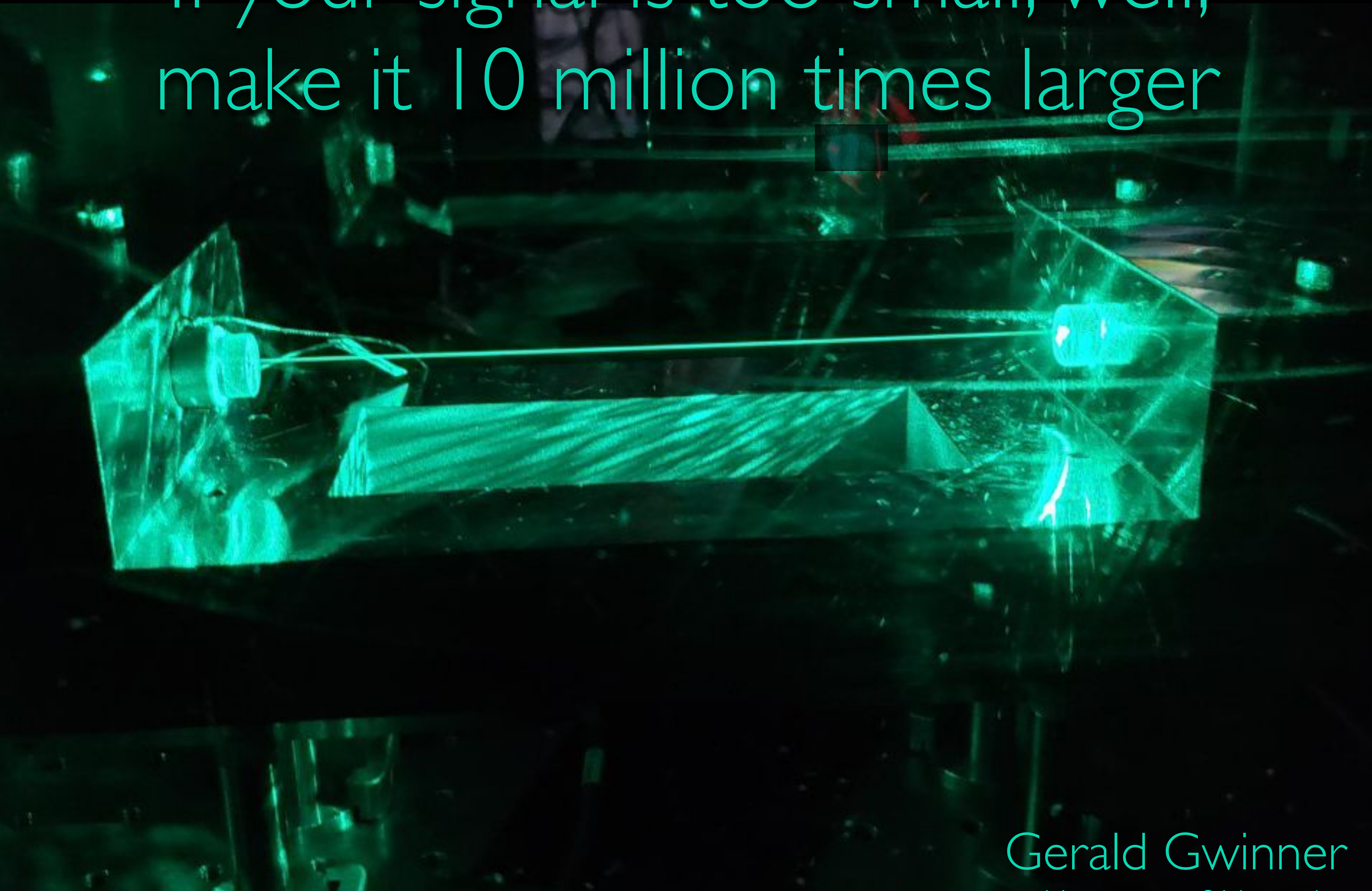
If your signal is too small, well, make it 10 million times larger



Gerald Gwinner
University of Manitoba

Photo by former PhD student Tim Hucko

Jos signaalisi on liian pieni, tee siitä 10 miljoonaa kertaa suurempi

Jyväskylä

Mean daily minimum °C (°F)	−10.9 (12.4)	−11.5 (11.3)	−8.1 (17.4)	−2.4 (27.7)	2.8 (37.0)	8.2 (46.8)	11.2 (52.2)	9.5 (49.1)	5.1 (41.2)	0.6 (33.1)	−3.2 (26.2)	−7.5 (18.5)	−0.5 (31.1)

Mean daily minimum °C (°F)	−13.5 (7.7)	−13.3 (8.1)	−9.1 (15.6)	−3.4 (25.9)	2.5 (36.5)	8.5 (47.3)	11.8 (53.2)	9.6 (49.3)	4.9 (40.8)	−1.3 (29.7)	−6.7 (19.9)	−10.6 (12.9)	−1.7 (28.9)

Rovaniemi

Mean daily minimum °C (°F)	−21.4 (−6.5)	−18.3 (−0.9)	−10.7 (12.7)	−2.0 (28.4)	4.5 (40.1)	10.7 (51.3)	13.5 (56.3)	12.1 (53.8)	6.4 (43.5)	−0.5 (31.1)	−9.2 (15.4)	−17.8 (0.0)	−2.7 (27.1)

Winnipeg

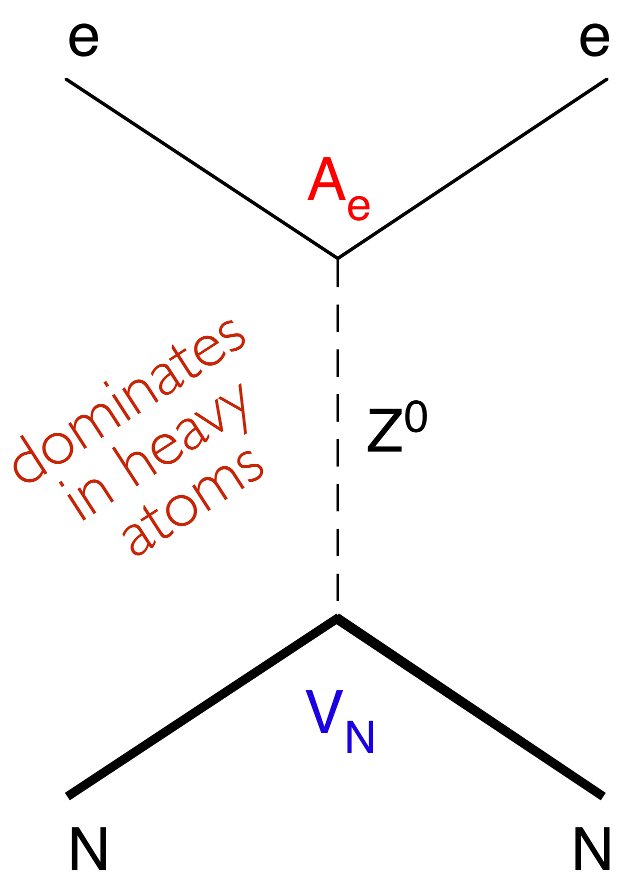
Gerald Gwinner
University of Manitoba

Photo by former PhD student Tim Hucko

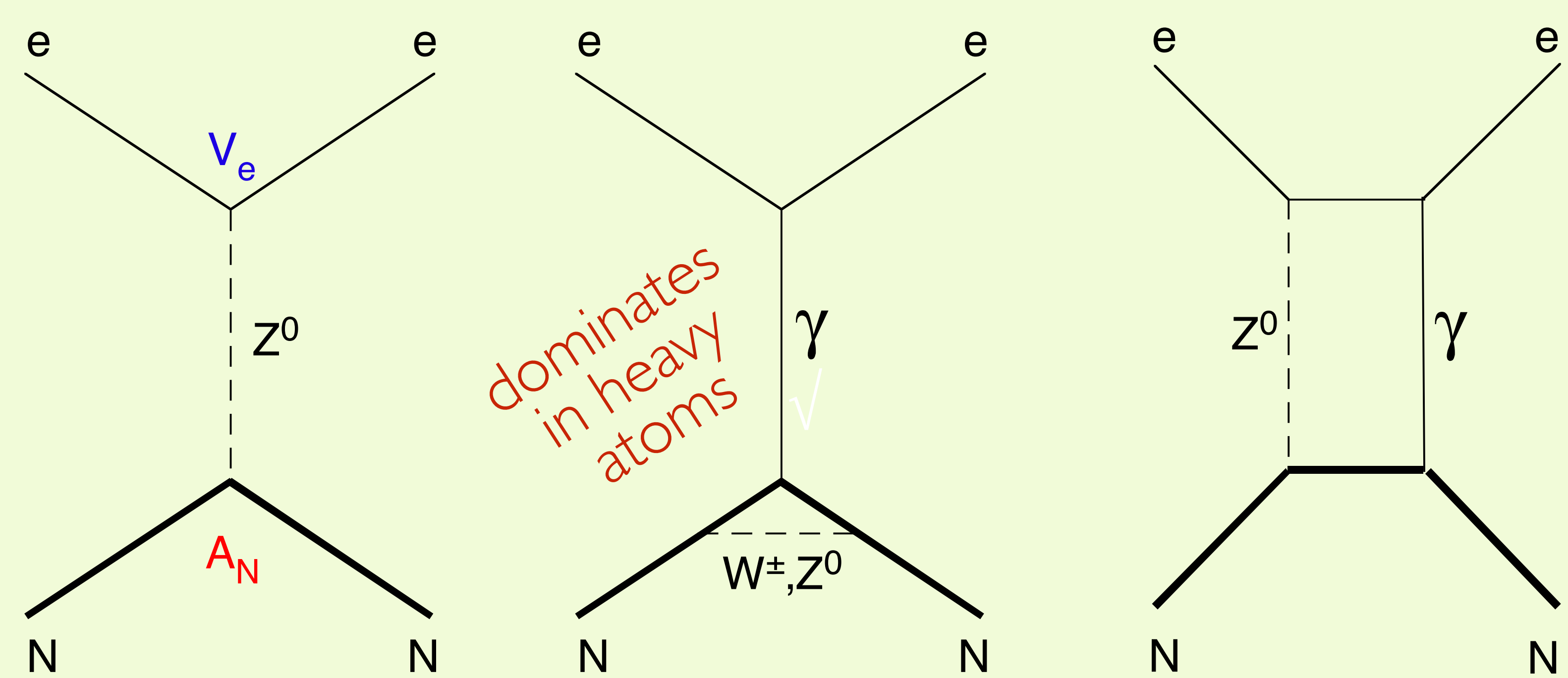
Atomic Parity Violation

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

Fermi constant → generic strength of weak interaction

weak interaction has "zero" range → electron must be in nucleus

$$H_{APV}^{NSI} = \frac{G_F}{2\sqrt{2}} \underbrace{\gamma_5}_{\propto Z^2} \delta(\mathbf{r}) \underbrace{Q_W}_{\propto N}$$

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

every serious formula needs this

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

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

- highly non-trivial in many-electron systems, requires state-of-art atomic structure theory
- **only feasible in hydrogen-like (alkali) systems currently**
- Cs (Wood, Boulder, 1997)
- **in Fr (Z=87) , APV effect is 18x larger**

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

test !

Standard Model:

$$\kappa_{1p} = \frac{1}{2}\left(1 - 4\sin^2\theta_W\right) \approx 0.024$$

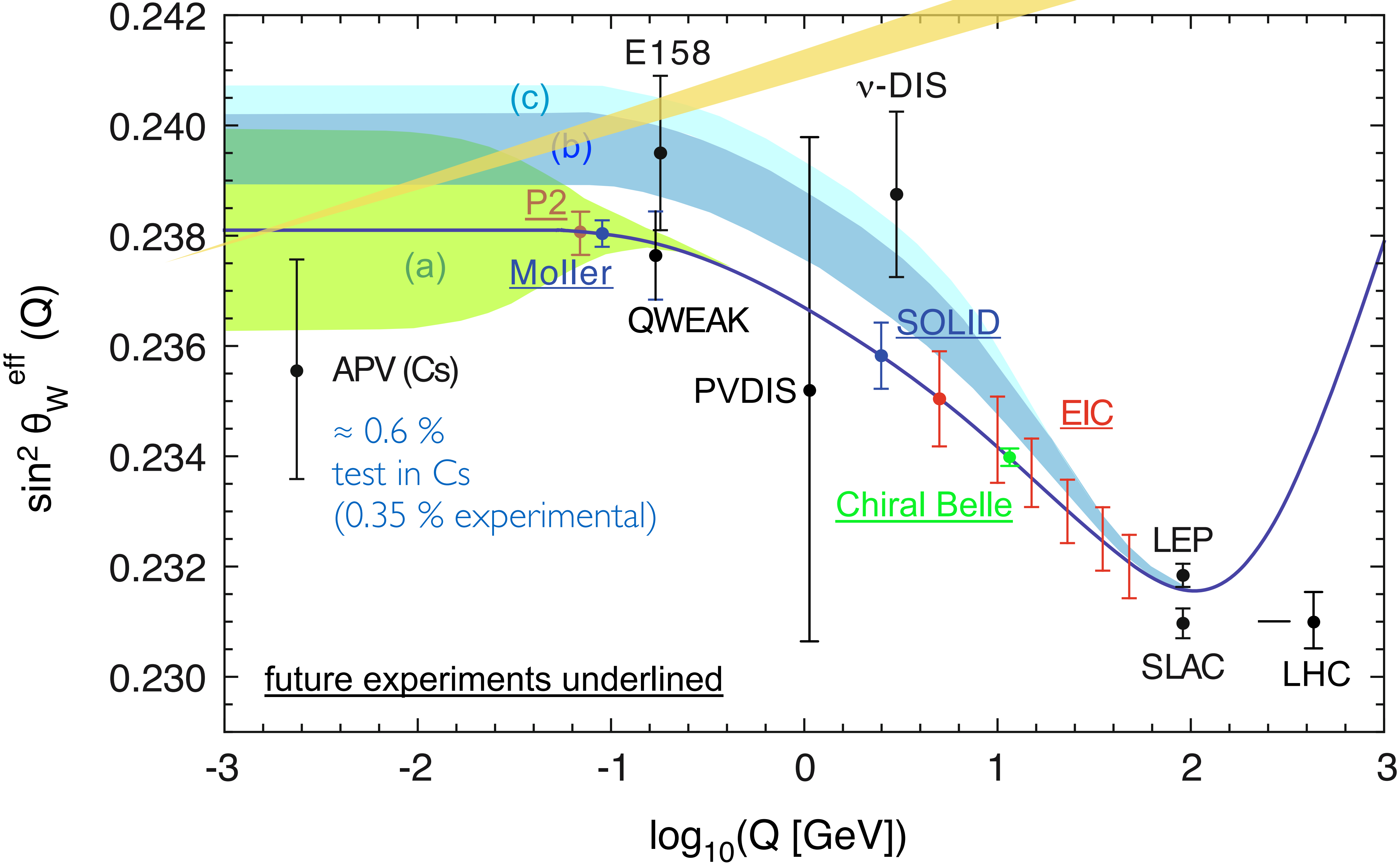
$$\kappa_{1n} = -\frac{1}{2} \quad \Rightarrow \quad Q_W^{APV} \approx N$$

