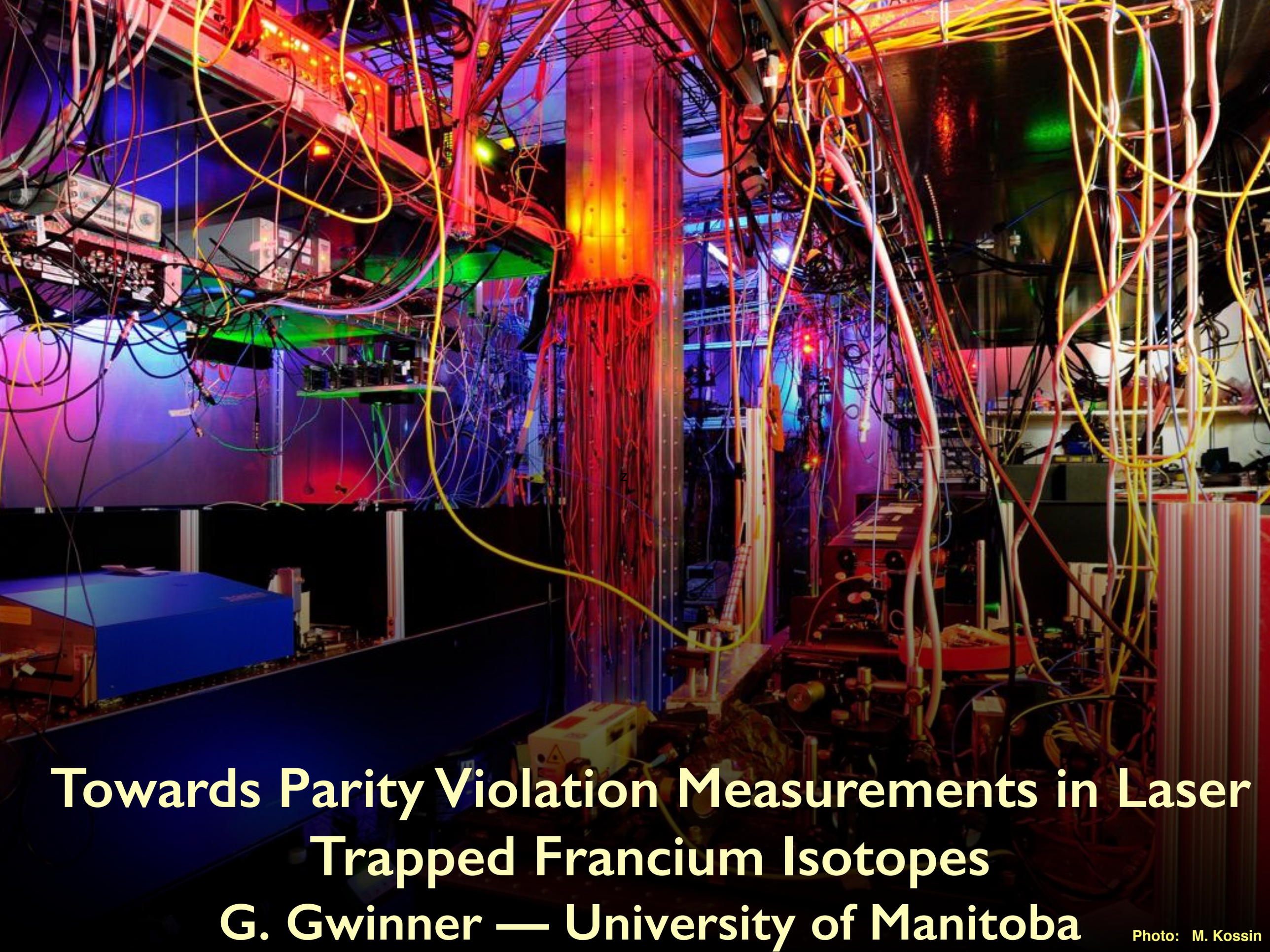


Towards Parity Violation Measurements in Laser Trapped Francium Isotopes

G. Gwinner — University of Manitoba

Photo: M. Kossin

ISAC + actinide target: great place to study fundamental symmetries in heavy atoms

