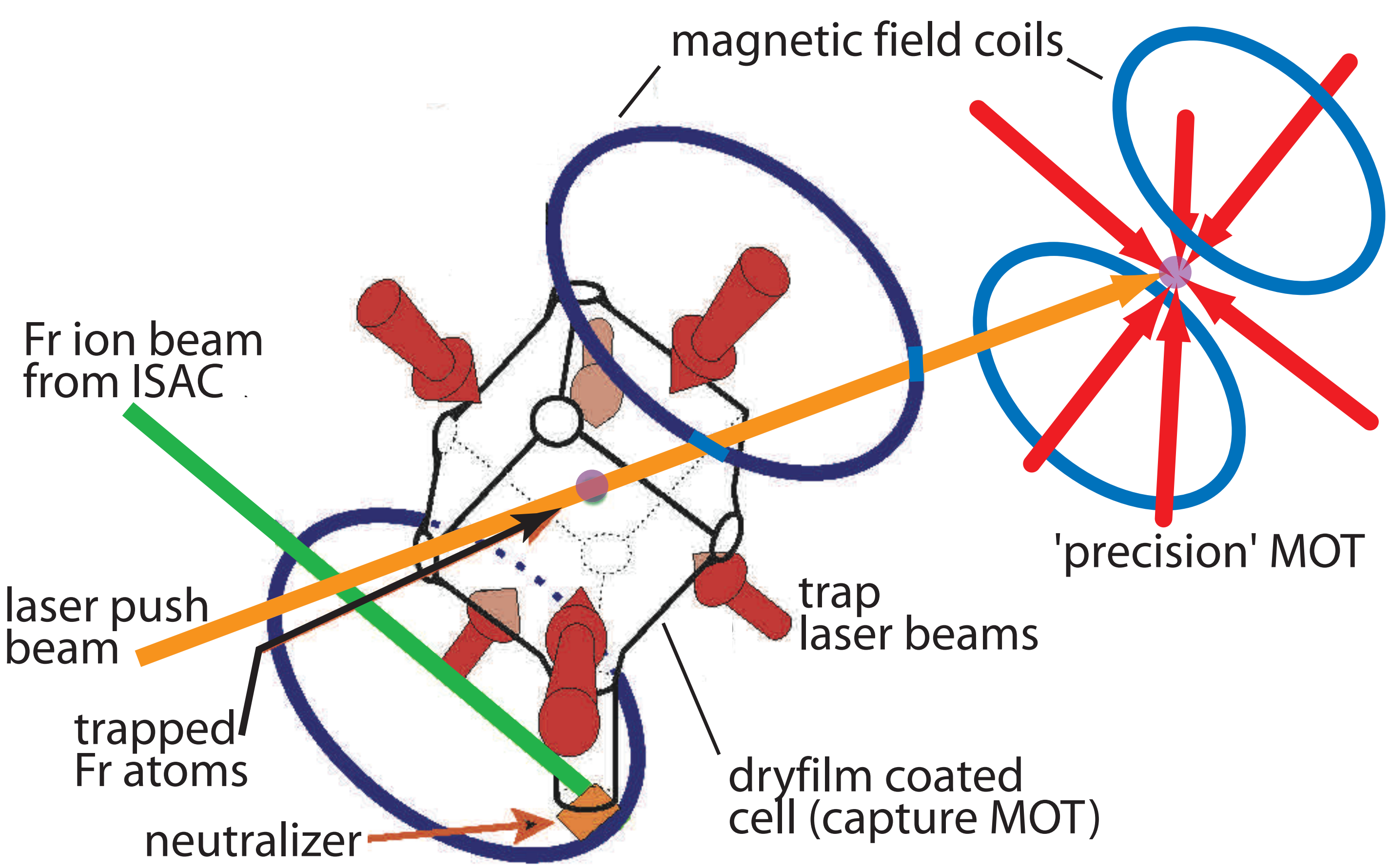


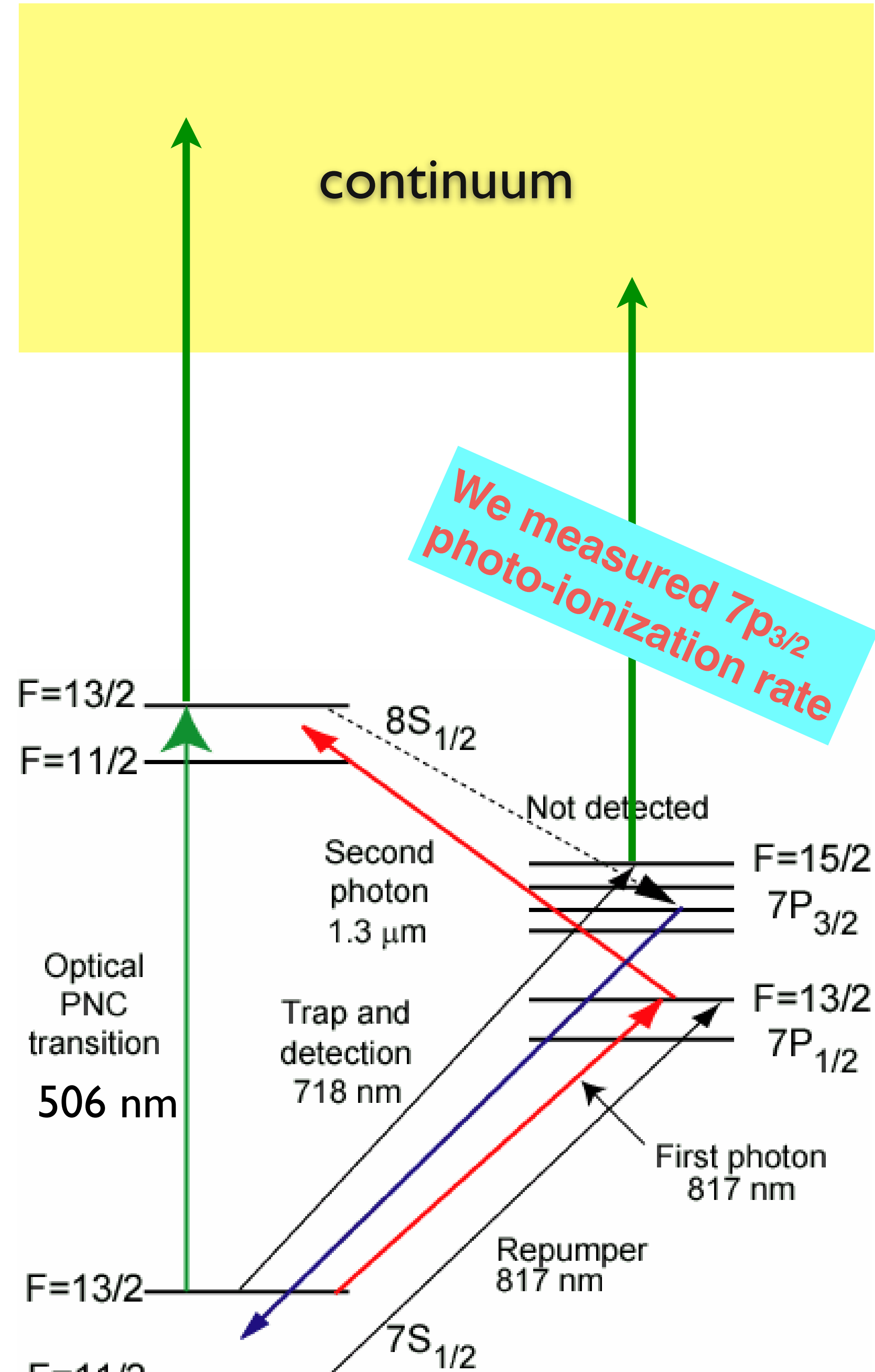
ISAC

A Francium APNC Experiment at TRIUMF

Boulder Cs: massive atomic beam
(10^{13} s^{-1} cm^{-2})