for offline reference

Electroweak tests

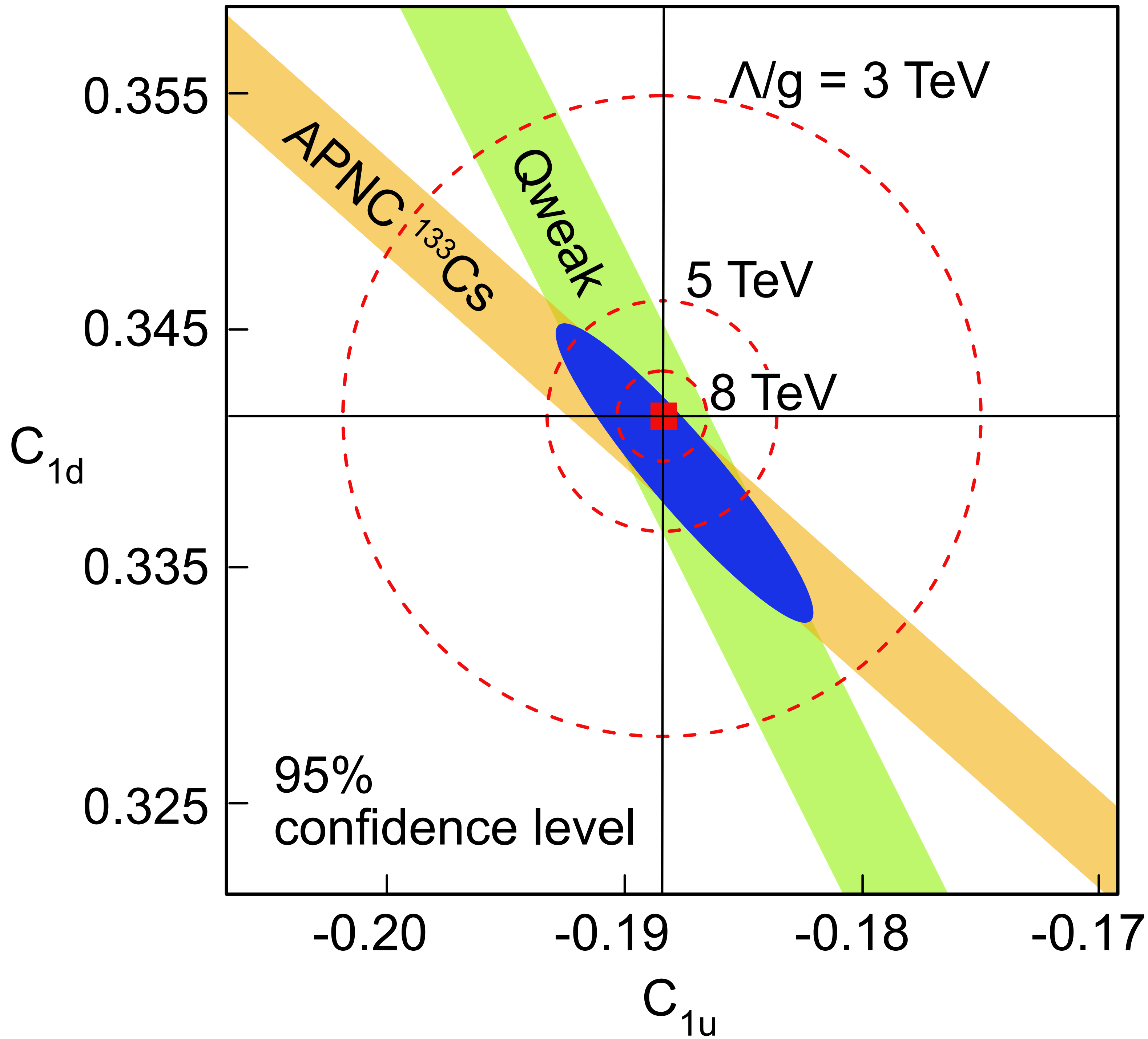
- The weak or Weinberg angle θ_W "runs" with momentum transfer
- APV is a unique test at very low momentum transfer

sensitivity to light dark bosons → low energy is good for something after all



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

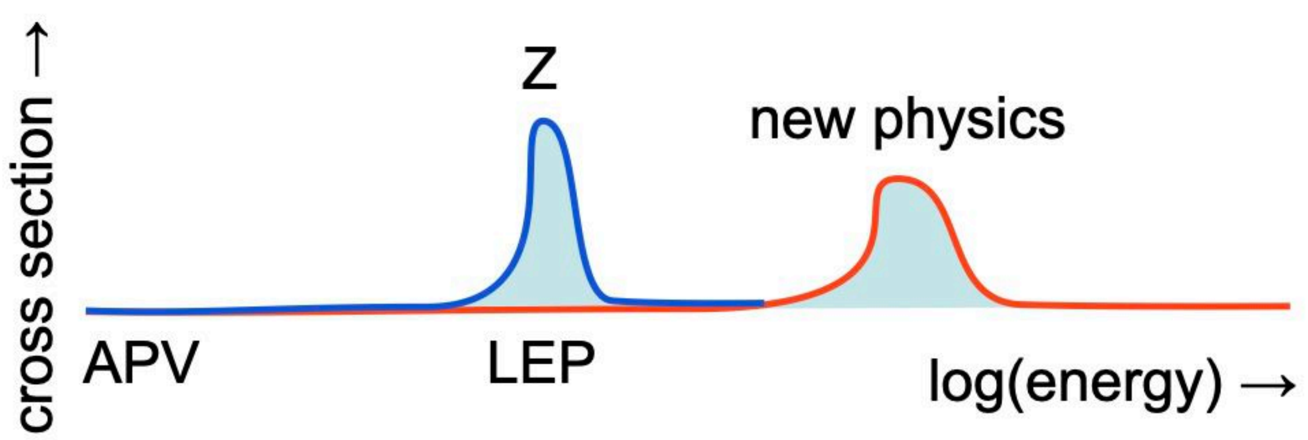
Physics sensitivity from contact interaction (LEP2 convention, g^2= 4pi)

	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

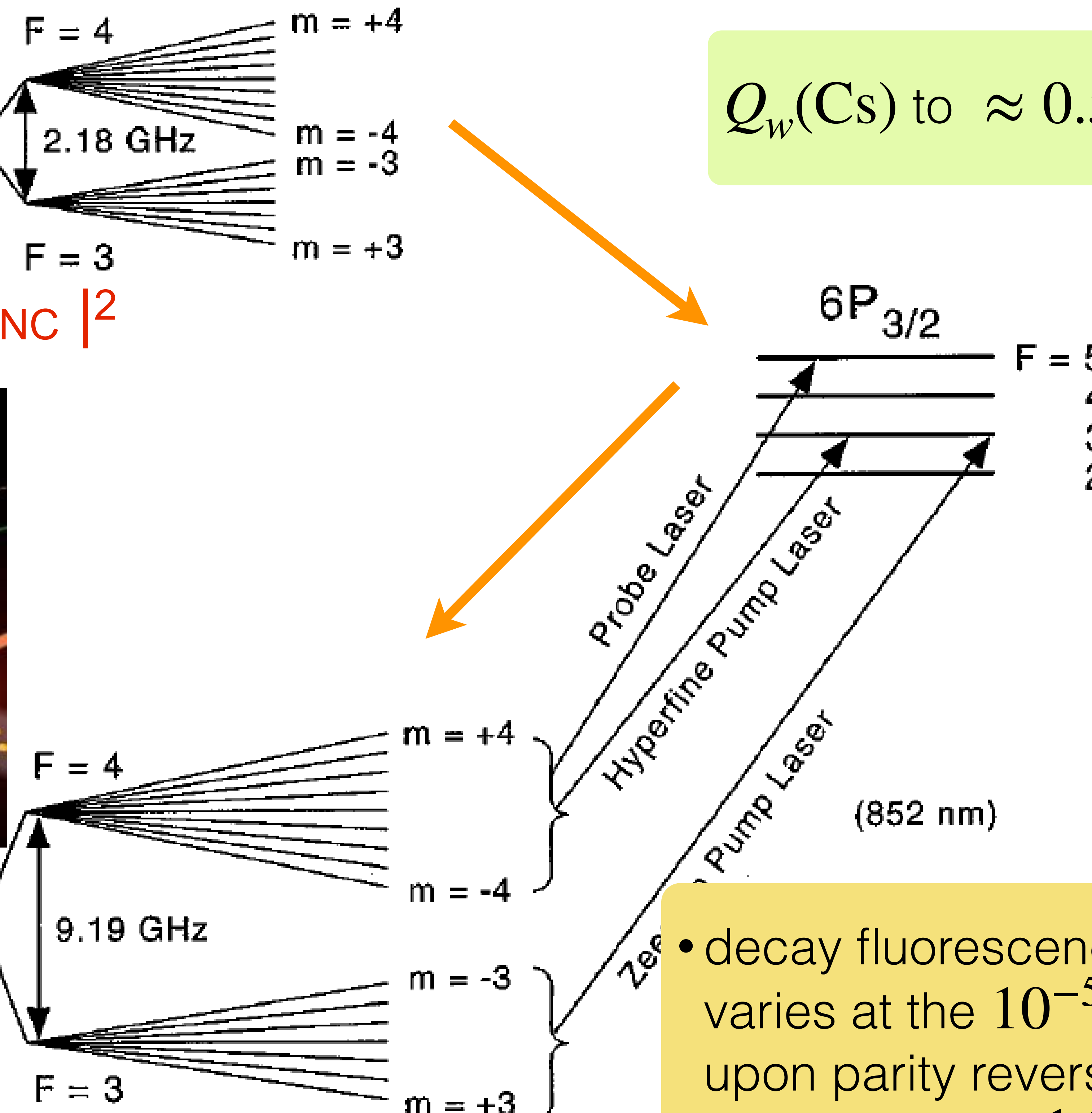


strong motivation to make progress on the APV front

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

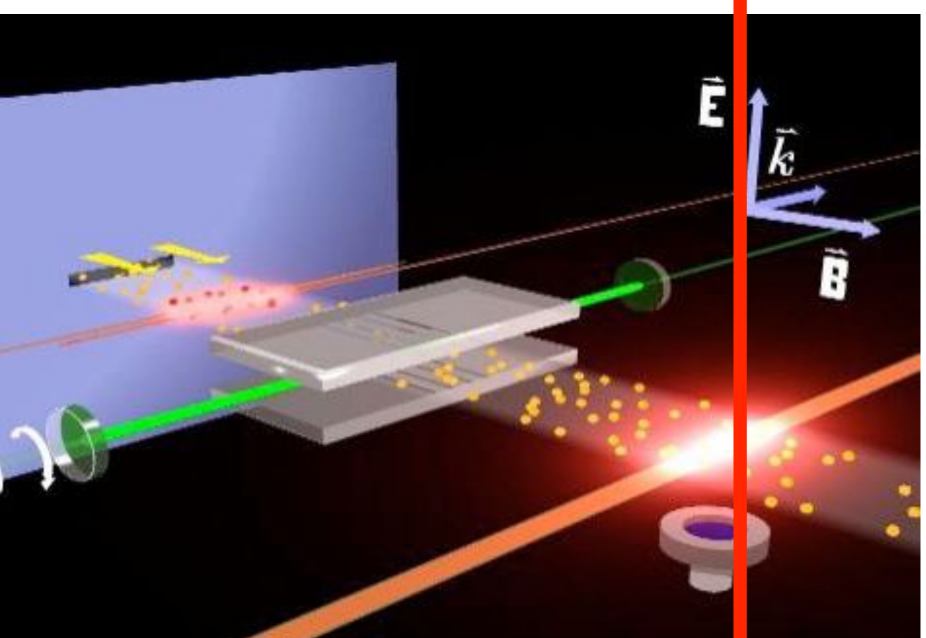
Bad news: The Cs experiment has been towering

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



$Q_w(\mathrm{Cs})$ to $\approx 0.5\,\%$

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

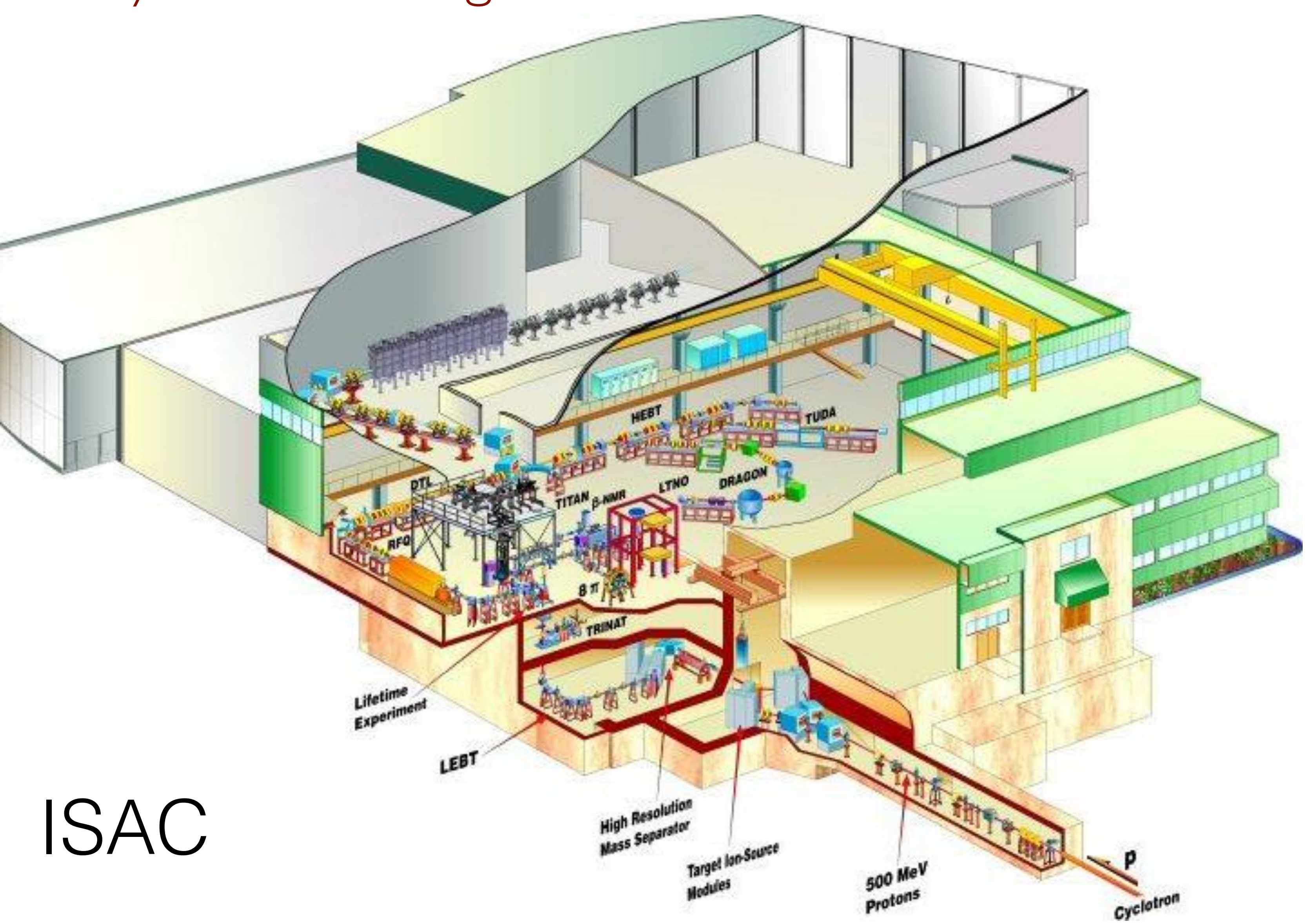


$\overline{|6s\rangle} = |6s + \epsilon p\rangle$

- decay fluorescence varies at the 10^{-5} level upon parity reversals
- measure to $< 1\,\%$