Atoms/nuclei provide access to fundamental symmetries, should be viewed as complementary to high energy approaches

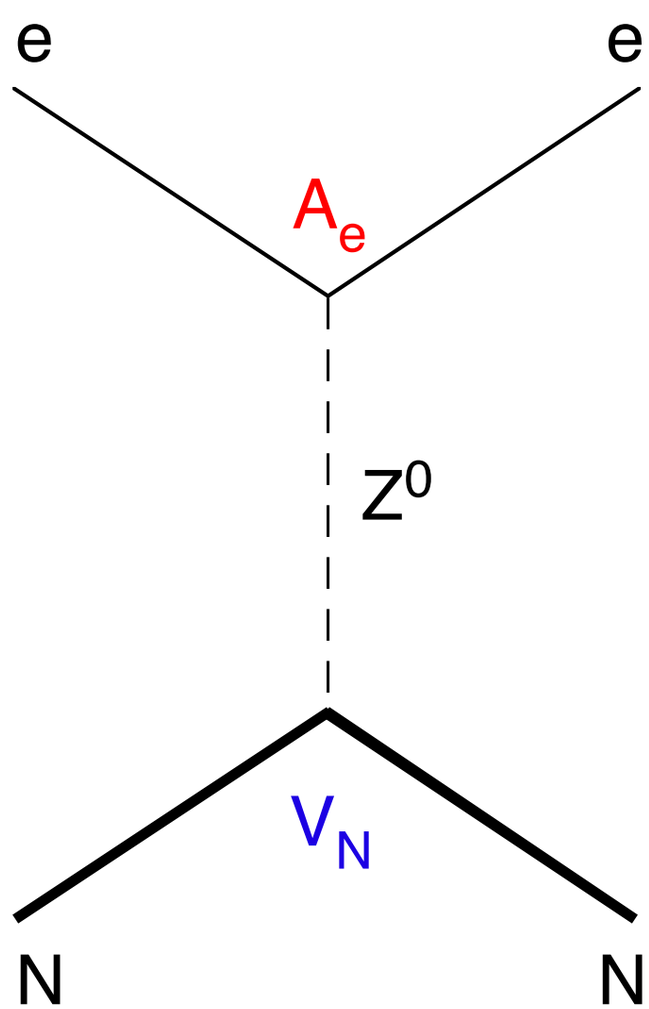
	Atom	**Nucleus**
Charged current weak interactions, β-decay	new powerful techniques (atom traps)	rich selection of spin, isospin, half-life
Neutral current weak interactions APNC anapoles	tremendous accuracy of atomic methods (lasers, microwaves) neutral (strong external fields) traps, cooling	huge enhancement of effects (high Z, deformation) over elementary particles rich selection of spin, isospin, Z, N, deformation
Permanent electric dipole moments		
Lorentz-symmetry & CPT violation	accuracy	selection of spin, Z, N