key figure: 10^{10} 6s-7s excitations /sec

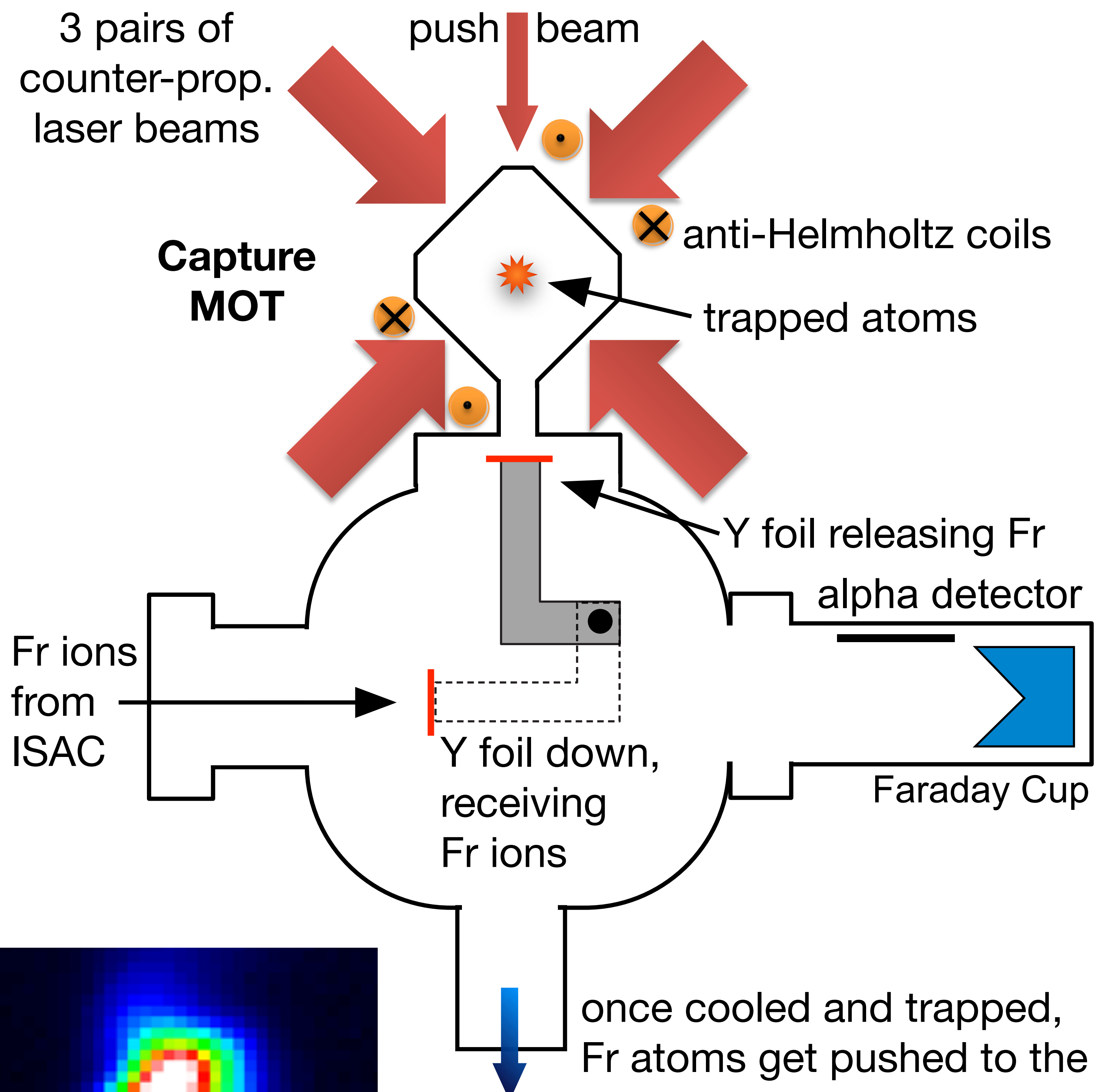
Fr trap:
excitation rate per atom: 30 s^{-1}
but asymmetry 18x larger
APNC possible with 10^6 - 10^7 atoms!