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



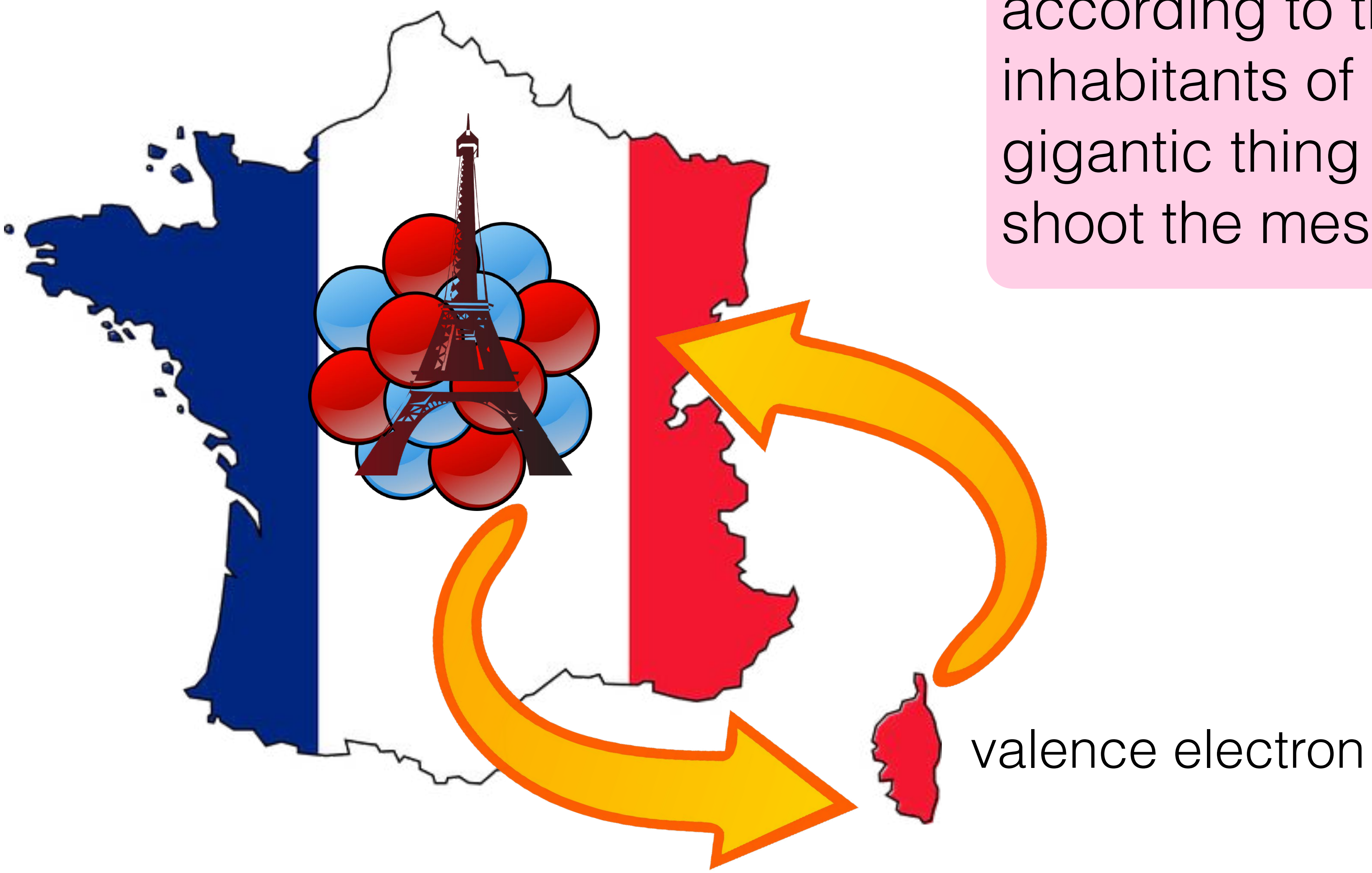
ISAC

Atomic parity violation in Fr

France and the Rutherford atom are very similar:

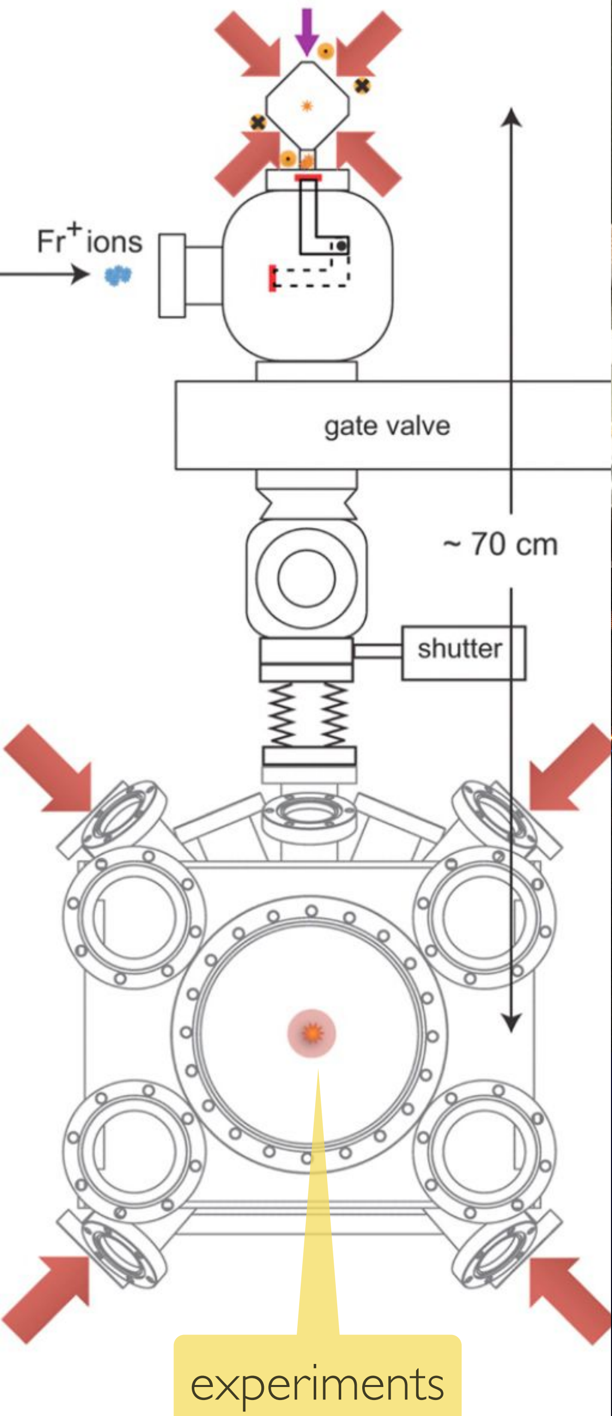
Gigantic thing in the middle and nothing worth mentioning around it

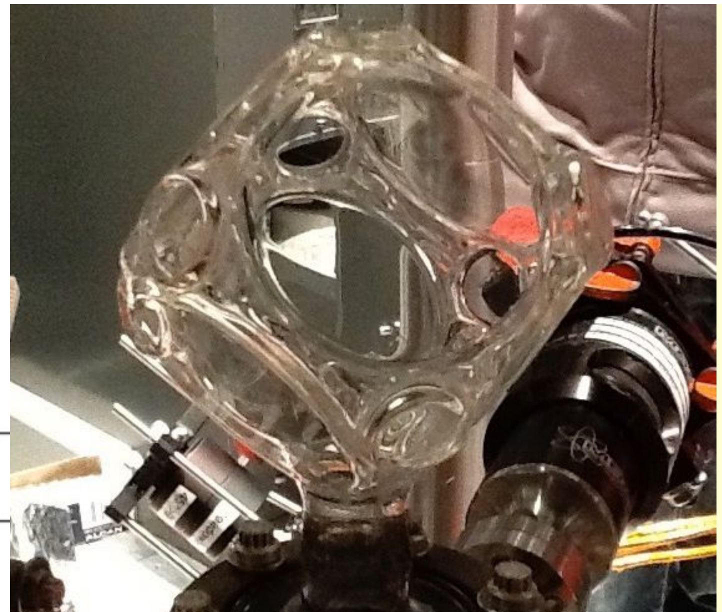
according to the inhabitants of the gigantic thing — don’t shoot the messenger

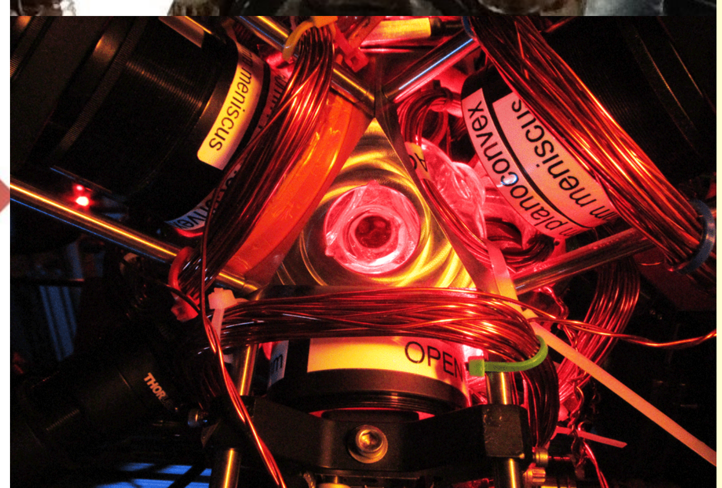


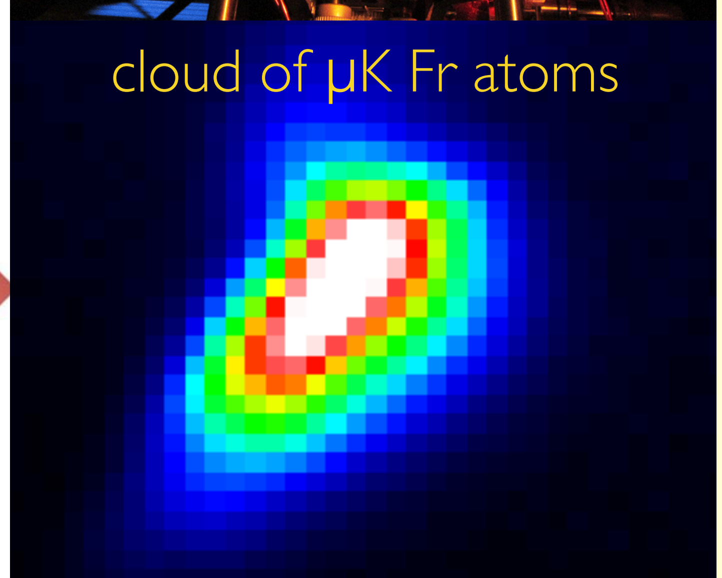
The Francium Trapping Facility at TRIUMF/ISAC