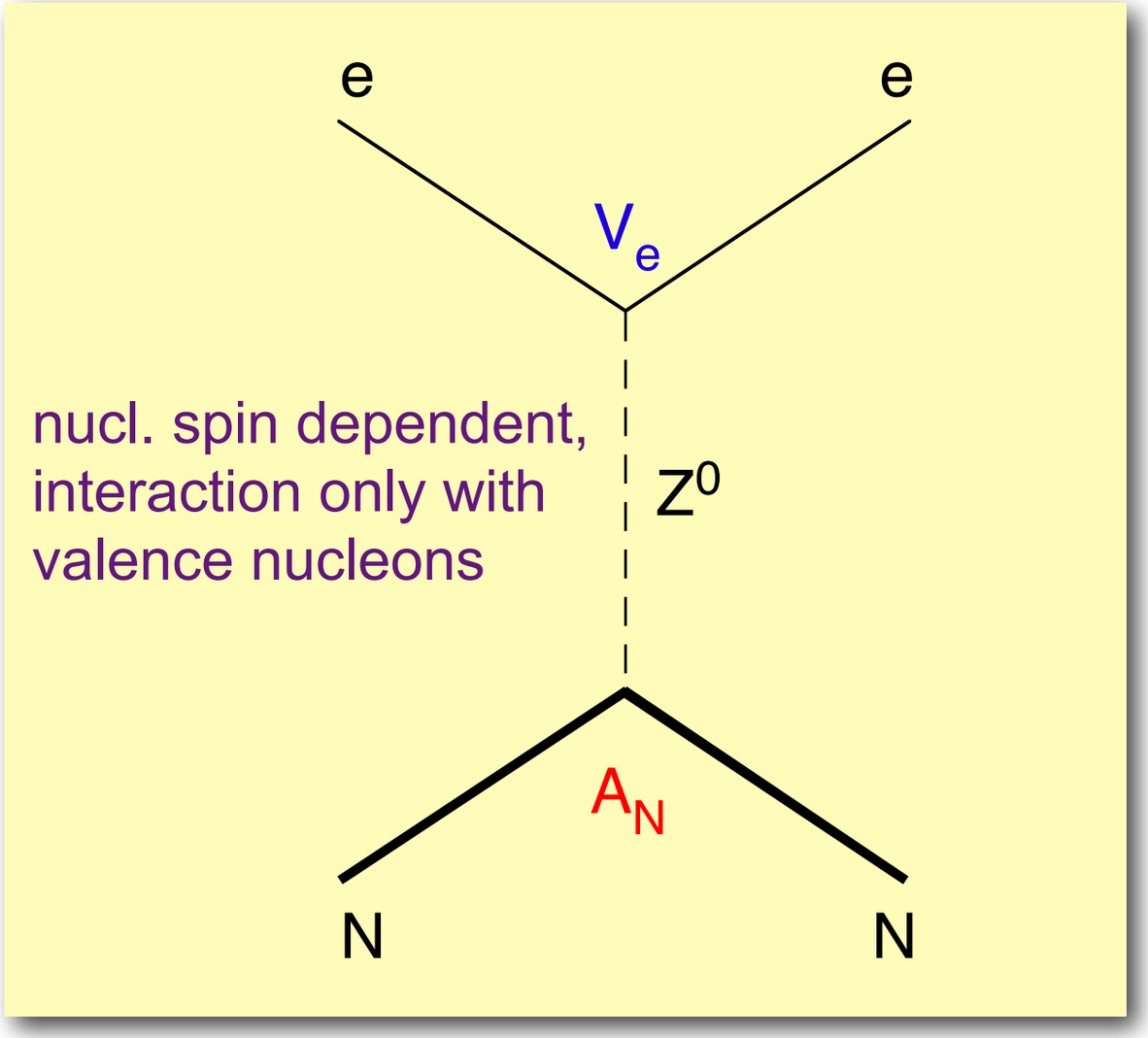
Some of most promising new candidates are heavy, radioactive systems (Rn, Fr)
Radioactive beam facilities are crucial

Demanding, long experiments → strong motivation for dedicated beam delivery

Atomic Parity Violation

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





nucl. spin *independent* interaction: coherent over all nucleons

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

$\langle n's' | H_{PNC} | np \rangle \propto Z^3$

Drive s → s E1 transition!

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

use interference:

$$f \propto | A_{PC} + A_{PNC} |^2$$
$$\approx A_{PC}^2 + A_{PC} A_{PNC} \cos \varphi$$

The nuclear-spin independent APNC Hamiltonian for a pointlike nucleus:

$$H_{\rm PNC}^{nsi} = \frac{G}{\sqrt{2}} \frac{Q_W}{2} \gamma_5 \, \delta(\mathbf{r}).$$