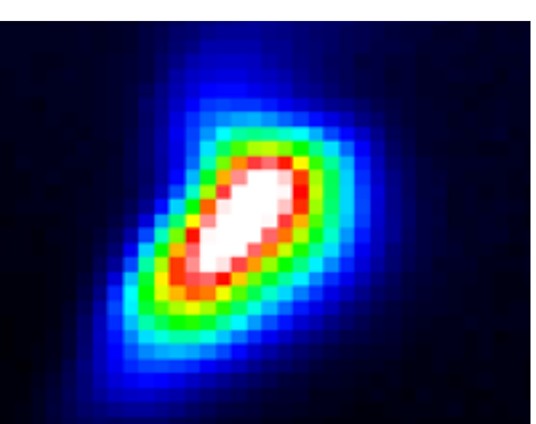




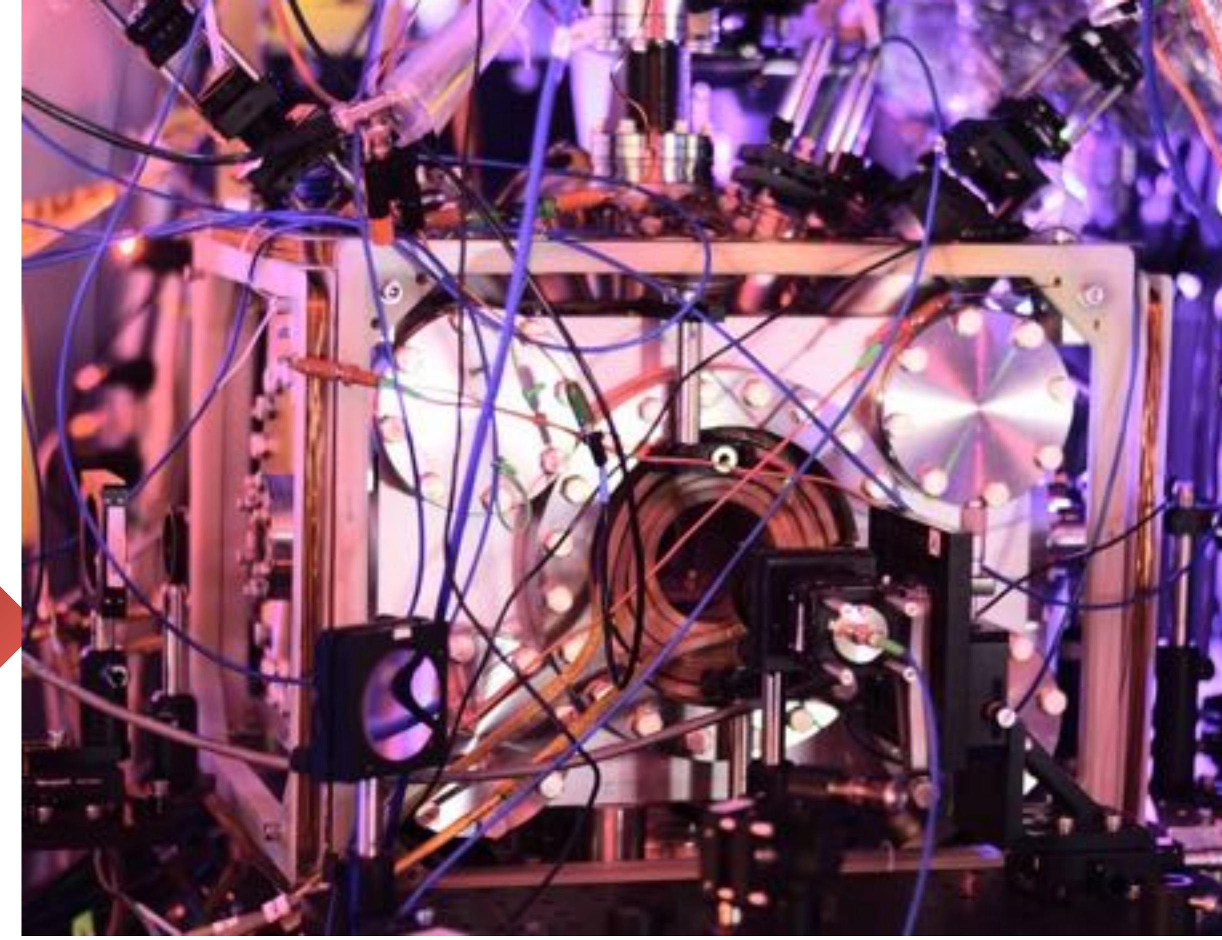
The Francium Trapping Facility at TRIUMF/ISAC