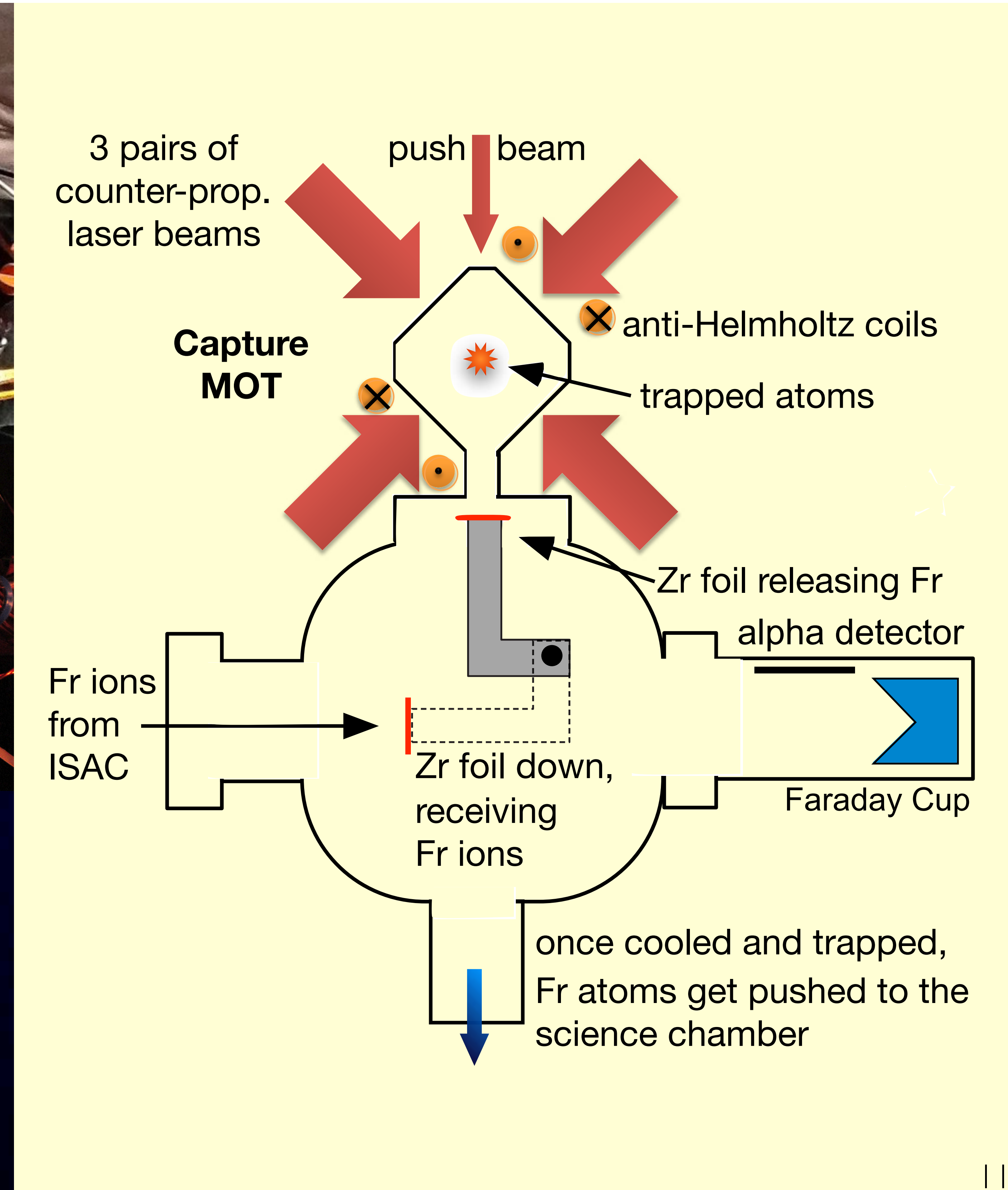
part 1: online capture trap



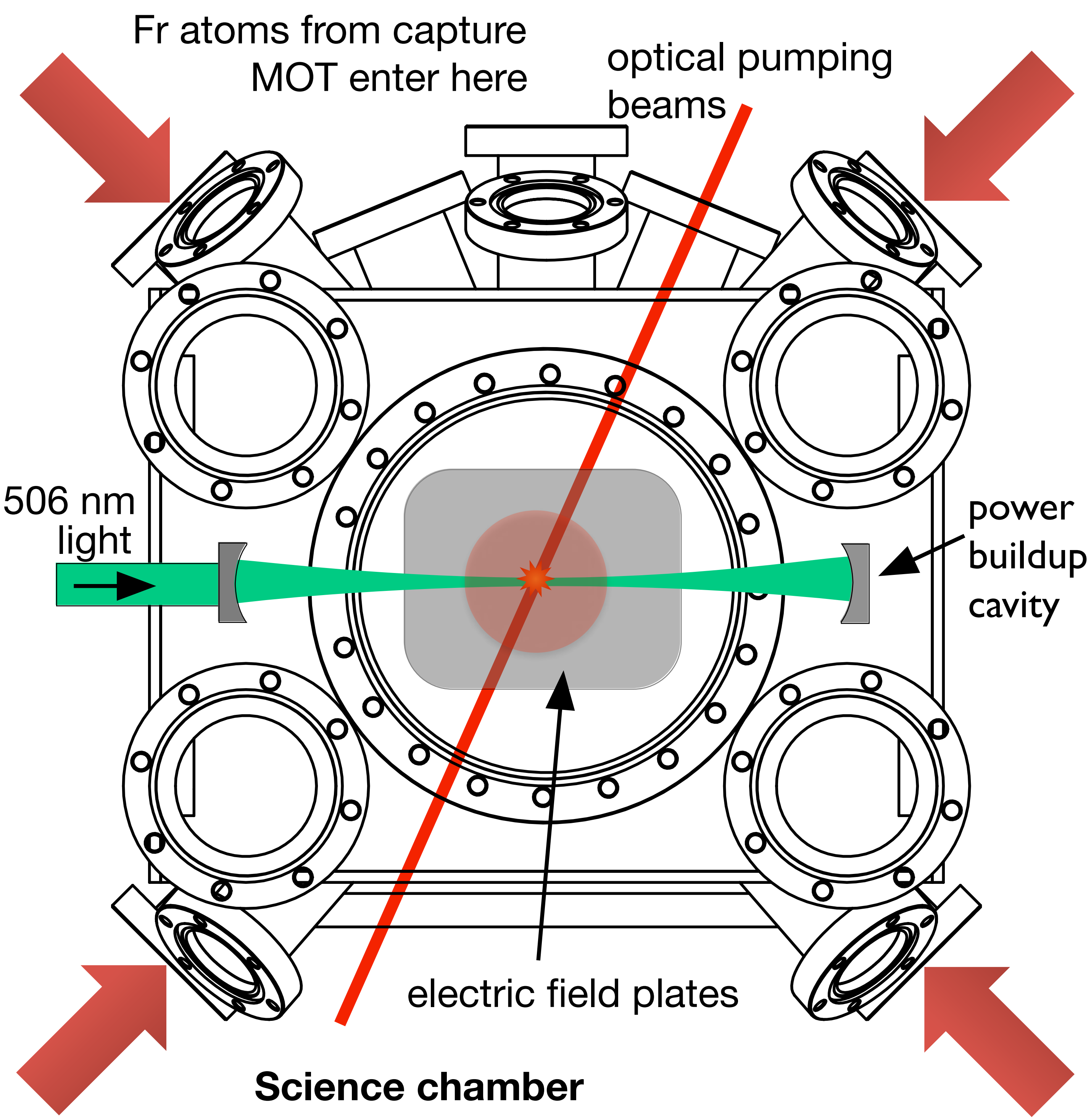




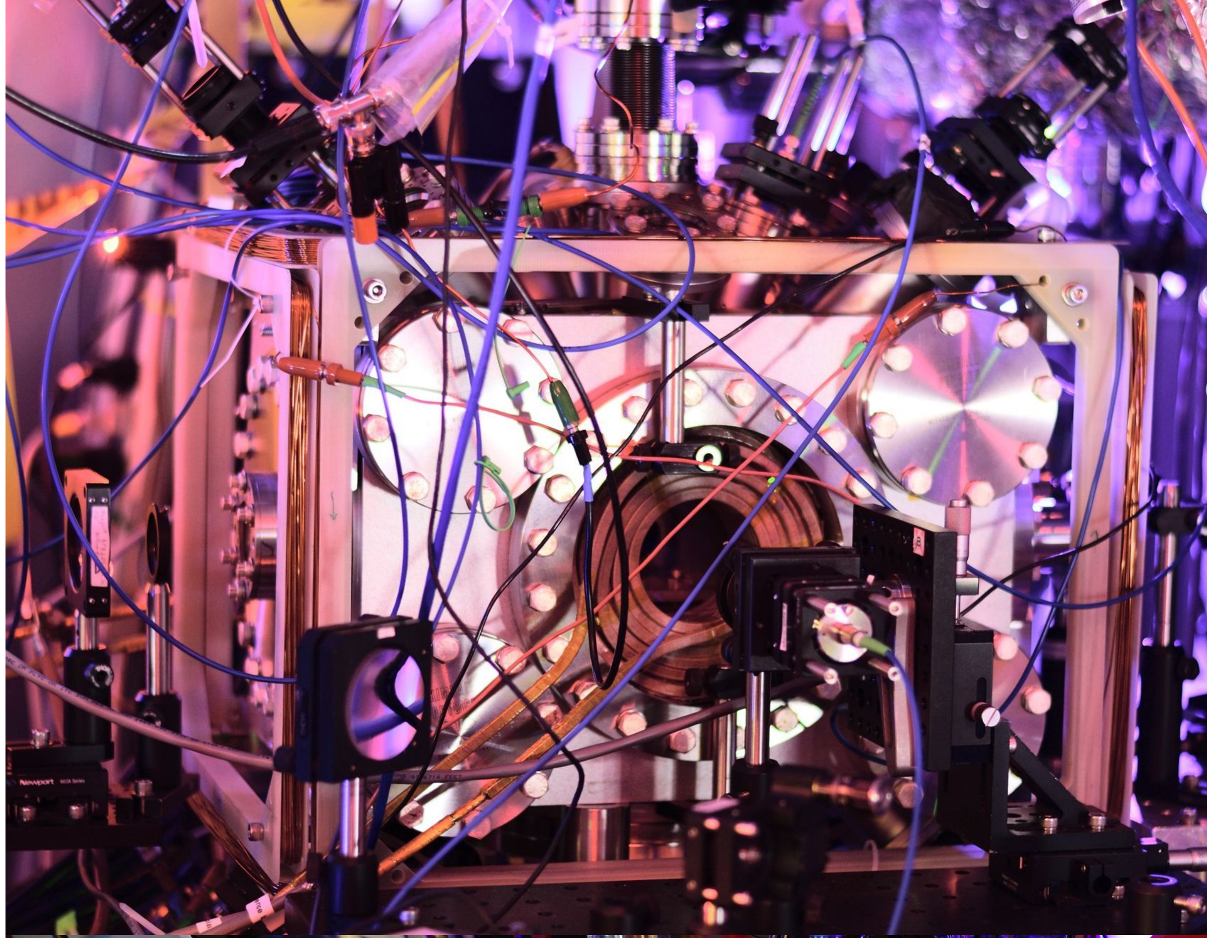


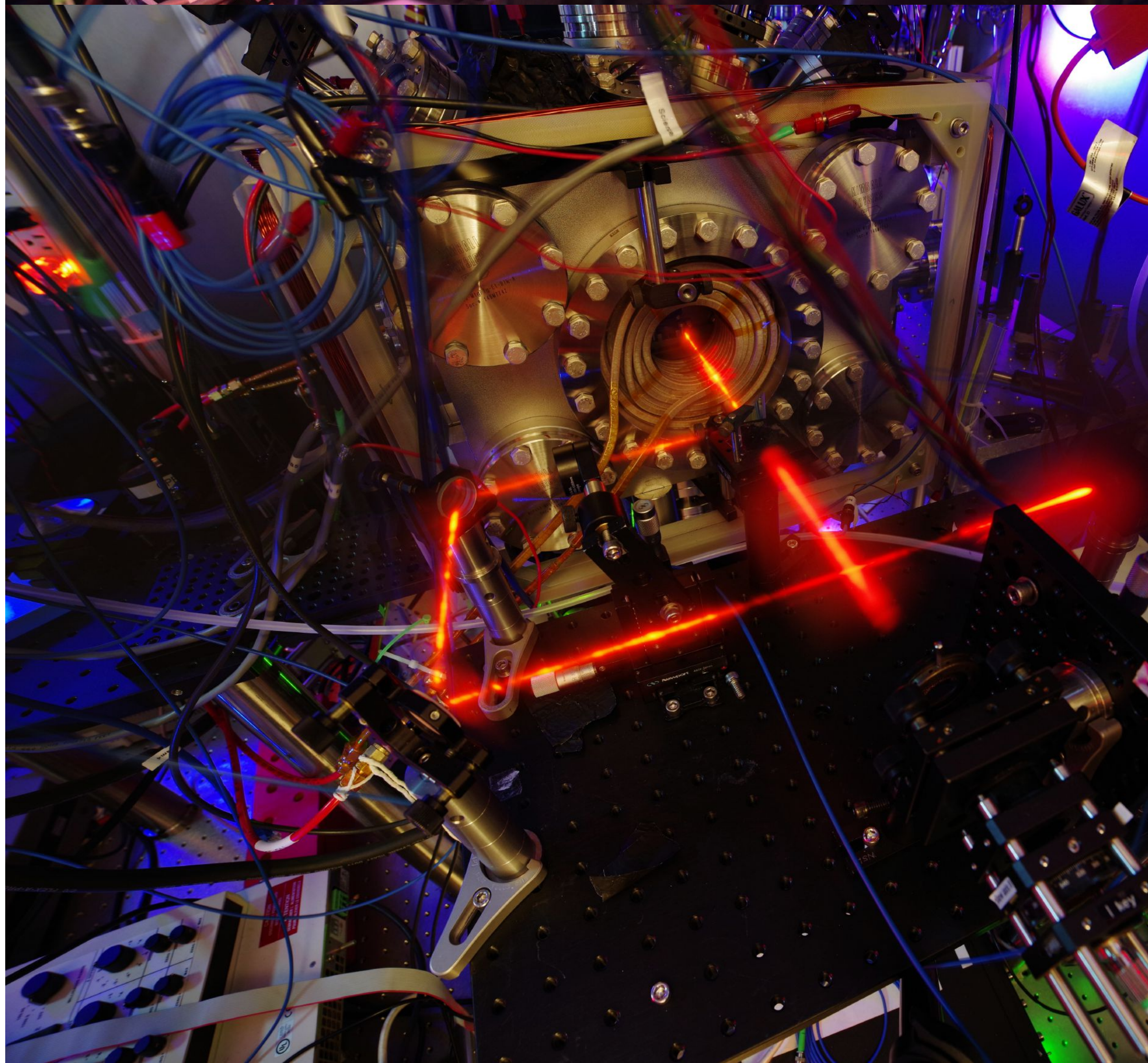


Part 2: Science chamber



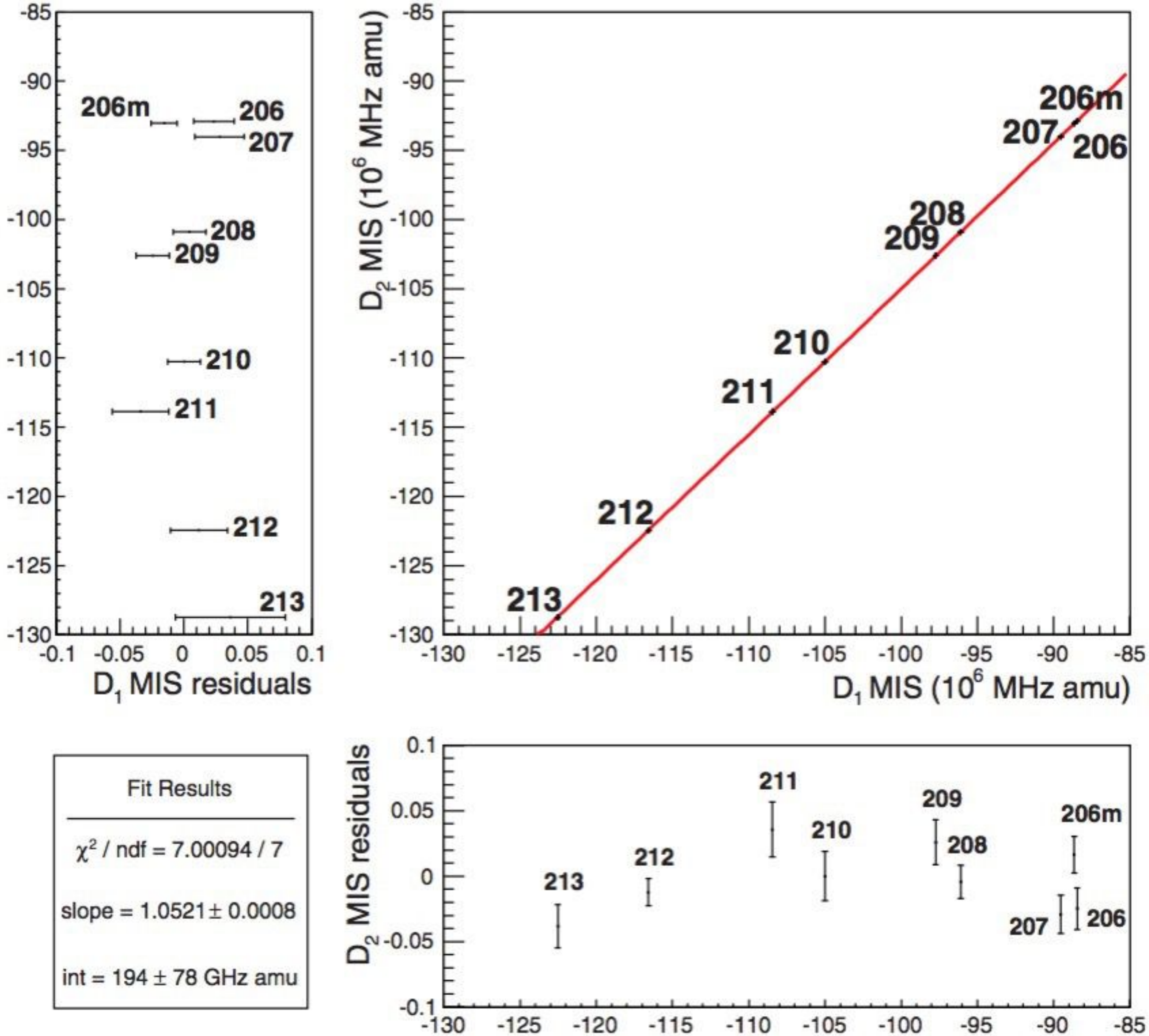
Science chamber





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)

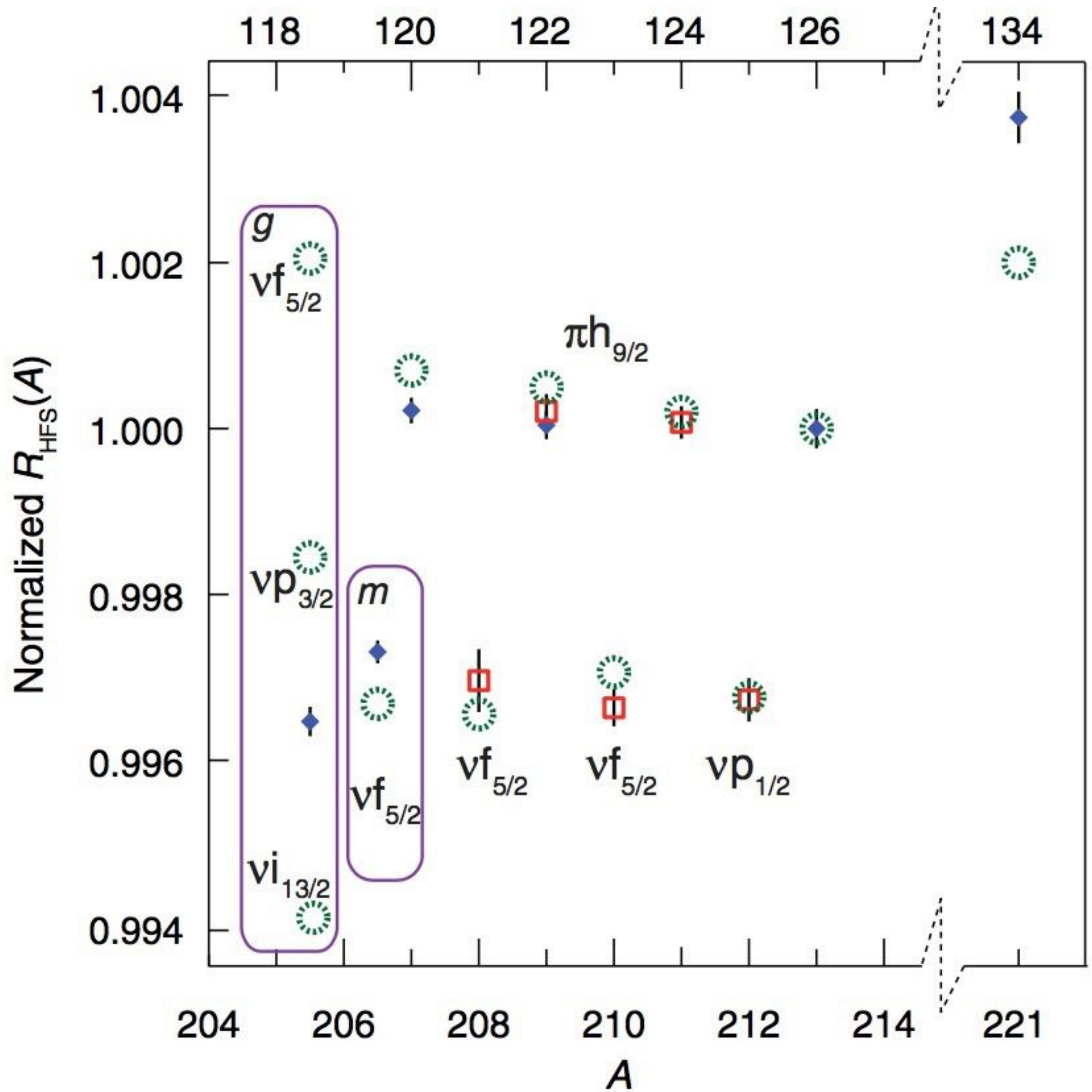


Benchmarks state-of-the-art atomic theory in Fr by Safranova and others.