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

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

The "nuclear weak charge"
contains the weak interaction physics

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

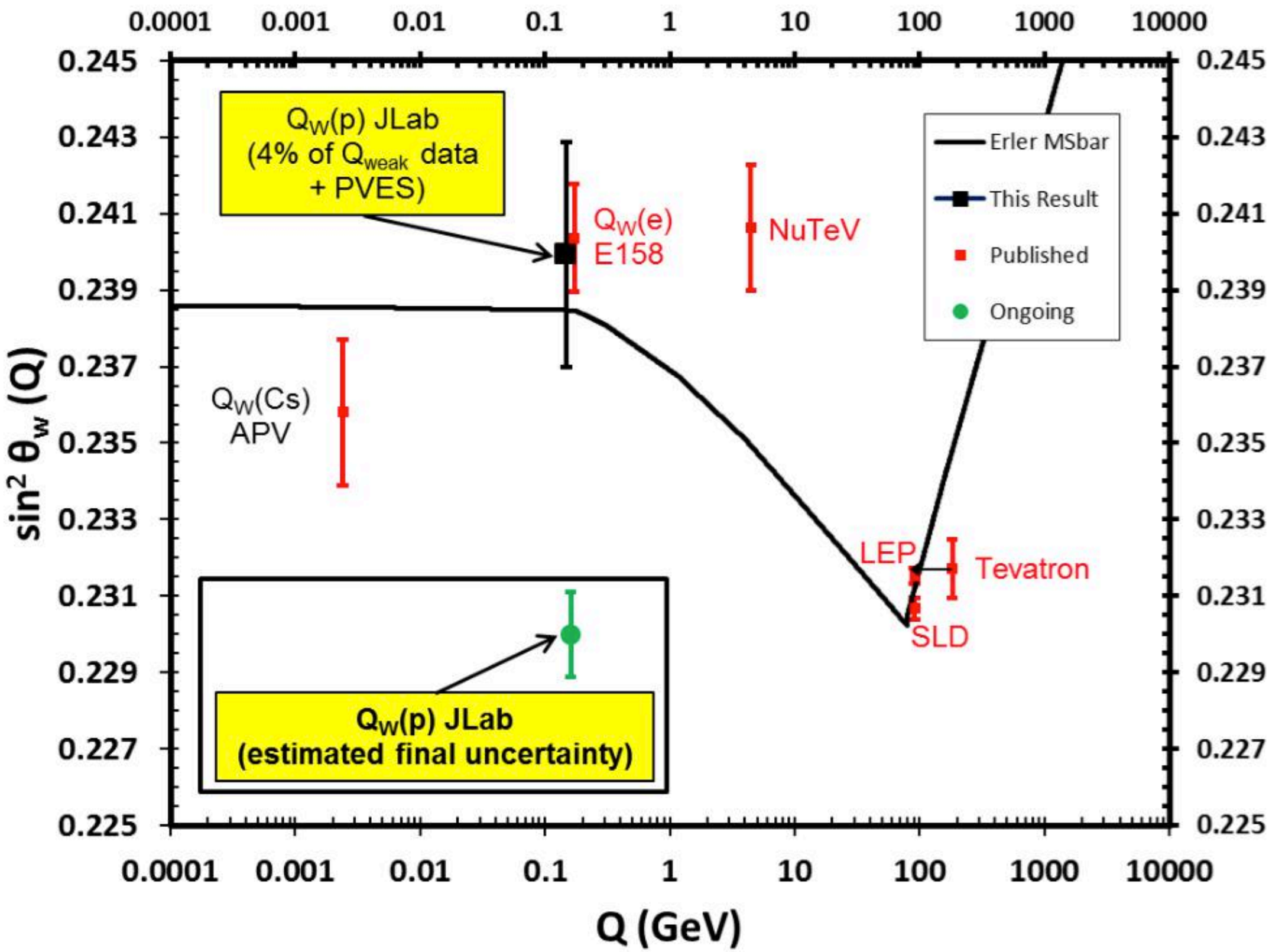
$$\propto < n'L' | \frac{d}{dr} | nL > |_{r=0} \qquad R_{nL} \approx r^L Z^{L+1/2}$$