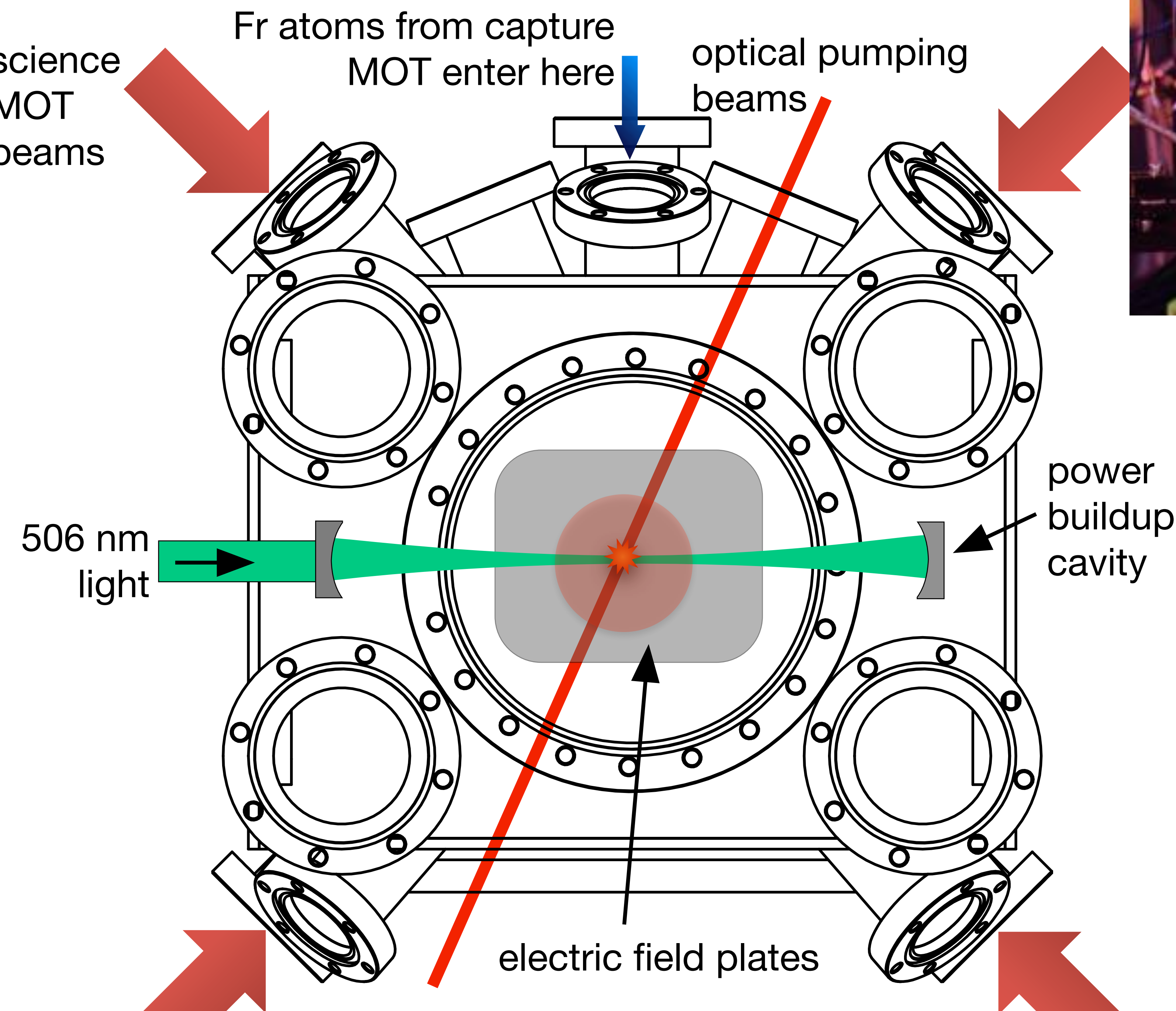
part 1: online capt





Science chamber





Science chamber

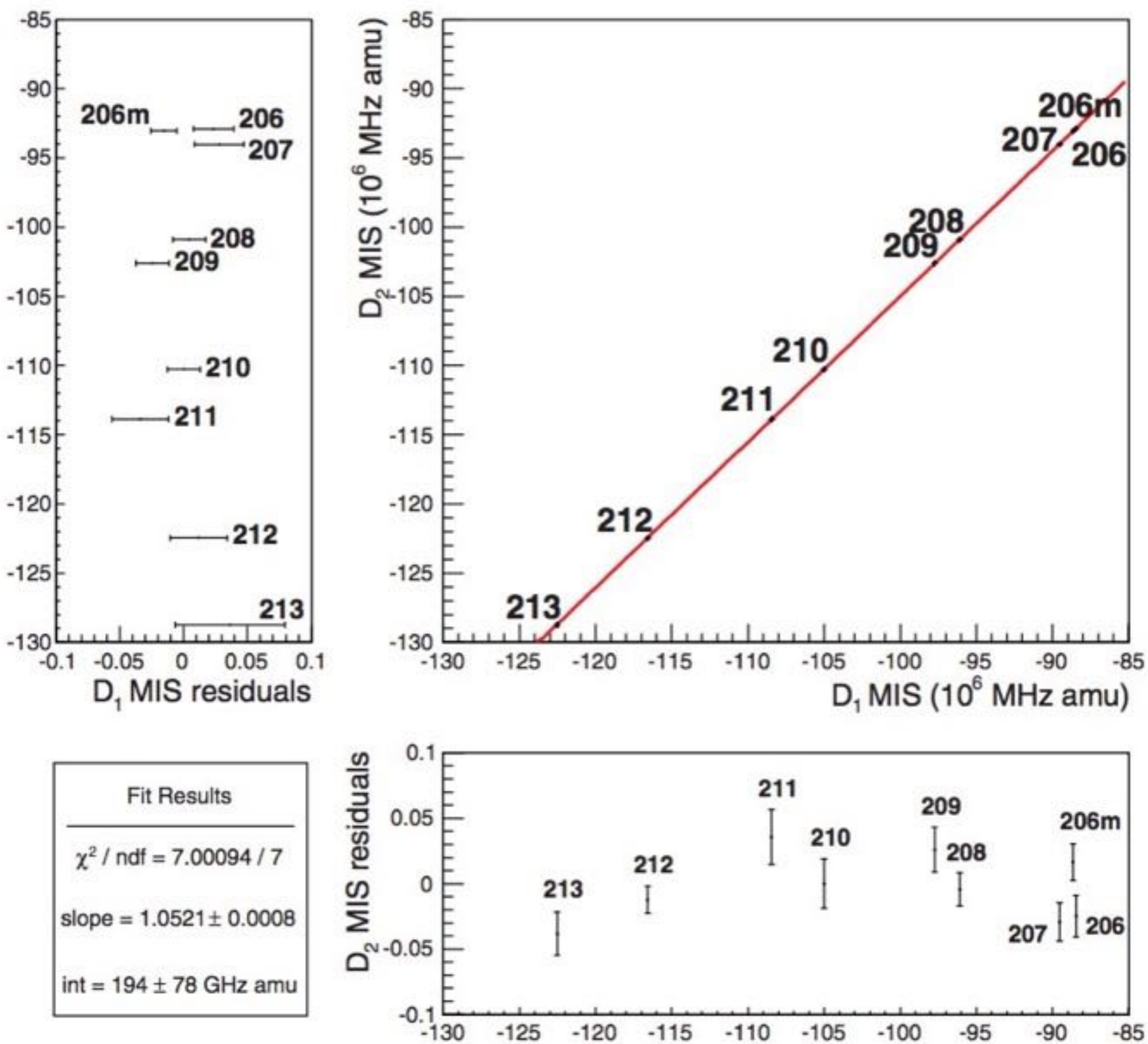
transparent field plates

operate APV experiment inside MOT

UHV-compatible power buildup cavity (1000x)

D1 isotope shifts in a string of light francium isotopes

Collister et al., Phys Rev A 90, 052502 (2014) and A **92**, 019902(E) (2015)