for offline reference

Hyperfine anomaly in light francium isotopes

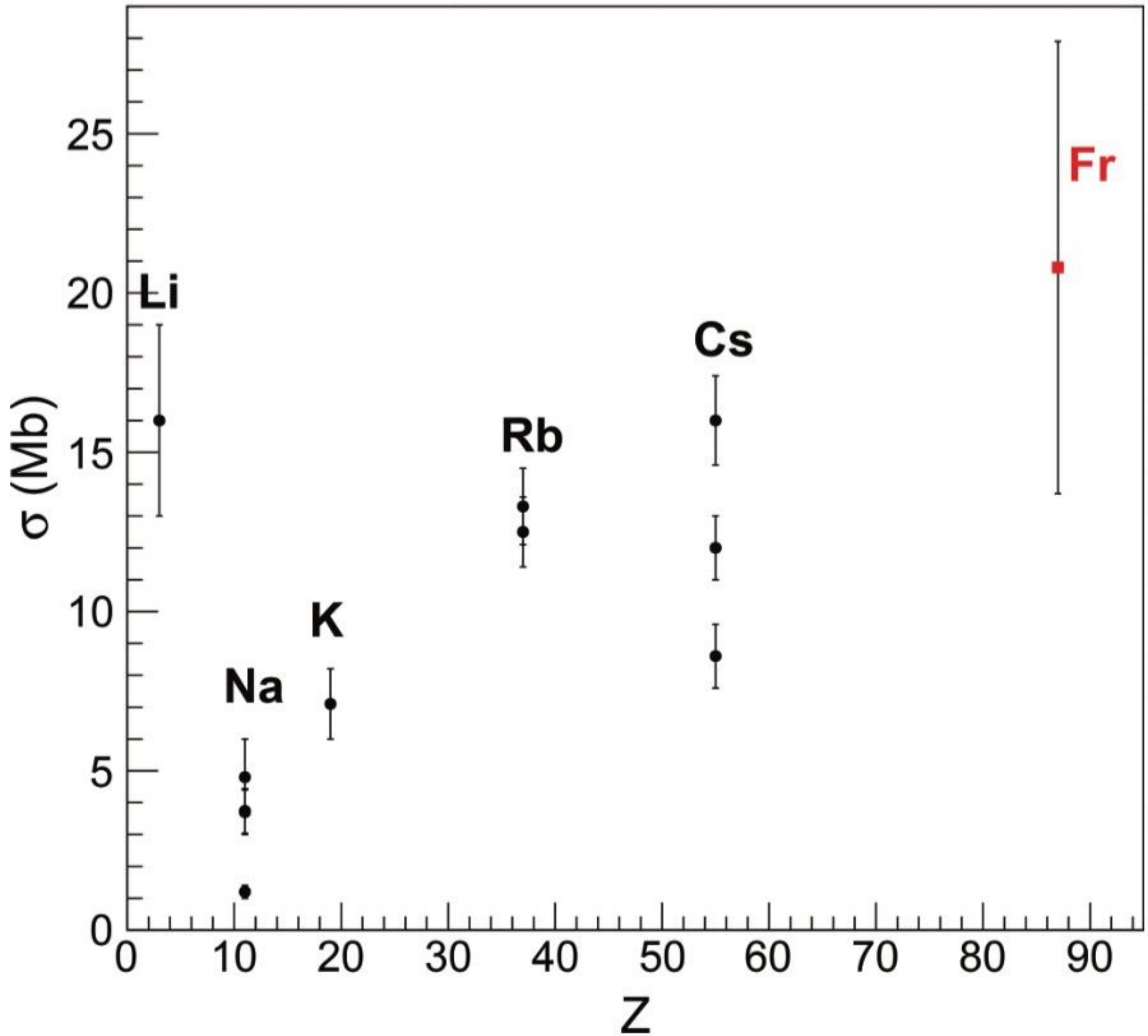
Zhang et al., Phys Rev Lett 115, 042501 (2015)



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

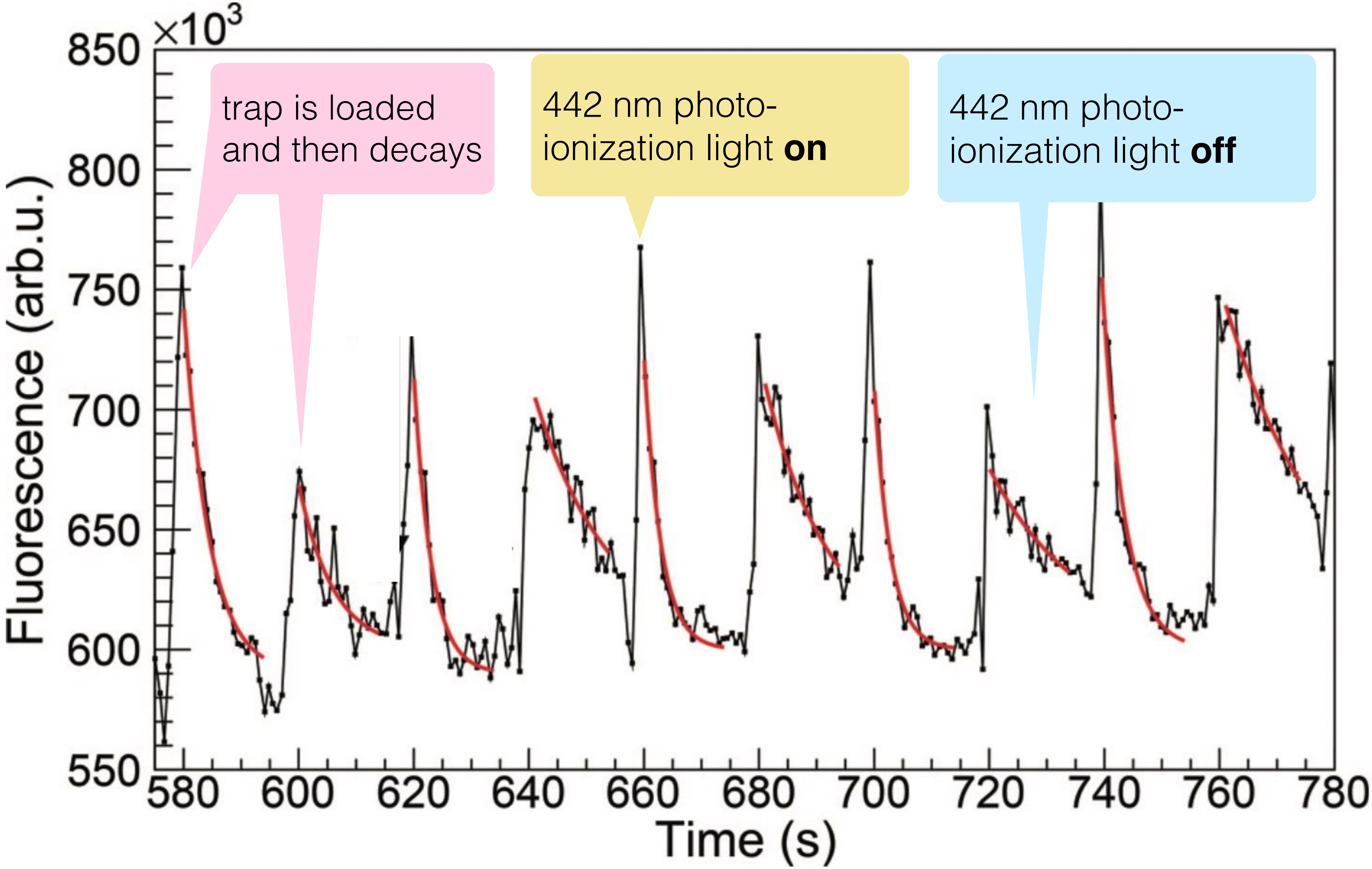
for offline reference

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

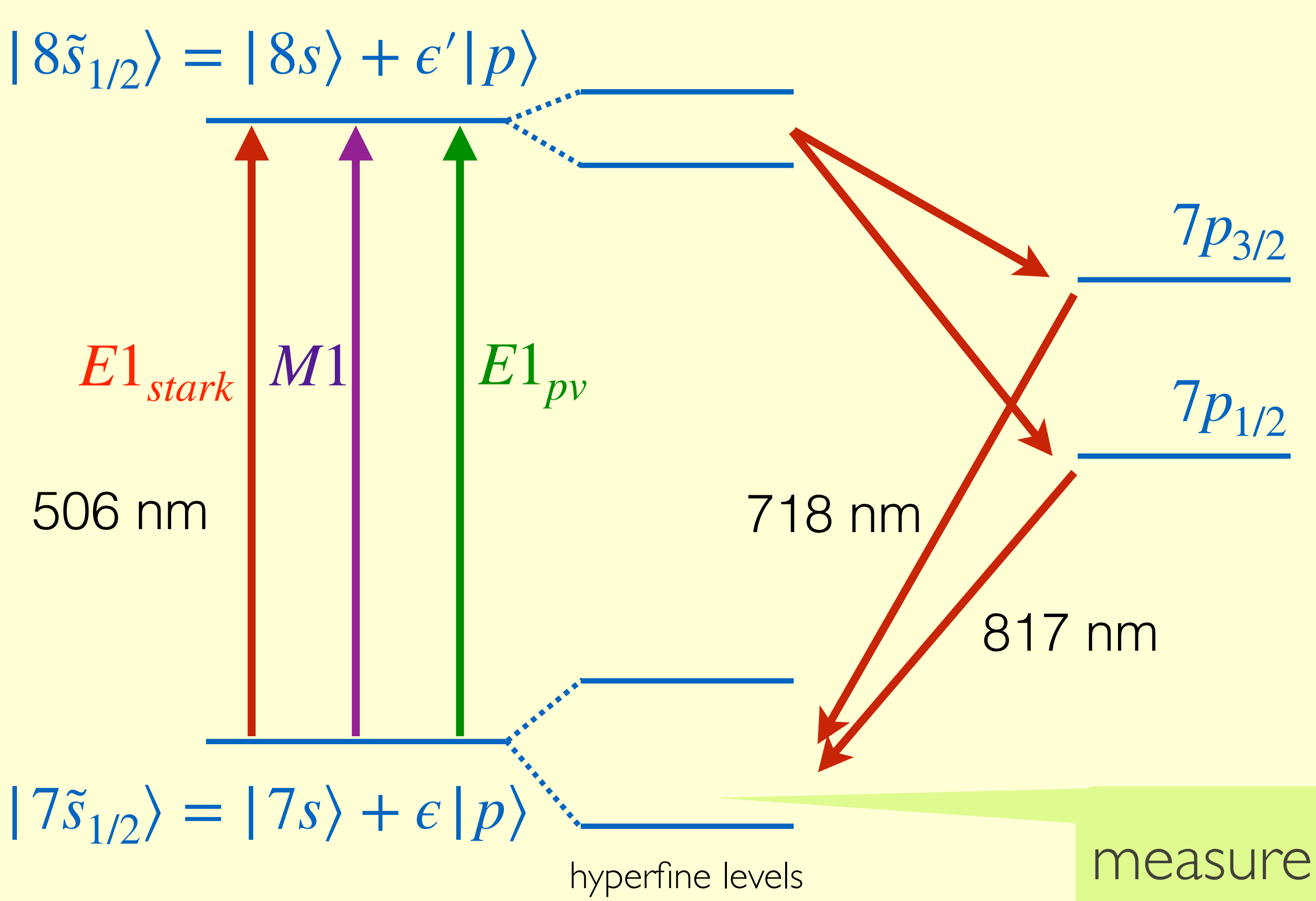


for offline reference

Photo-ionization cross-section of the 7p3/2 state in francium



Stark interference APV measurement in Fr



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

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

measure on different hyperfine transitions → access to NSD anapole

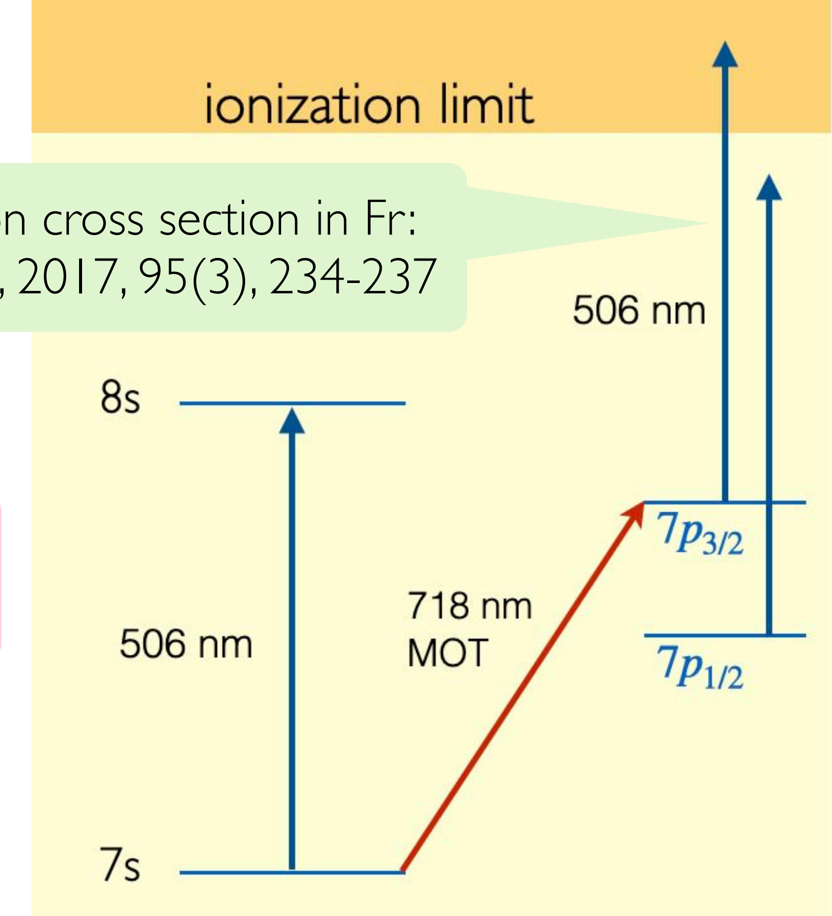
- observe **interference** between the Stark-induced and PV amplitudes ($f_{eff} \approx 10^{-16.5}$)
- IF term **changes sign** under parity transformations (e.g. electric field reversals)
  - modulation of decay fluorescence (in Fr $\approx 10^{-4}$) → extract weak charge of Fr
- $M1$ always present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