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

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

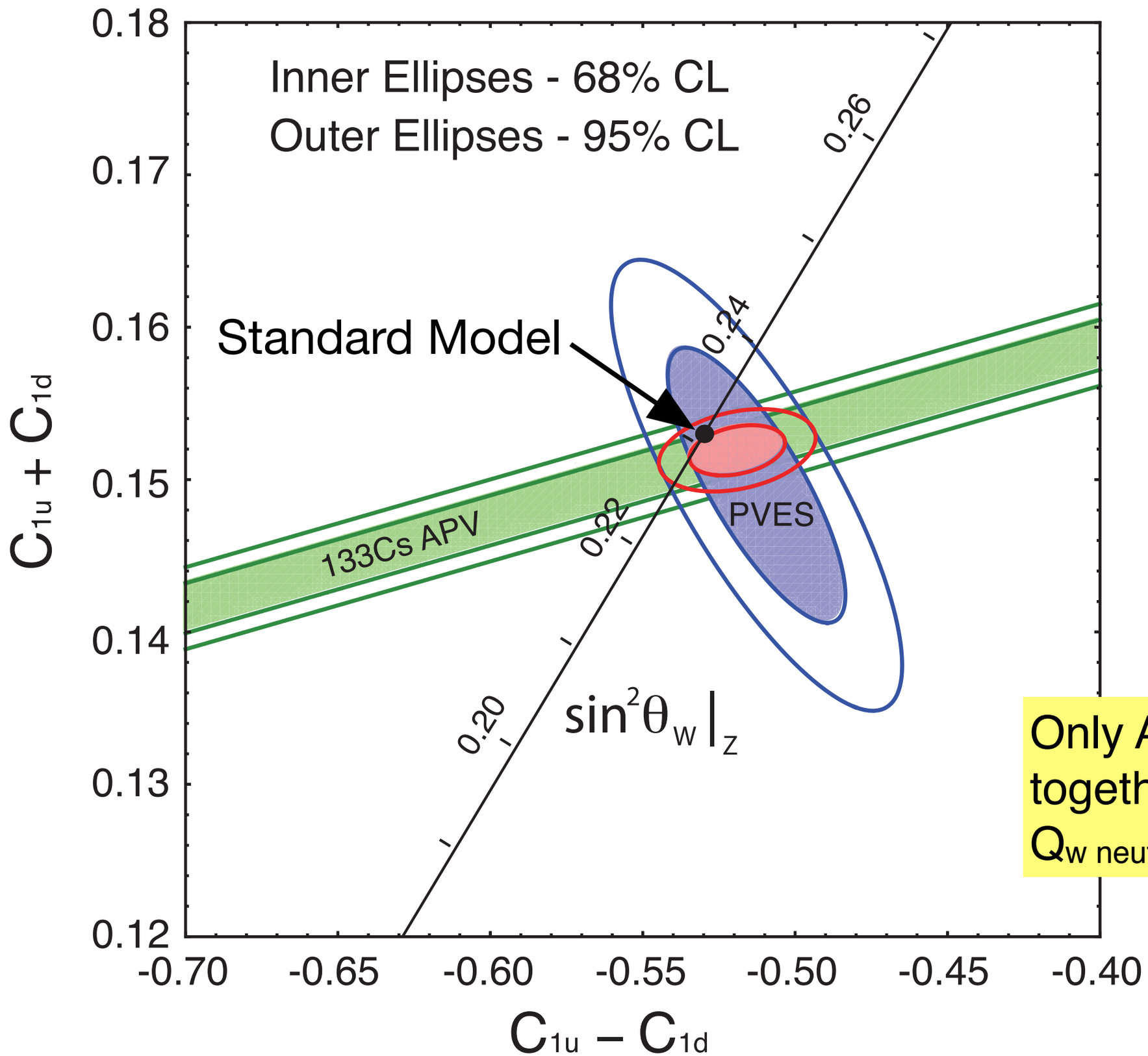
Bouchiat, 1974

Weak Mixing Angle: Running of $\sin^2 \theta_W$



Qweak collaboration (talk by R. Carlini, CIPANP 2015)

APNC uniquely provides the orthogonal constraint ($C_{1u} + C_{1d}$)