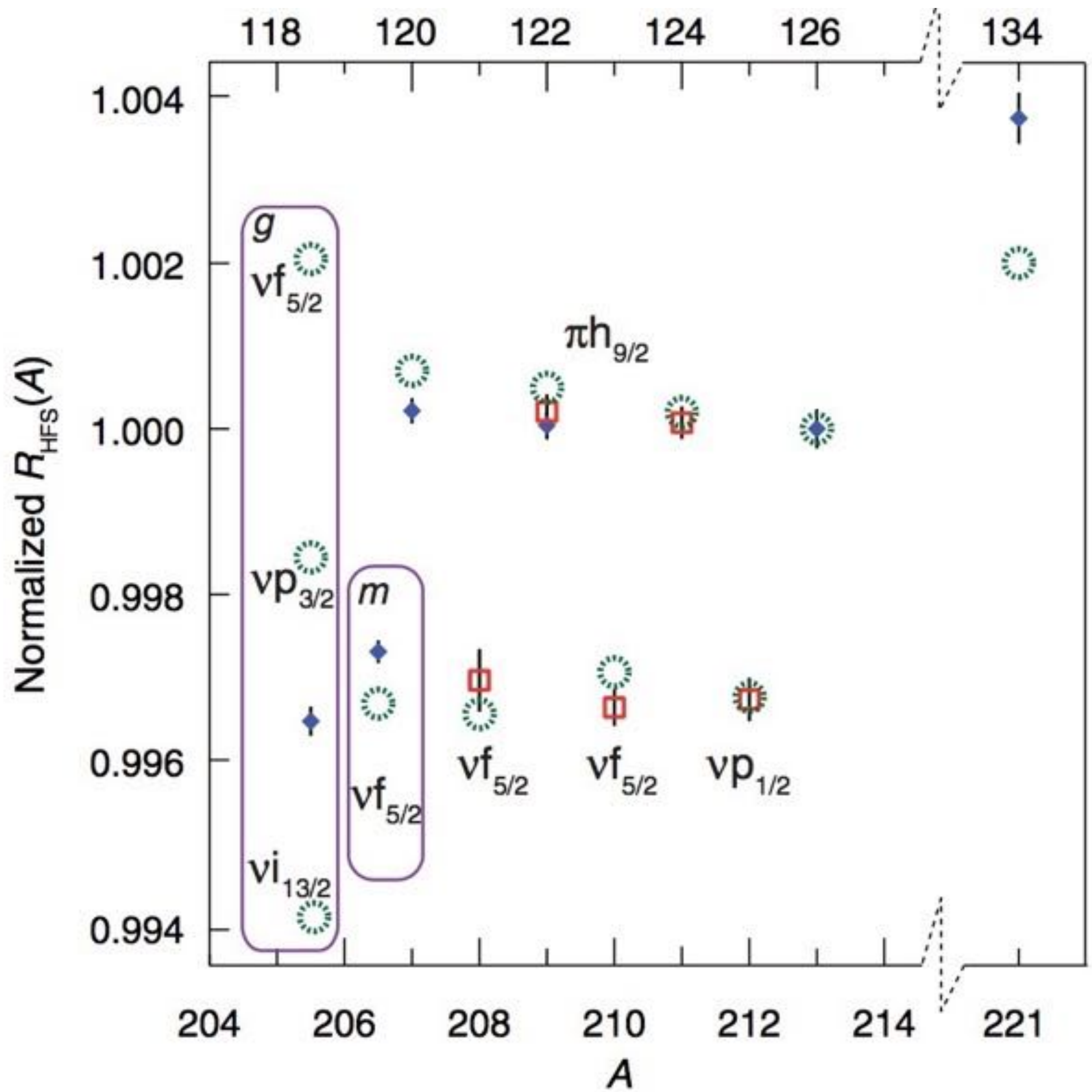


Benchmarks state-of-the-art atomic theory in Fr by Safranova and others.

offline ref.

Hyperfine anomaly in light francium isotopes

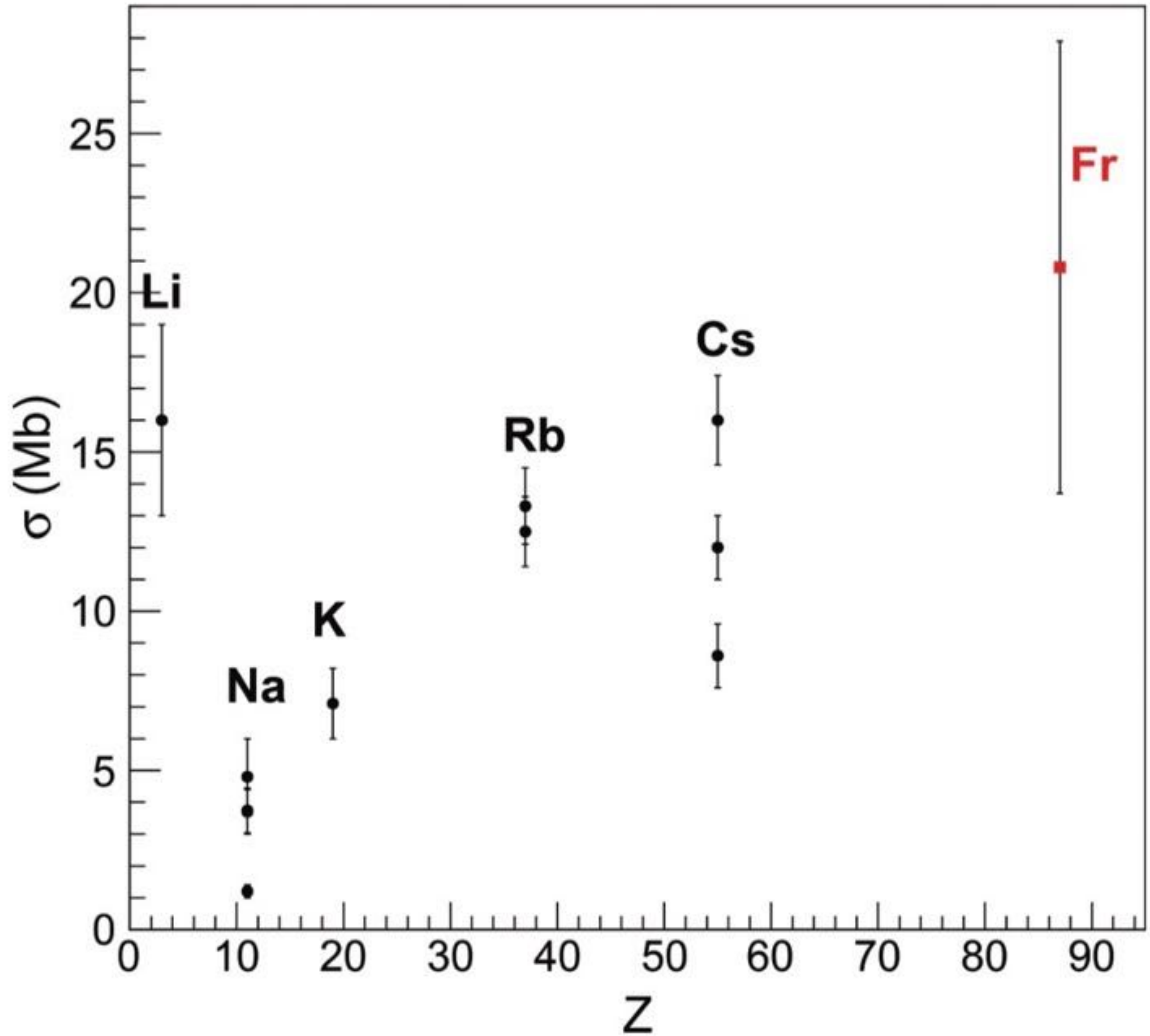
Zhang et al., Phys Rev Lett 115, 042501 (2015)



Reconfirms that in terms of nuclear structure, 208-213 are "good" nuclei for APNC/ anapoles

offline ref.