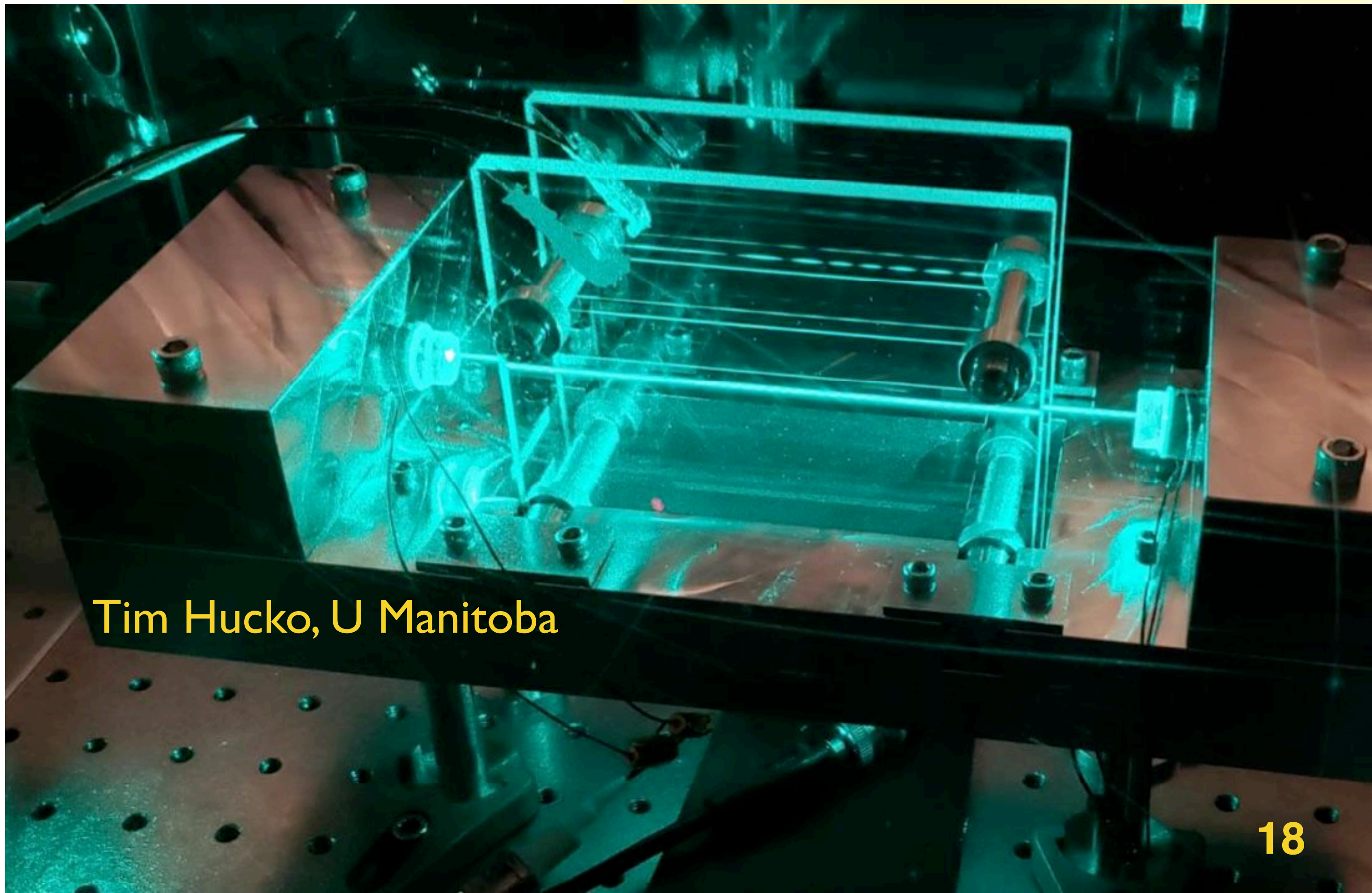
7s-8s spectroscopy: Apparatus

- 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 ≈ 400 μs
    - miraculously (to me) PBC able to maintain lock!
    - → 40 kW/cm² of 506 nm light available for spectroscopy

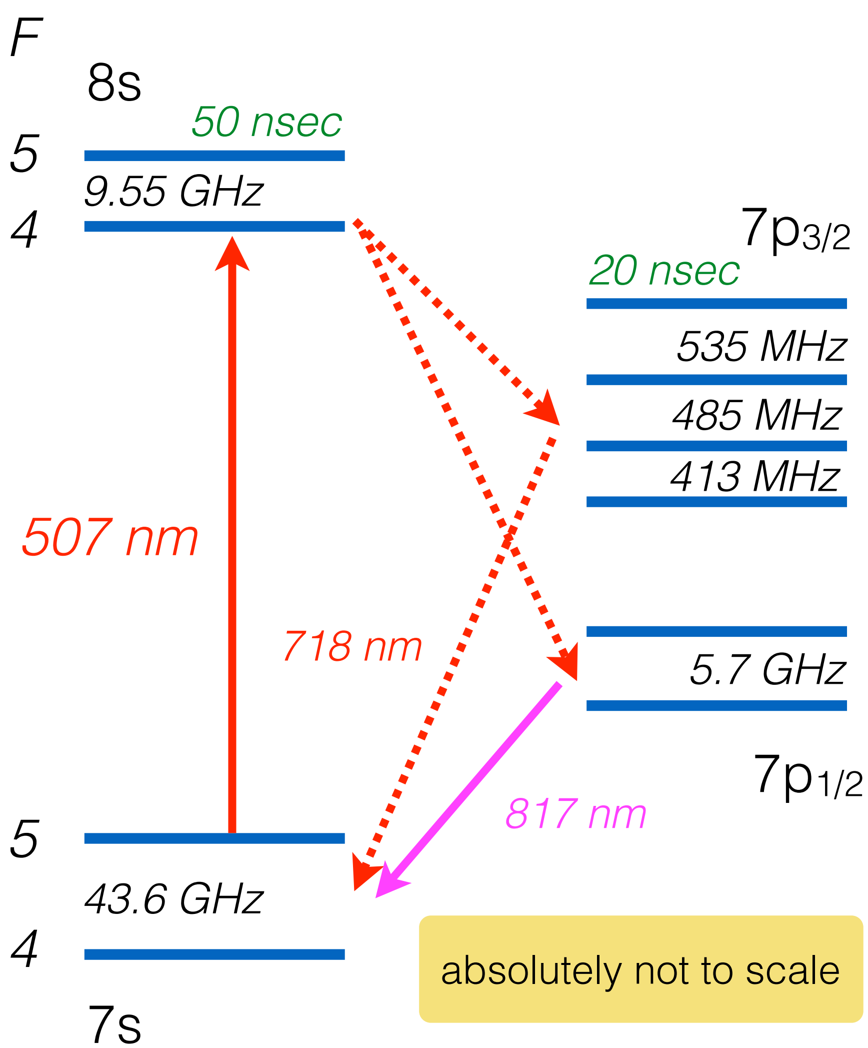
gets worse on ≈ 1yr time scale → oxygen depletion in UHV?

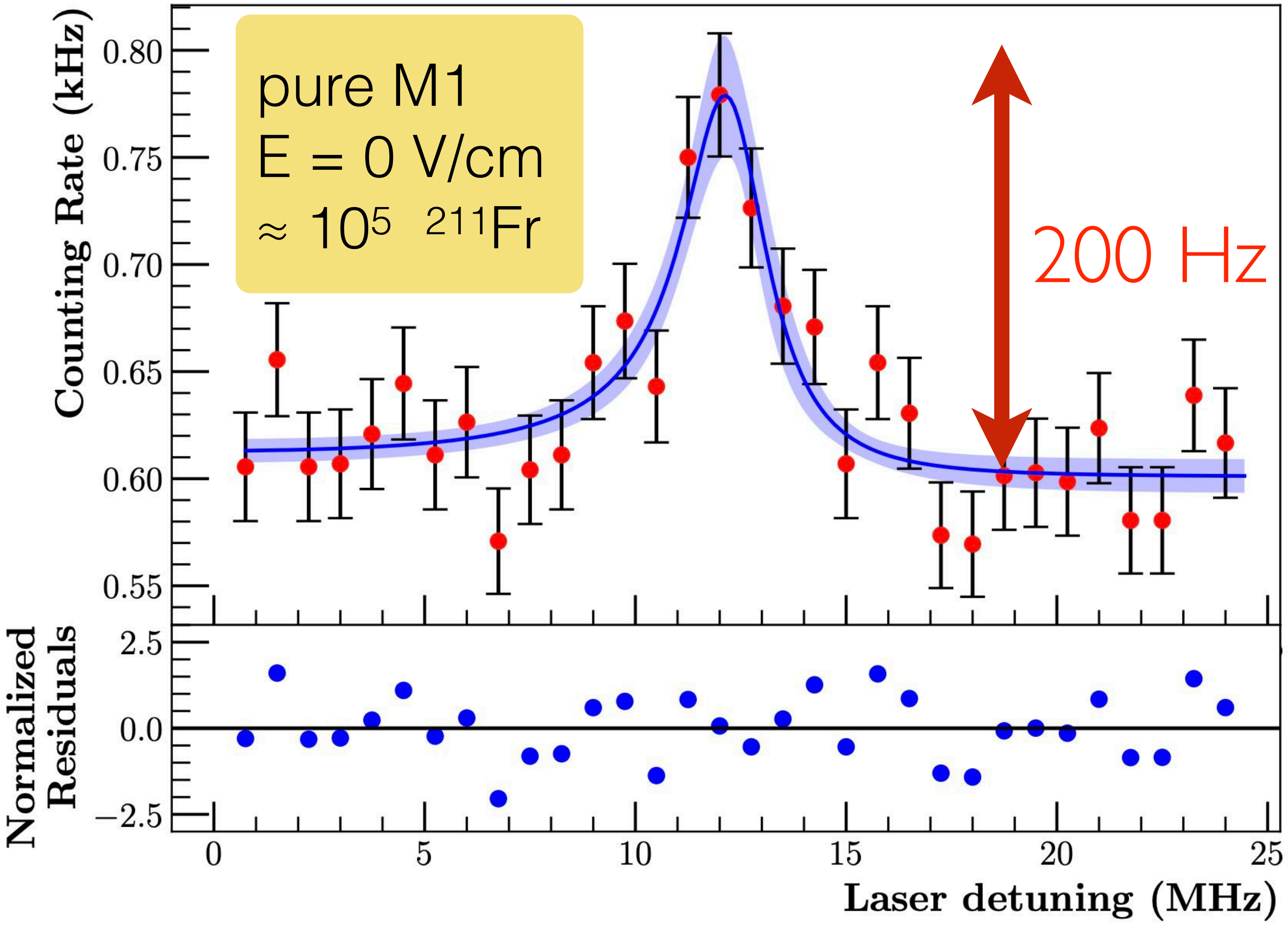
measured $7p_{3/2}$ photo-ionization cross section in Fr: Collister *et al.* 2017, Can J Phys, 2017, 95(3), 234-237





7s-8s spectroscopy: pure M1





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

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

$M1_{hf}$ calculable from known hyperfine splitting to $\lesssim 1\,\%$

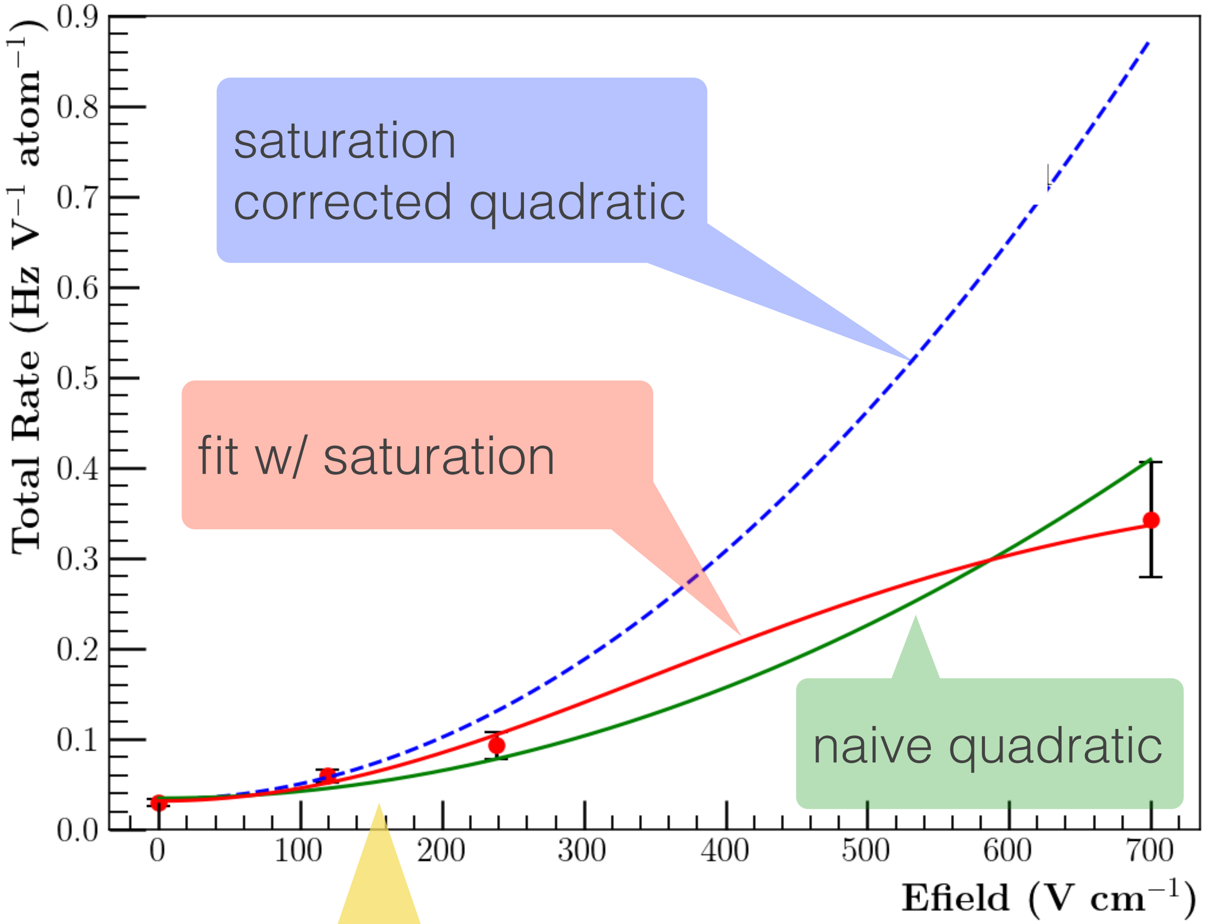
very hard to calculate

$\Delta F = \mp 1$

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

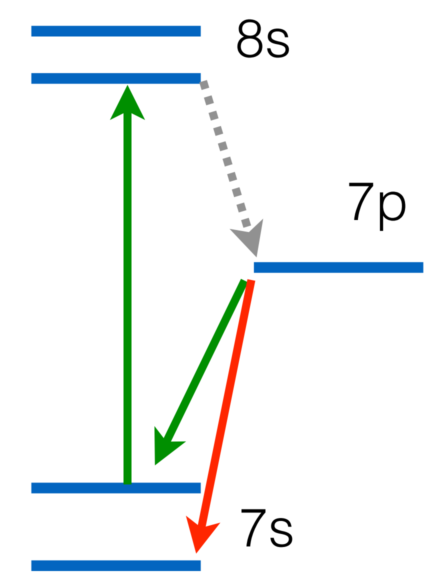
- only had time for $\Delta F = -1$ transition