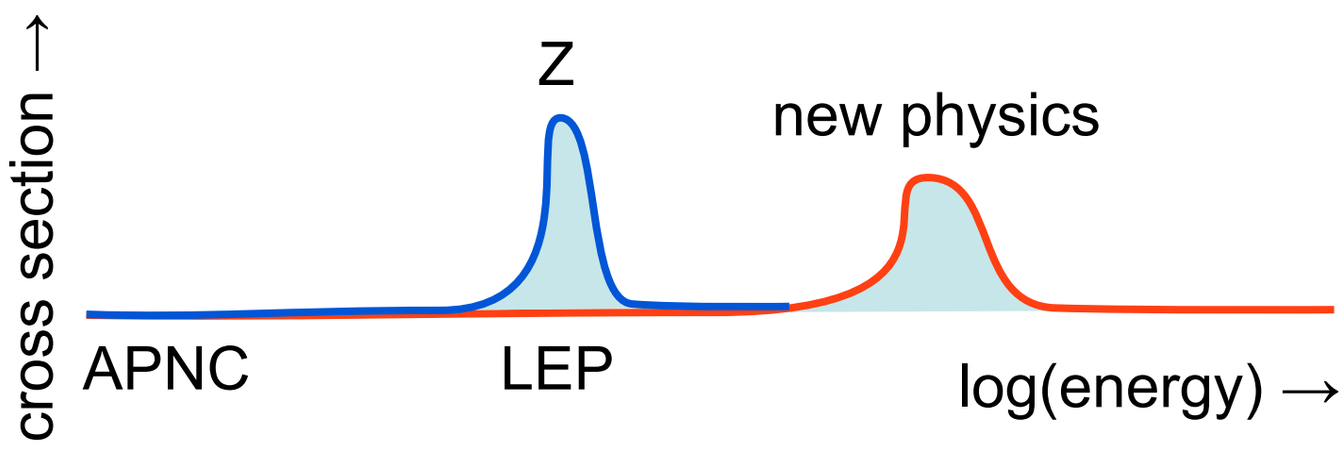
Only APV and Qweak together can extract $Q_{w\ neutron}$

D. Androic et al., Phys. Rev. Lett. 111, 141803 (2013)

Implications on 'new physics' from the Boulder Cs experiment (adapted from D. Budker, WEIN 98)

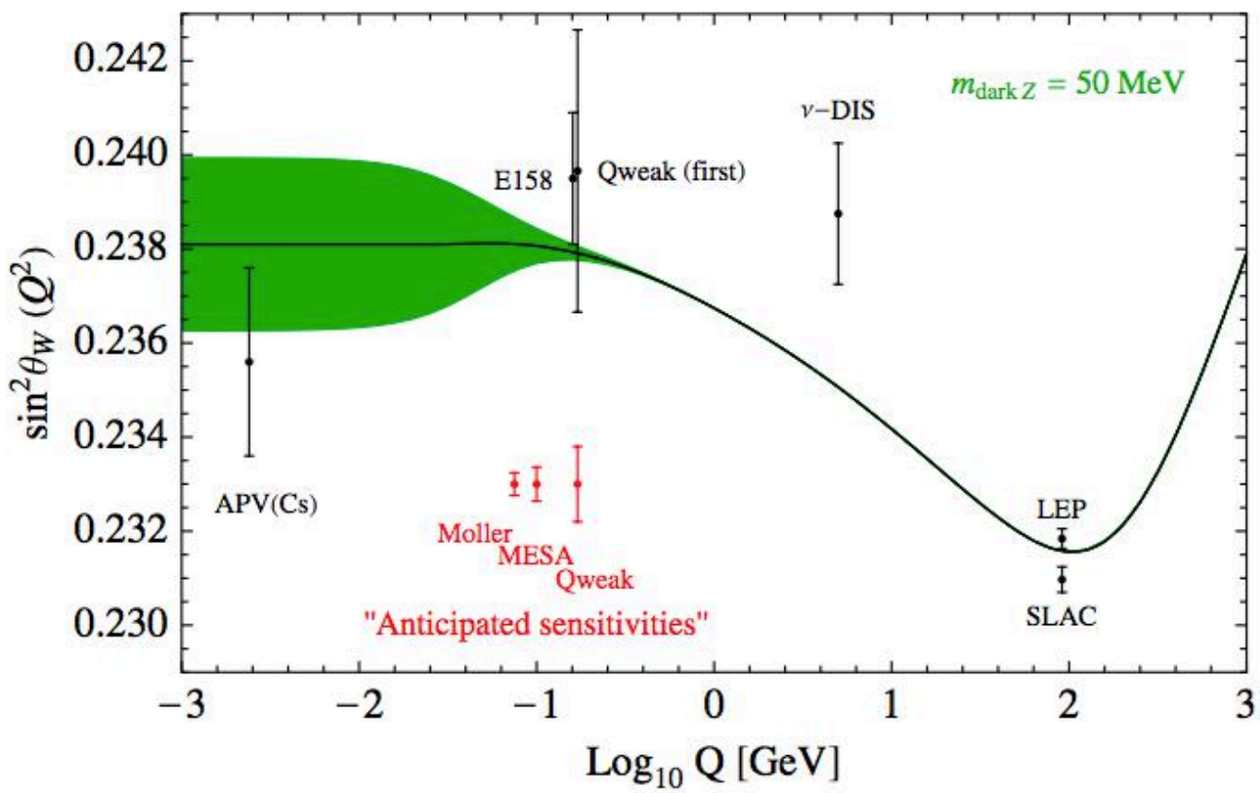
New Physics	Parameter	Constraint from atomic PNC	Direct constraints from HEP
Oblique radiative corrections	$S+0.006T$	S = -0.56(60) *	S=−0.13 ± 0.1 (−0.08) T=−0.13 ± 0.11 (+0.09)
Z_x-boson in SO(10) model	$M(Z_x)$	> 1.4 TeV *	> 820 GeV LHC > 2 (→ 5) TeV
Leptoquarks	M_S	>0.7 TeV	> 256 GeV, >1200 GeV indir.