Francium $7p_{3/2}$ photoionization — Collister et al. 2017, Can J Phys



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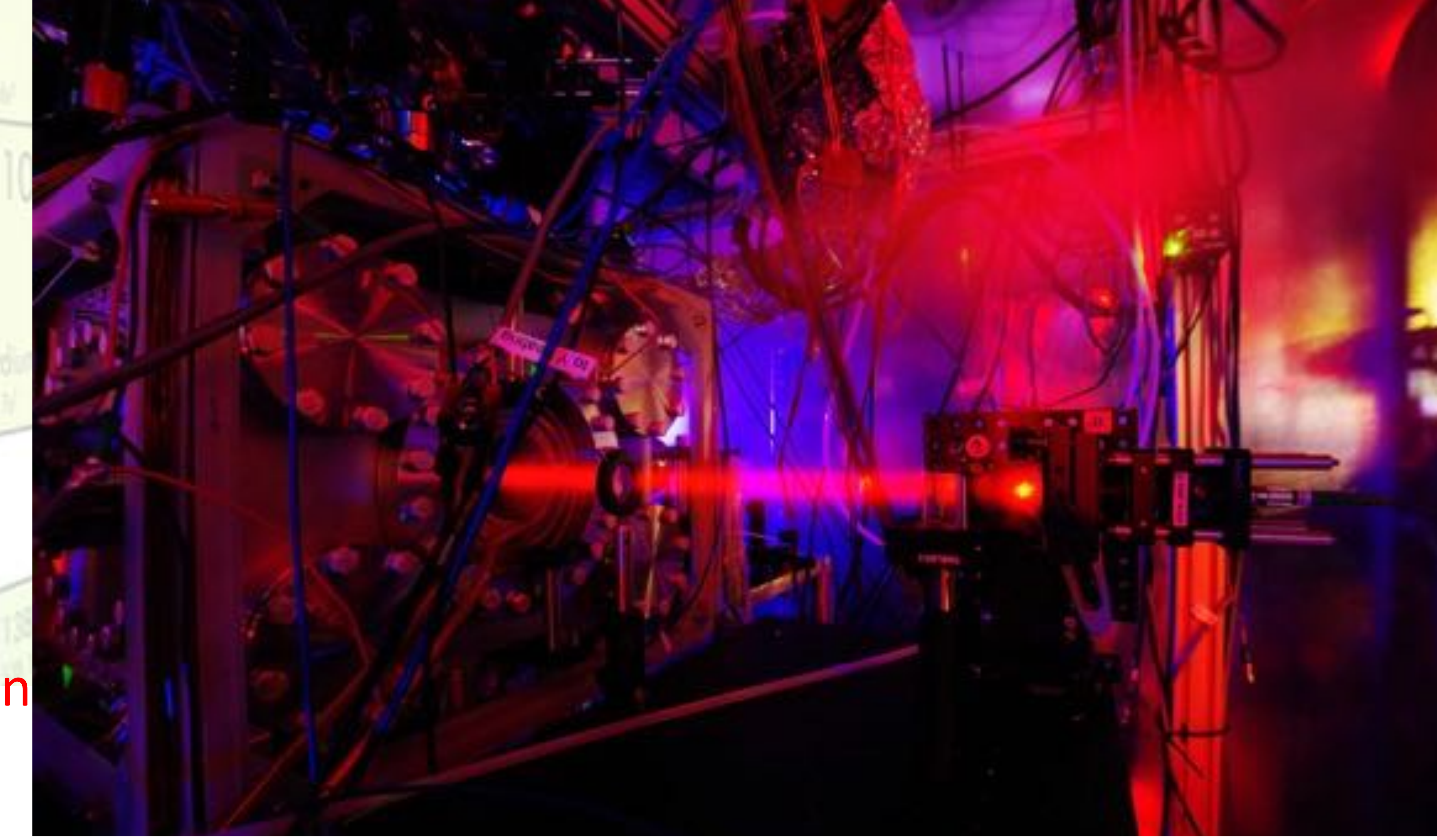
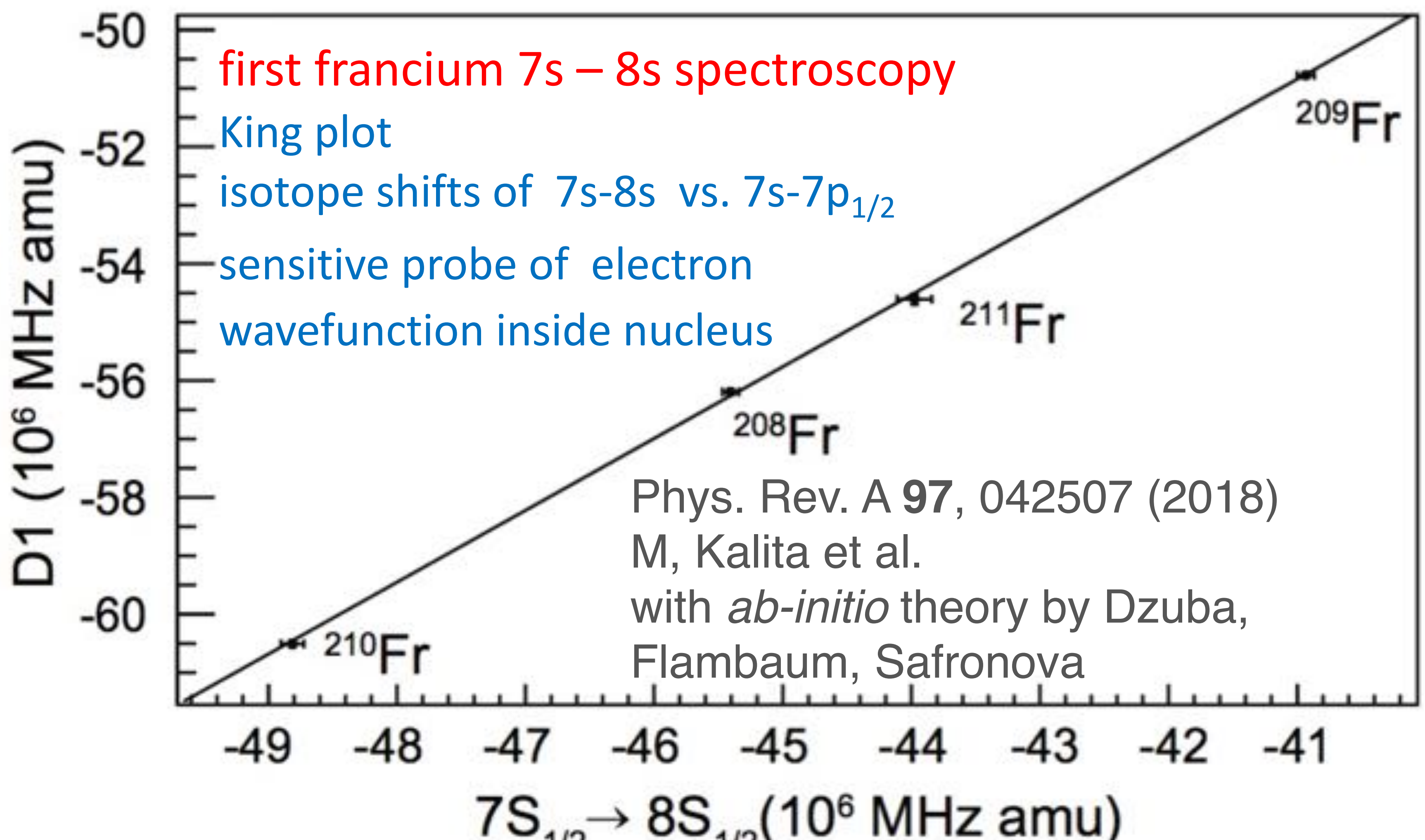