7s-8s spectroscopy: E1 Stark amplitude and hyperfine pumping



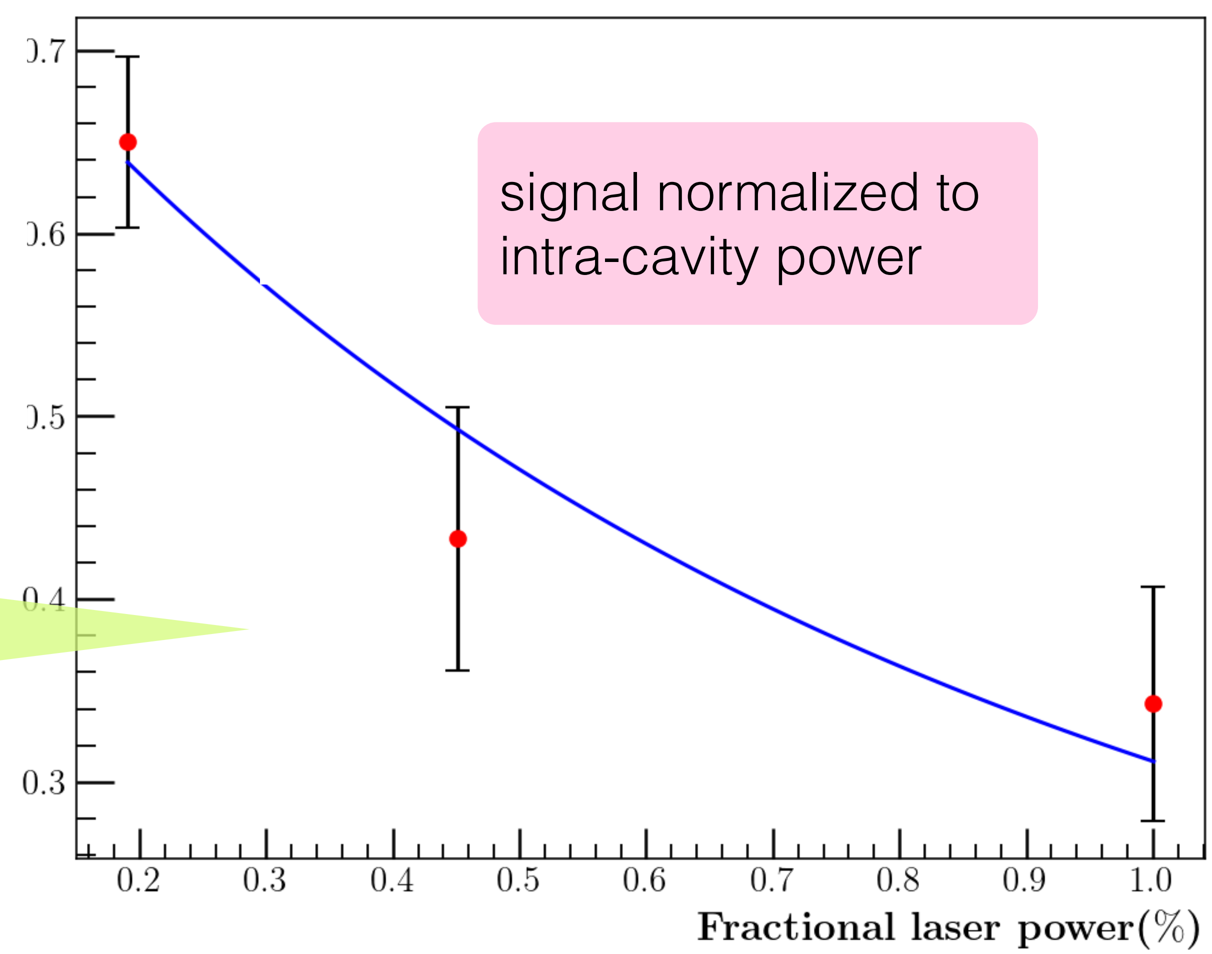
- Hyperfine pumping saturates the quadratic rise of $E1_{Stark}$

$$R \propto \frac{1-e^{-R/R_{sat}}}{R/R_{sat}}$$



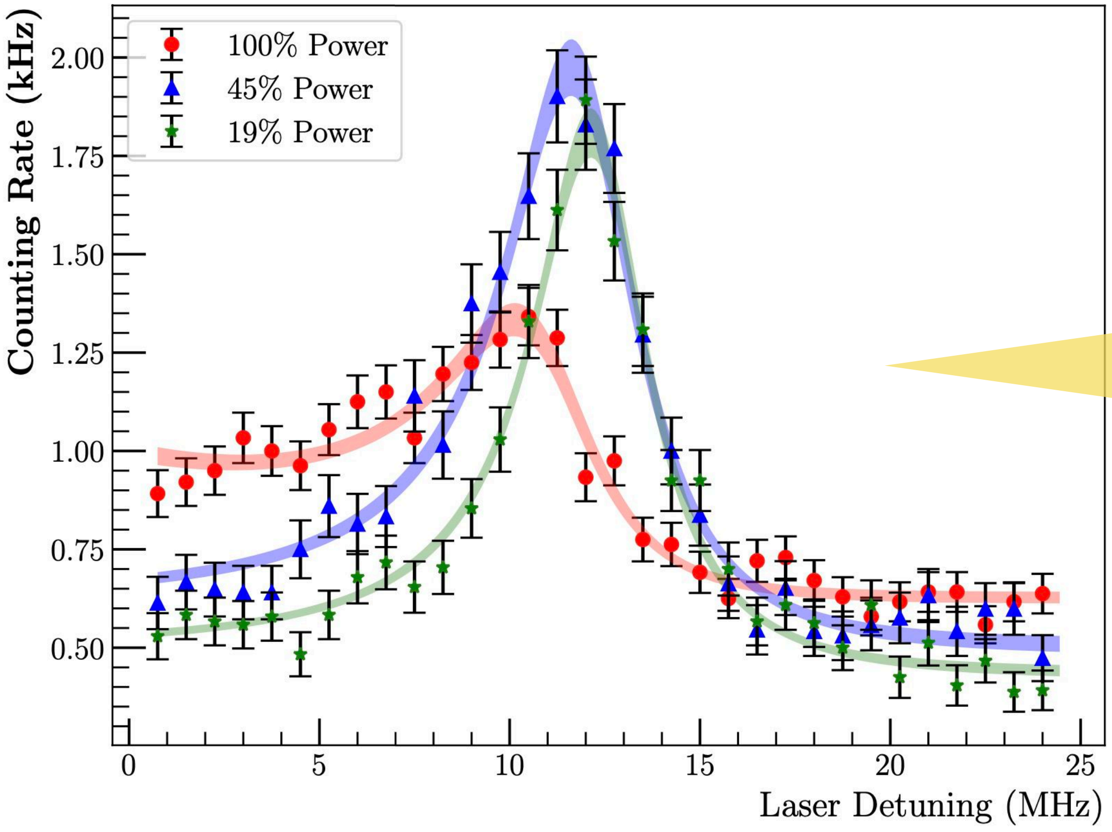
- vary electric field
- keep 506 nm PBC power fixed

- electric field fixed at 700 V/cm
- vary PBC intensity between ≈ 9 and 43 kW/cm^2



- we obtain a consistent saturation parameter

7s-8s spectroscopy: E1 Stark amplitude and hyperfine pumping



- also observe consistent saturation broadening
- exponential decay of atom cloud skews resonances
- not normalized to atom #

- final result:
- can put good constraints on the relativistic M1 matrix element
- good agreement with theory
  - better than in Cs!

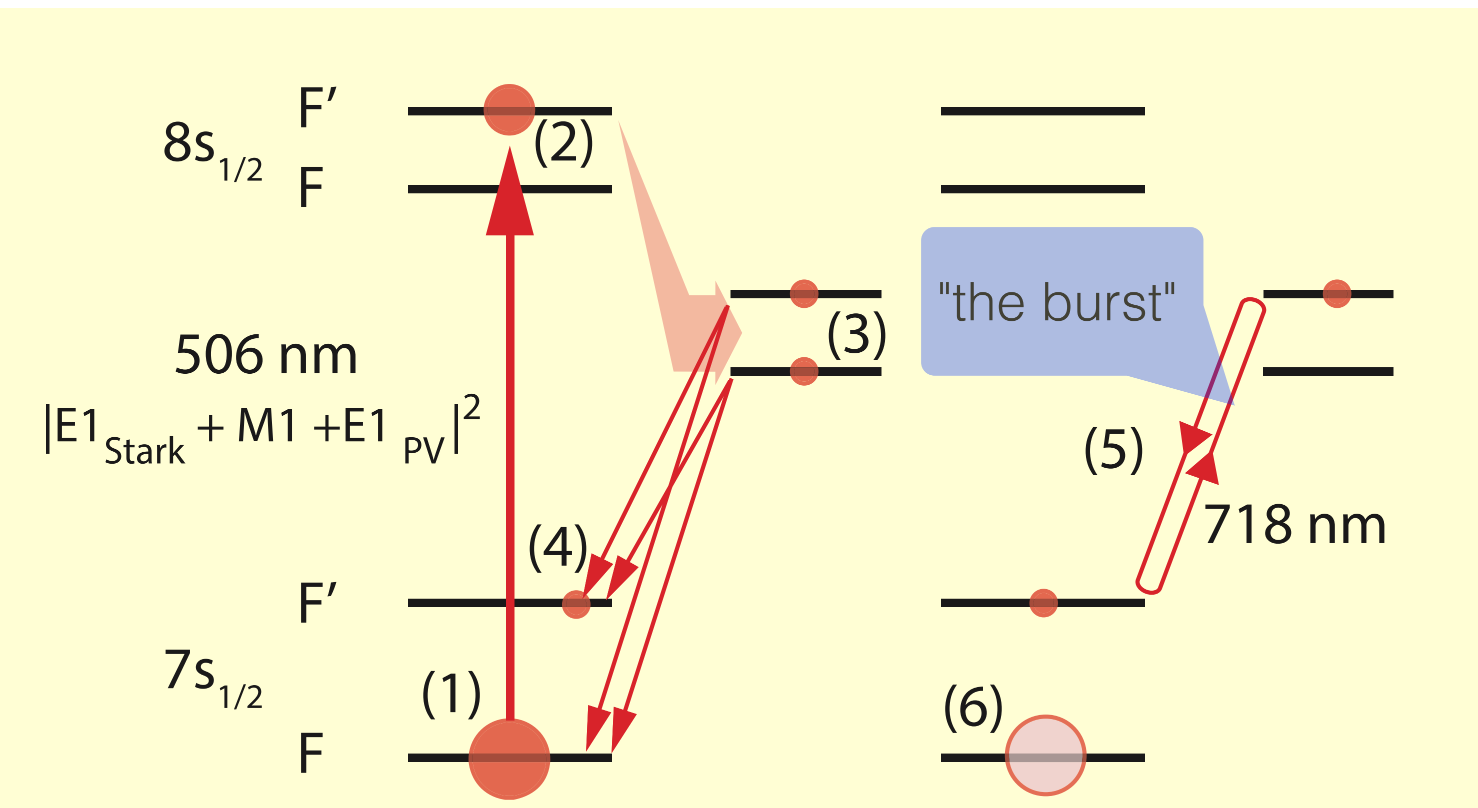
TABLE I. A comparison of the relativistic component for the Fr $7s \to 8s$ reduced $M1$ matrix element between theory and experimental values.

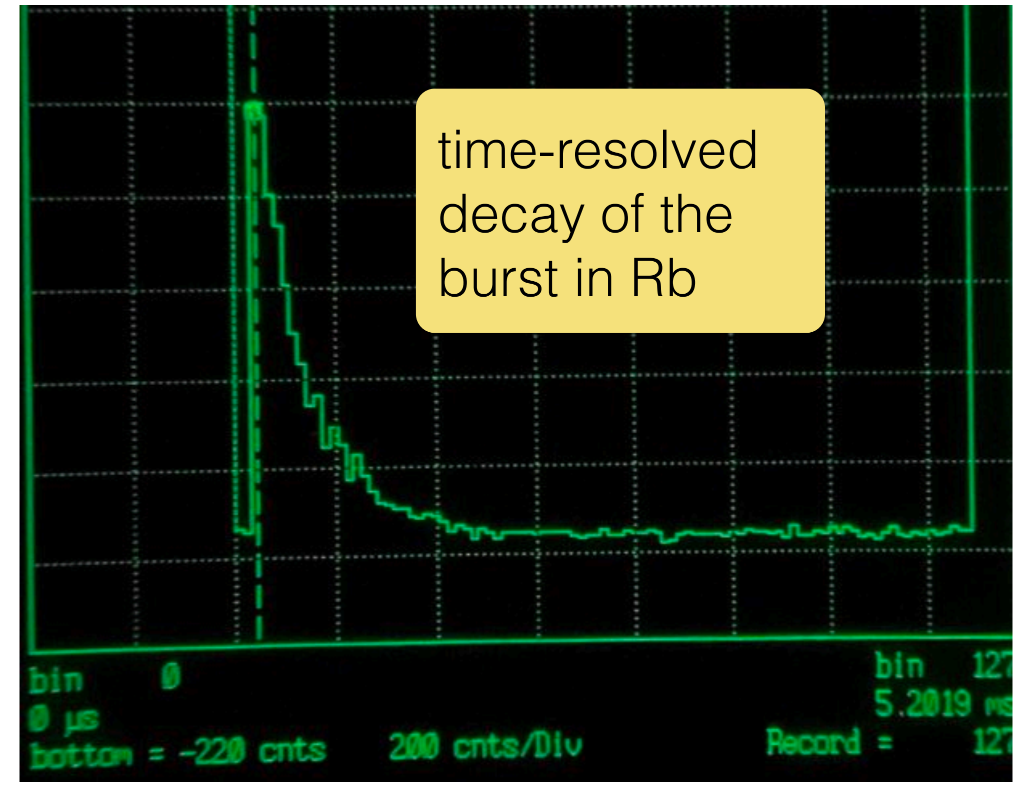
References	$M_{\rm rel}^{\rm RME}(\times 10^{-5}\mu_{\rm B}/c)$
Theory	
Savukov *et al.*[1], 1999	113
Safronova *et al.*[13], 2017	No Breit: 139.9
	Breit: 137.4
Experimental	
This work	$152(12)_{\rm expt}(1)_{\rm theo}$

preliminary

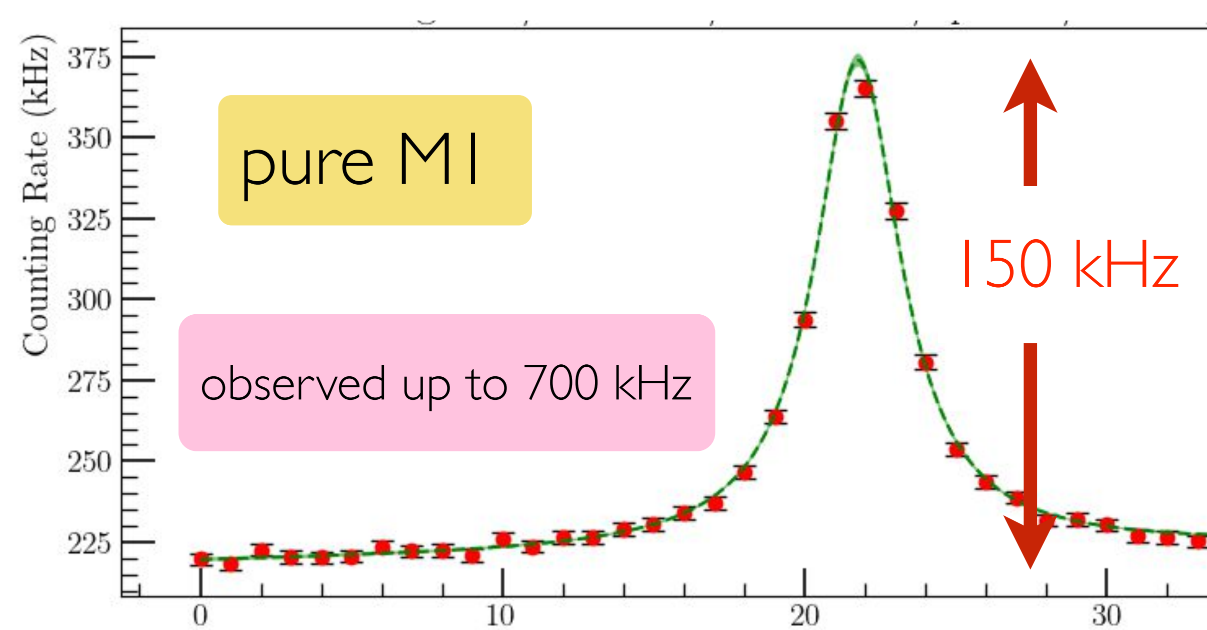
7s-8s: Boosting the signal

- photon detection efficiency 1/4000 (PMT 10% QE, solid angle, filters, ...)
- for APV need to take this to near-perfect efficiency
- → "burst fluorescence" using D2 cycling transition