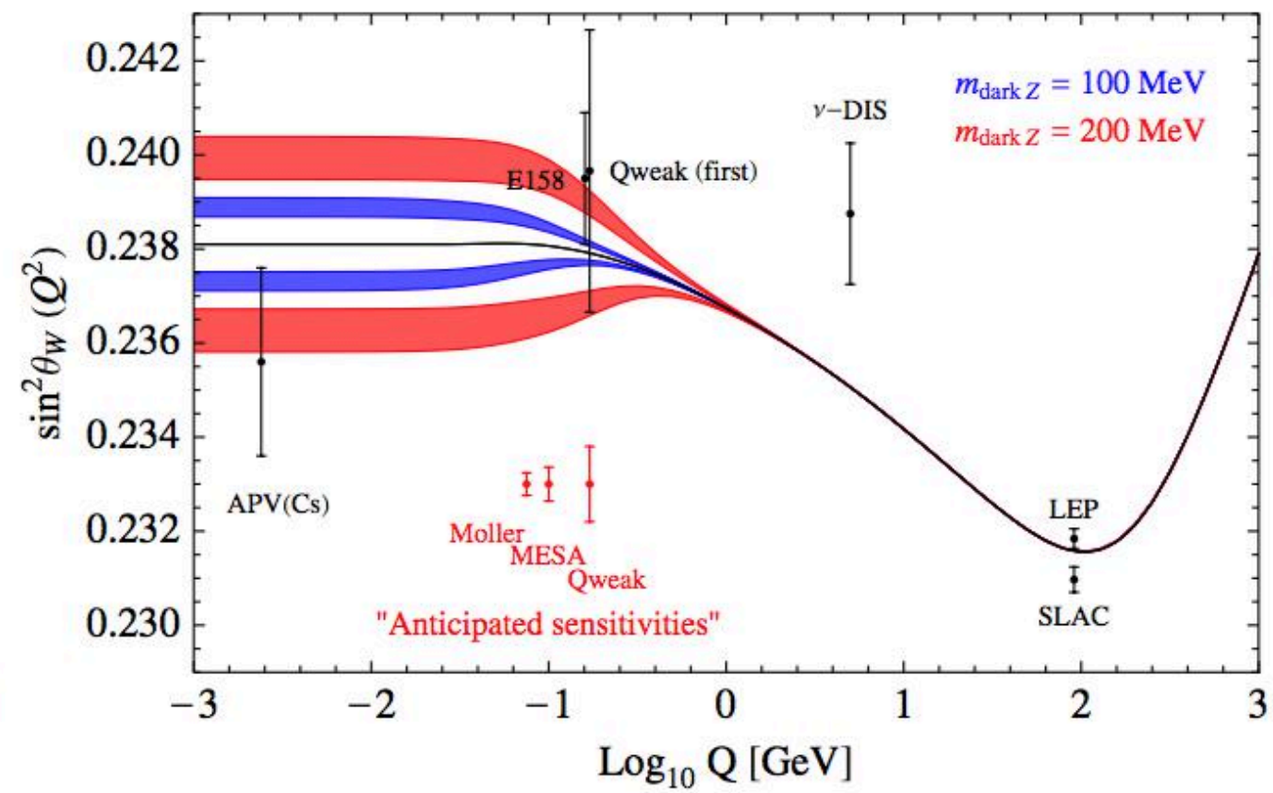
Why are low-energy experiments such as APV relatively sensitive to new physics at higher energy scales?