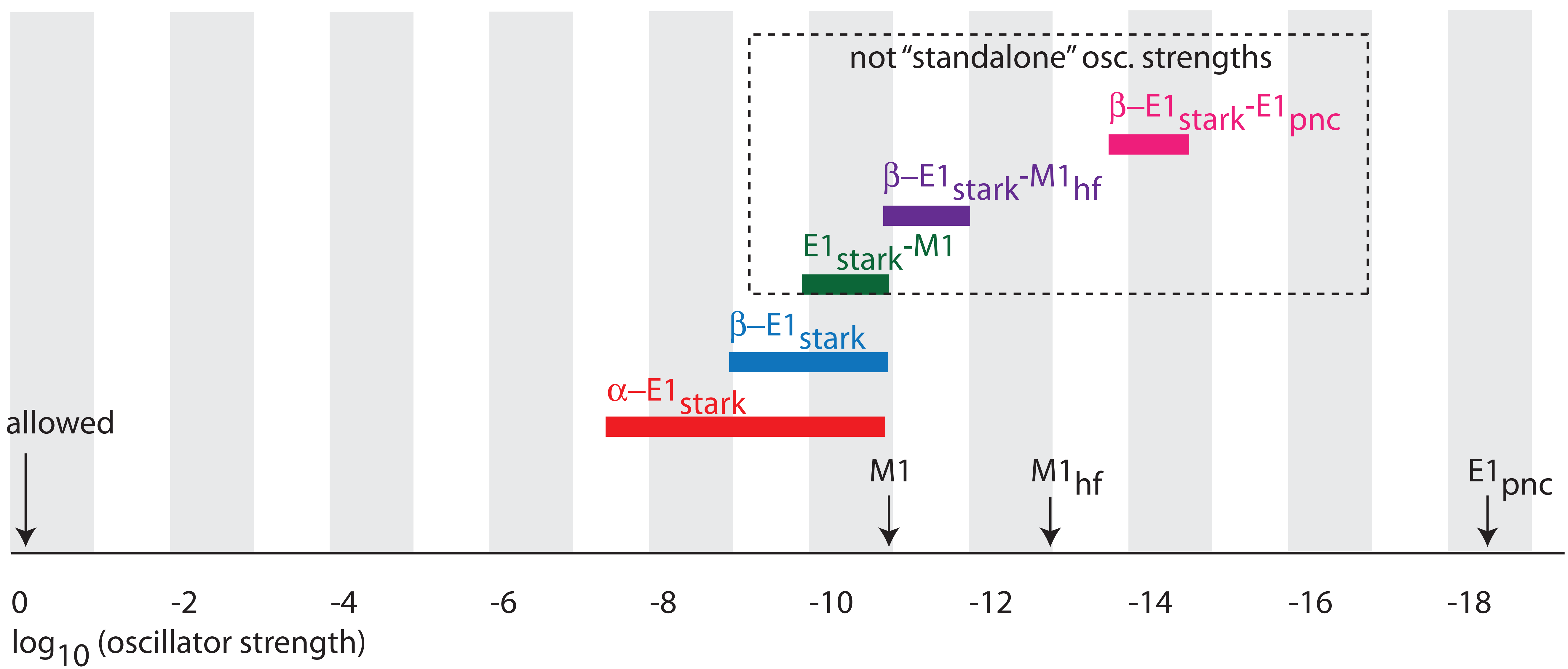
system now ready for
7s-8s spectroscopy campaign
towards APNC

built ultra-stable (10^{-10} level) reference cavity for 7s-8s spectr.



The next steps

- 7s-8s Stark spectroscopy is now ready to start
- Over 3 years, expect to work our way down towards detecting the APV amplitude



A Fr APNC experiment at TRIUMF

- data collection time (purely statistical, no duty factor)
  - 10^6 trapped atoms, 1.0% APNC: 2.3 hours
  - 10^7 trapped atoms, 0.1% APNC: 23 hours

➡But: most of the time needs to be spent on systematics.