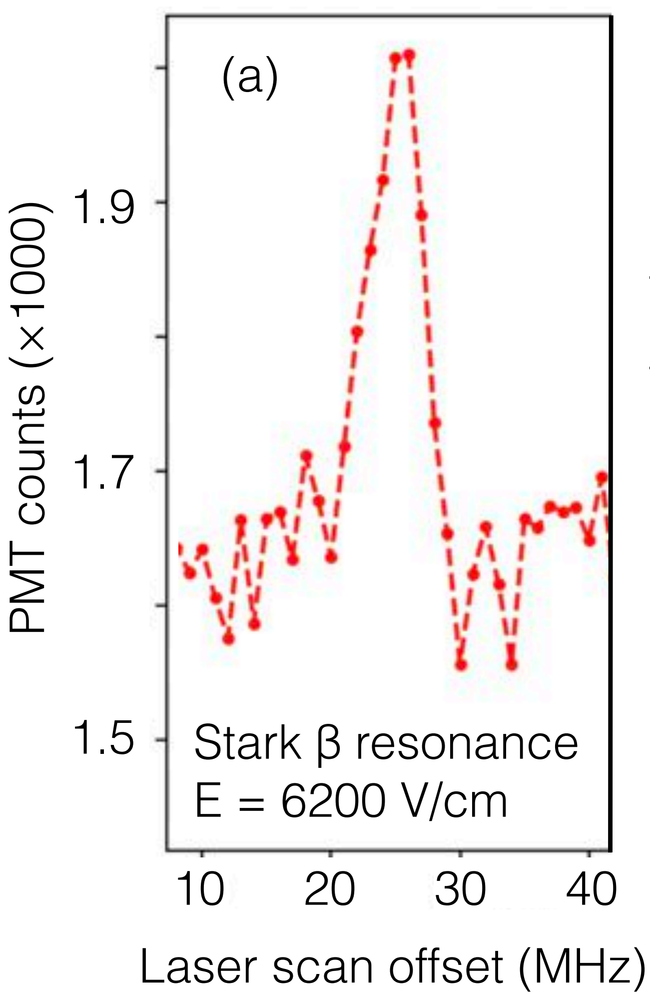
- ≈ 4000 burst photons from single atoms 7s-8s excitation

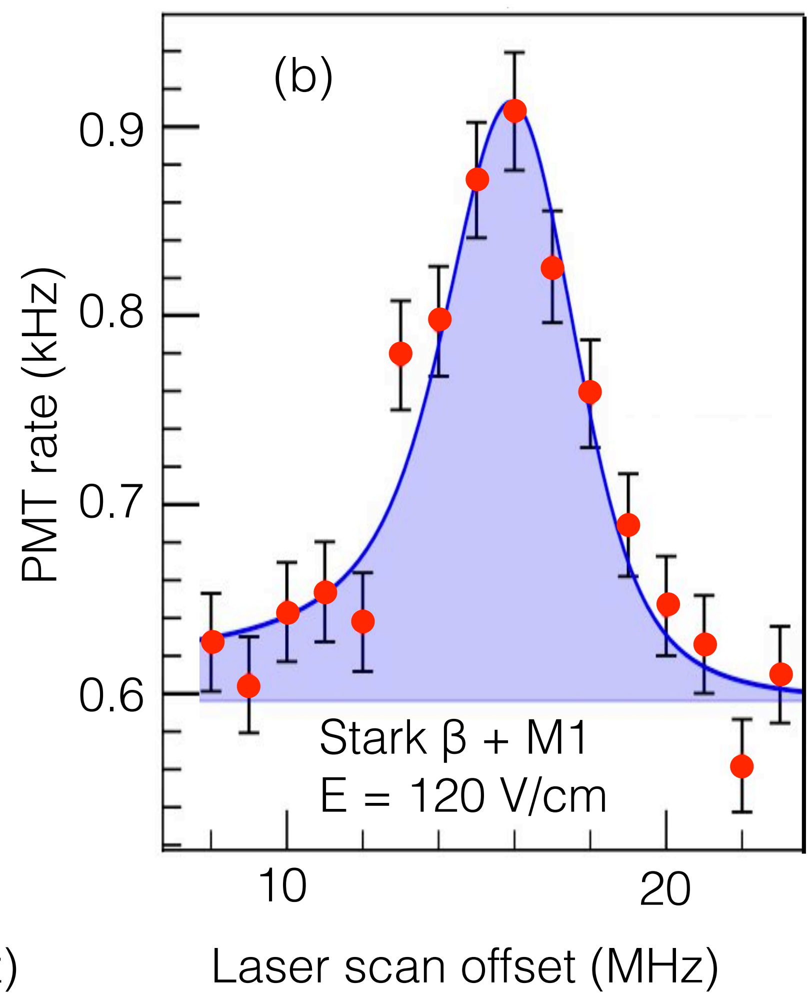


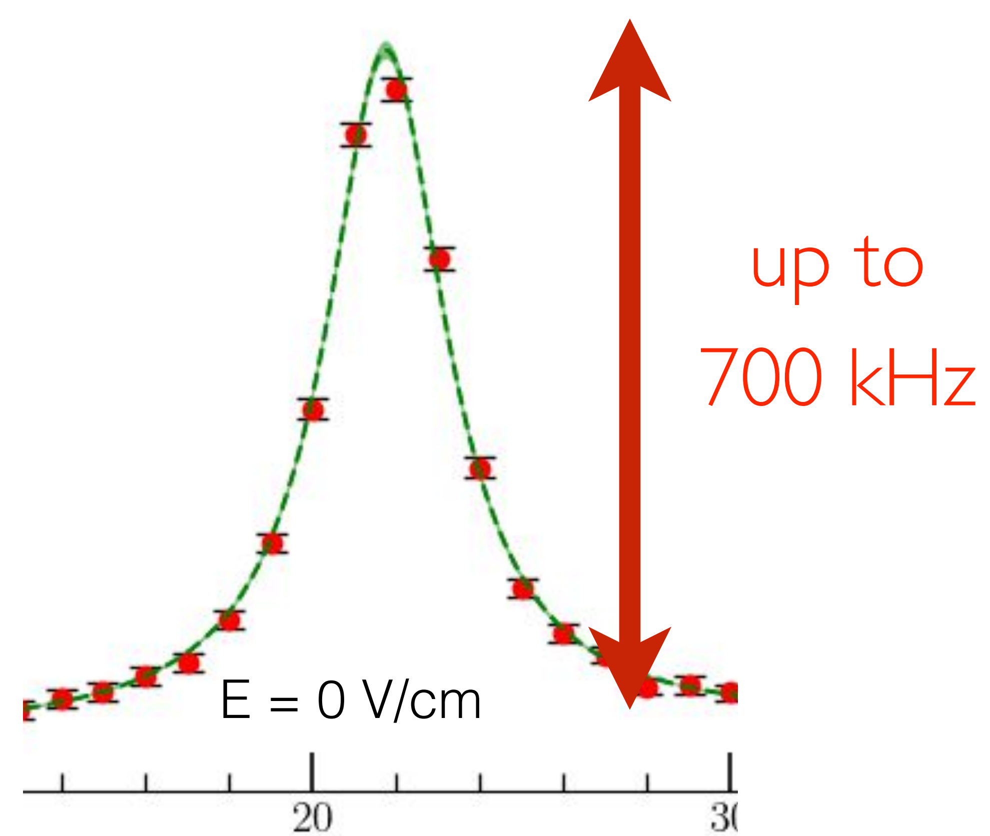
Signal progress 2018-23

cavity 2000x → burst 4000x

Sept 2018 | Sept 2021 | Aug 2023







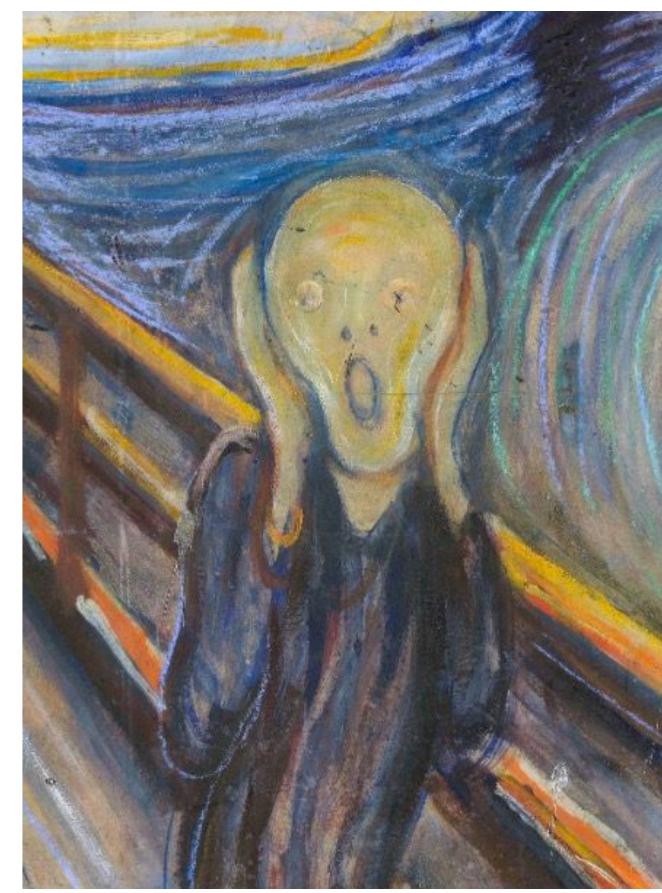
Where does Fr APV stand?

- In the following consider **only** statistical limitation
- M1 now produces up to 10^6 Hz of counting rate from maybe 200,000 atoms.
- For $E_{\text{Stark}} - E_{\text{pnc}}$ would choose around 300 - 400 V/cm → 10 MHz
- APV asymmetry $\approx 10^{-4}$
  - need 10^8 counts to see APV → takes around 10 sec
  - need 10^{12} counts for a 1% APV measurement → takes 1 day
  - need 10^{14} counts for a 0.1% APV measurement → 100 days
  - trap 10x more atoms → 10 days
- systematics and overhead make this significantly worse, so maybe 100 days? That still sounds alright (as long as I don't do the nights shifts)

What's in wait for me?

Stage	Yb	Fr	my age
Start project	1995	2018	
M1 measurement	2001	2021-23	
APV observed	2008	2026 (our plan) 2030 (as per Yb)	60 64
APV, BSM sensitivity	2018	2029 2040	62 74

any youngster interested to come to TRIUMF and take this project over?



Outlook and credits

- light intensity and detection now at "APV level"
- next step: optically pump 7s atoms into specific $|F, m_F = \pm F\rangle$ states
- to consider APV, need probably another 10x to 50x more atoms trapped

- U Manitoba/TRIUMF M1 team
    - T. Hucko[1], A. Sharma[1], I. Halilovic[1], T. Morshed[1], L. Xie[2], M. Kalita[2], G. Gwinner[1]
- TRIUMF: L. Croquette[4], J. Behr, A. Gorelov, A. Teigelhöfer, S. Malbrunot-Ettenauer, J. Lassen, R. Li
- U Maryland: L. Orozco
- some-time beamtime participation: S. Aubin (William & Mary), E. Gomez (San Luis Potosí)
- FrPNC alumni: M. Kossin[1], DeHart[1], R. Collister[1], J. Zhang[3], M. Tandecki[2] M. Pearson[2], K Shiells[1]

Funding: NSERC, NRC/TRIUMF, U Manitoba, U Maryland

student PD/Res.Assoc [1] Manitoba [2] TRIUMF [3] Maryland [4] McGill

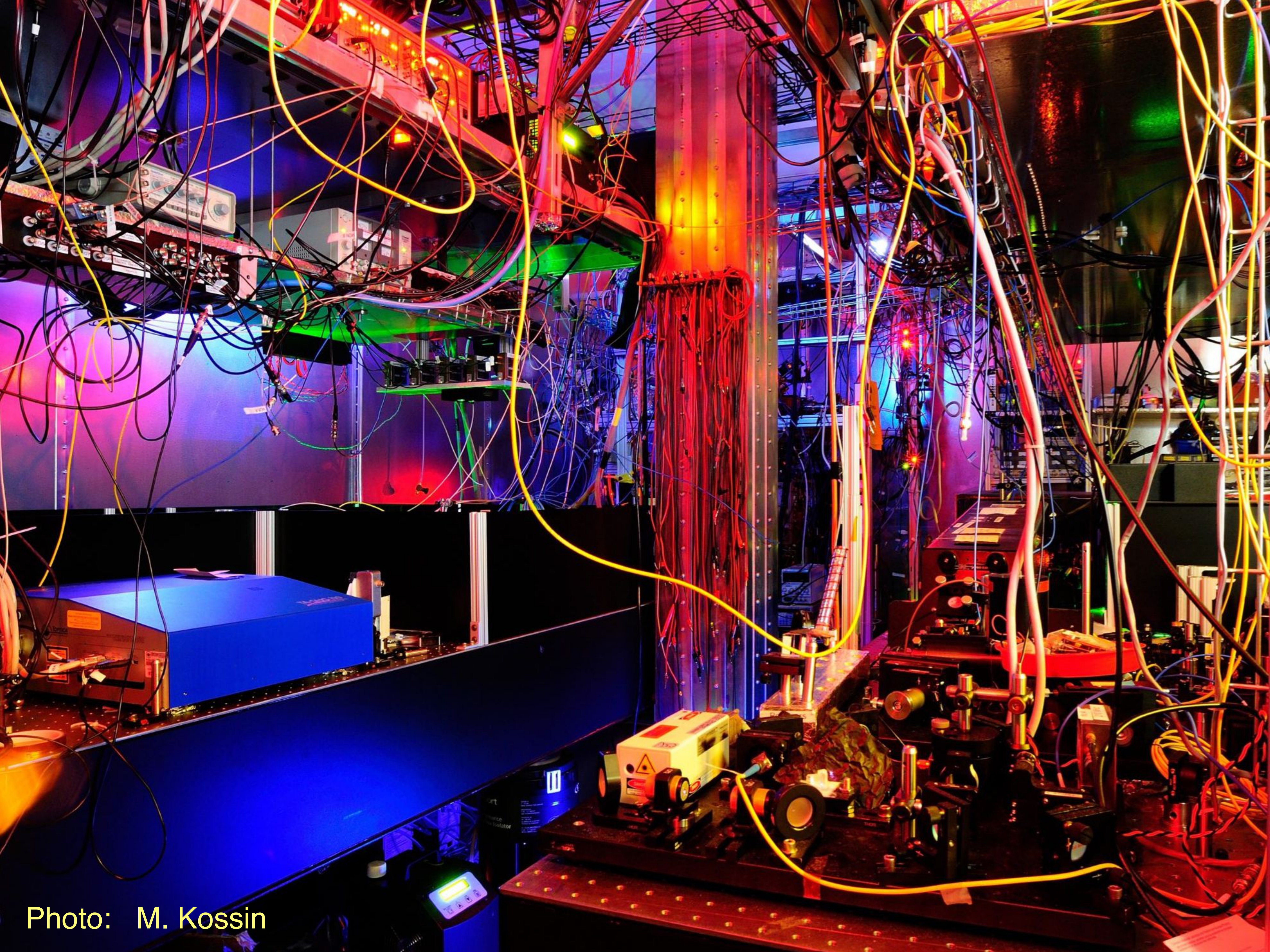


Photo: M. Kossin