- 1% neutron radius measurement in ^{208}Pb with PREX would put a 0.2 % uncertainty on Q_w in ^{212}Fr (Sil 2005)
- atomic theory similar to Cs, progress in this direction required to go beyond Wood et al.
- can expect that all aspects improve over time (already happening: new Cs (alkali) APNC calculations, Porsev 2009, Dzuba 2012)

A curiosity in francium: The nuclear charge radius is not experimentally known

also case in Po, At, Rn, Ra, Ac …

Can now do *ab-initio* calculations of 2s - 2p (x-ray and VUV) transitions in Li-like heavy elements to determine nuclear charge radius to 0.01 fm.
A. Senchuk, PhD Manitoba, publication in preparation

Currently no EBIT at radioactive beam facility that can charge-breed them.

However, Na-like ions might offer an initial path
Gillaspy et al. PRA 87, 062503 (2013)
NIST-MSU-Clemson-Manitoba collab.

Alt-Fact: This is the glow of a million francium atoms

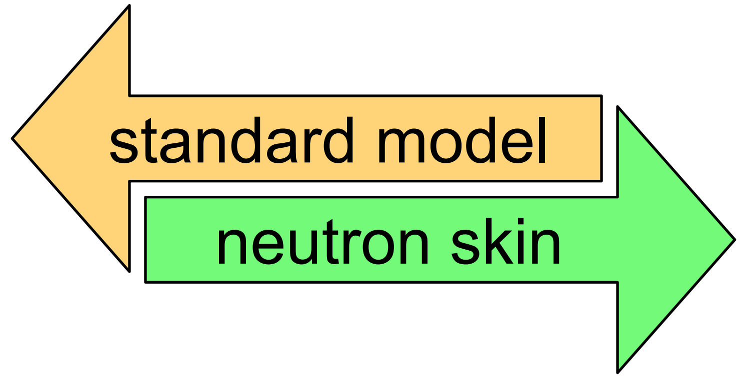
Manitoba: A. DeHart, T. Hucko, M. Kossin, A. Senchuk, GG, R. Collister

TRIUMF: J. Behr, A. Gorelov, M. Kalita, M. Pearson, M. Tandecki

L. Orozco, J. Zhang (Maryland), S. Aubin (William & Mary), E. Gomez (San Luis Potosi)

Photo: M. Kossin

parity violation in lead

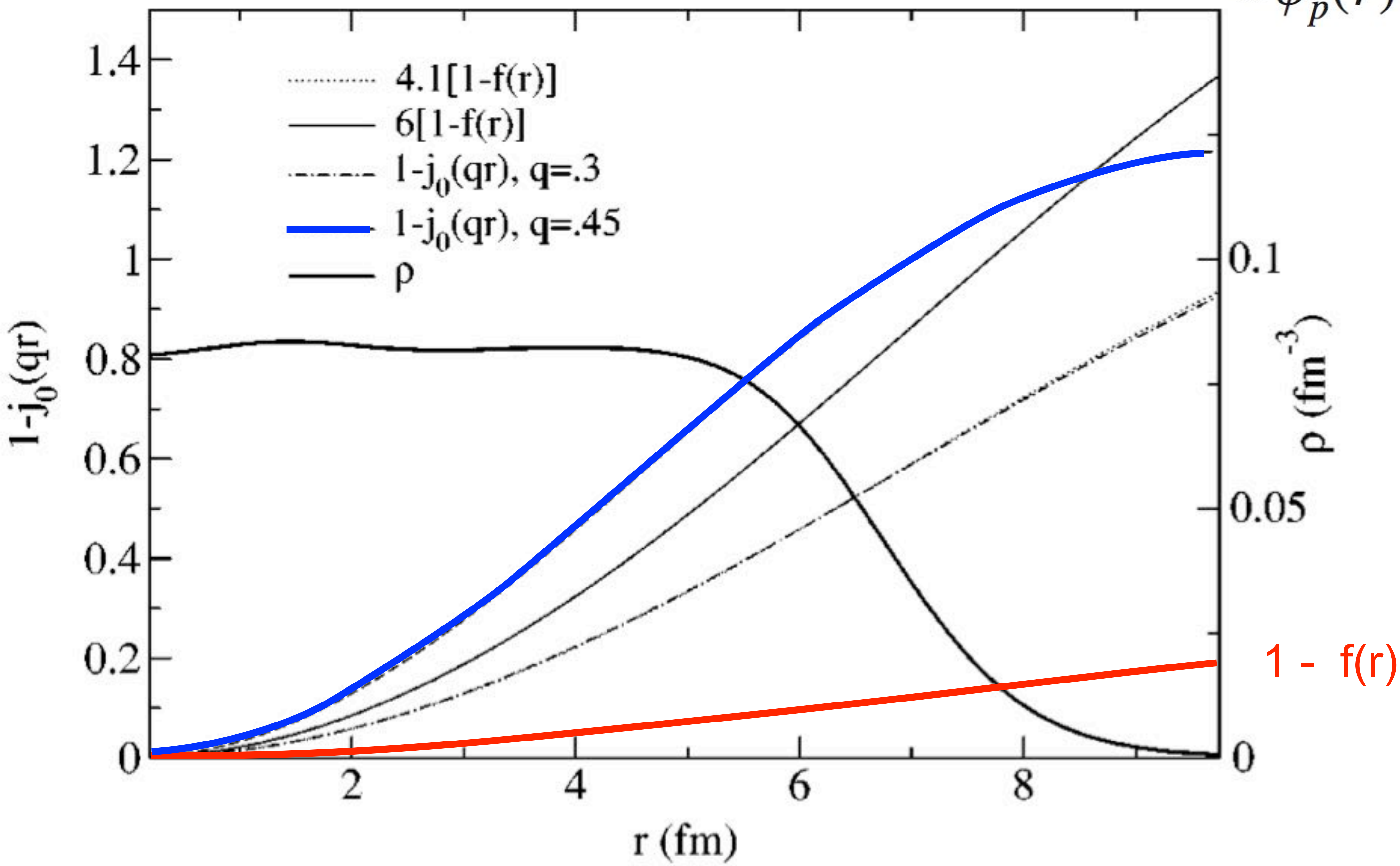


parity violation in francium

$$F_n(Q^2) = \frac{1}{4\pi}\int d^3r\, j_0(qr)\rho_n(r)$$

$$q_n = \int f(r)\rho_n(r)\, d^3r$$

$$\propto \psi_p^\dagger(r)\,\gamma_5\,\psi_s(r)$$



C. J. Horowitz, S. J. Pollock, P. A. Souder and R. Michaels, PRC 63 025501 (2001)