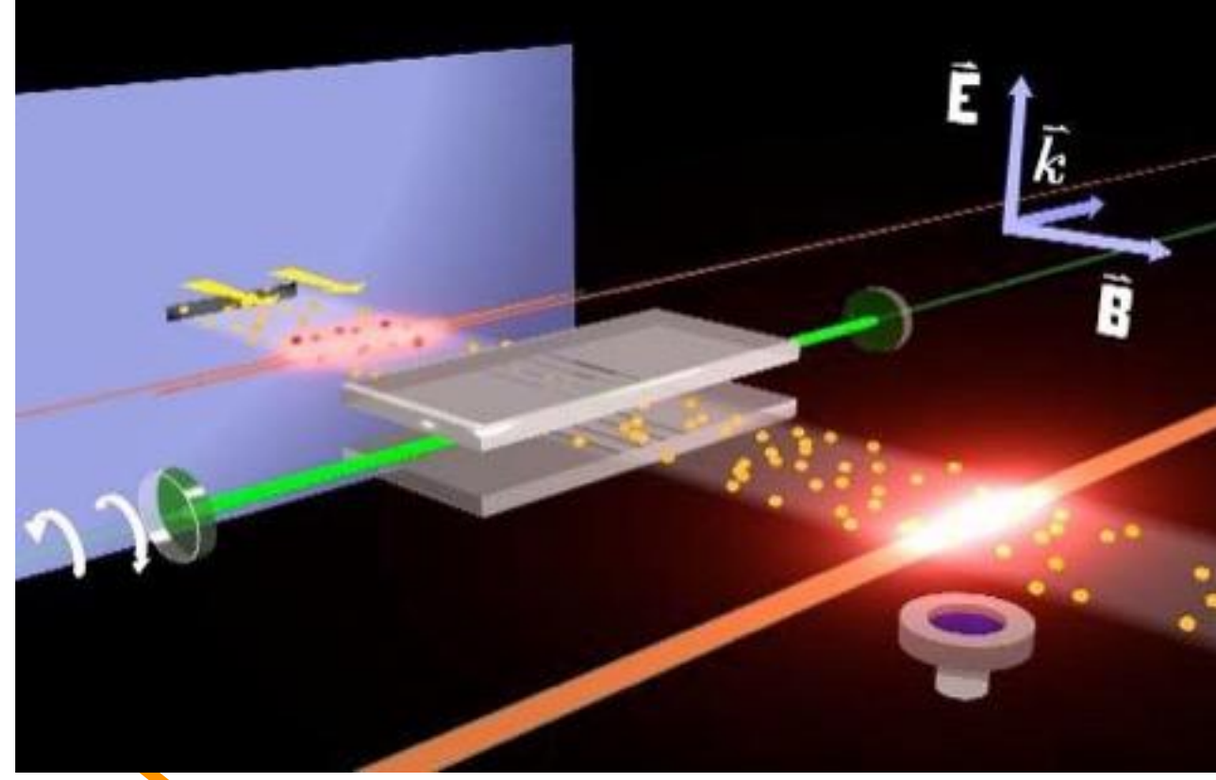
APNC can also constrain other scenarios, e.g. couplings to new light particles (e.g. Bouchiat & Fayet 05)

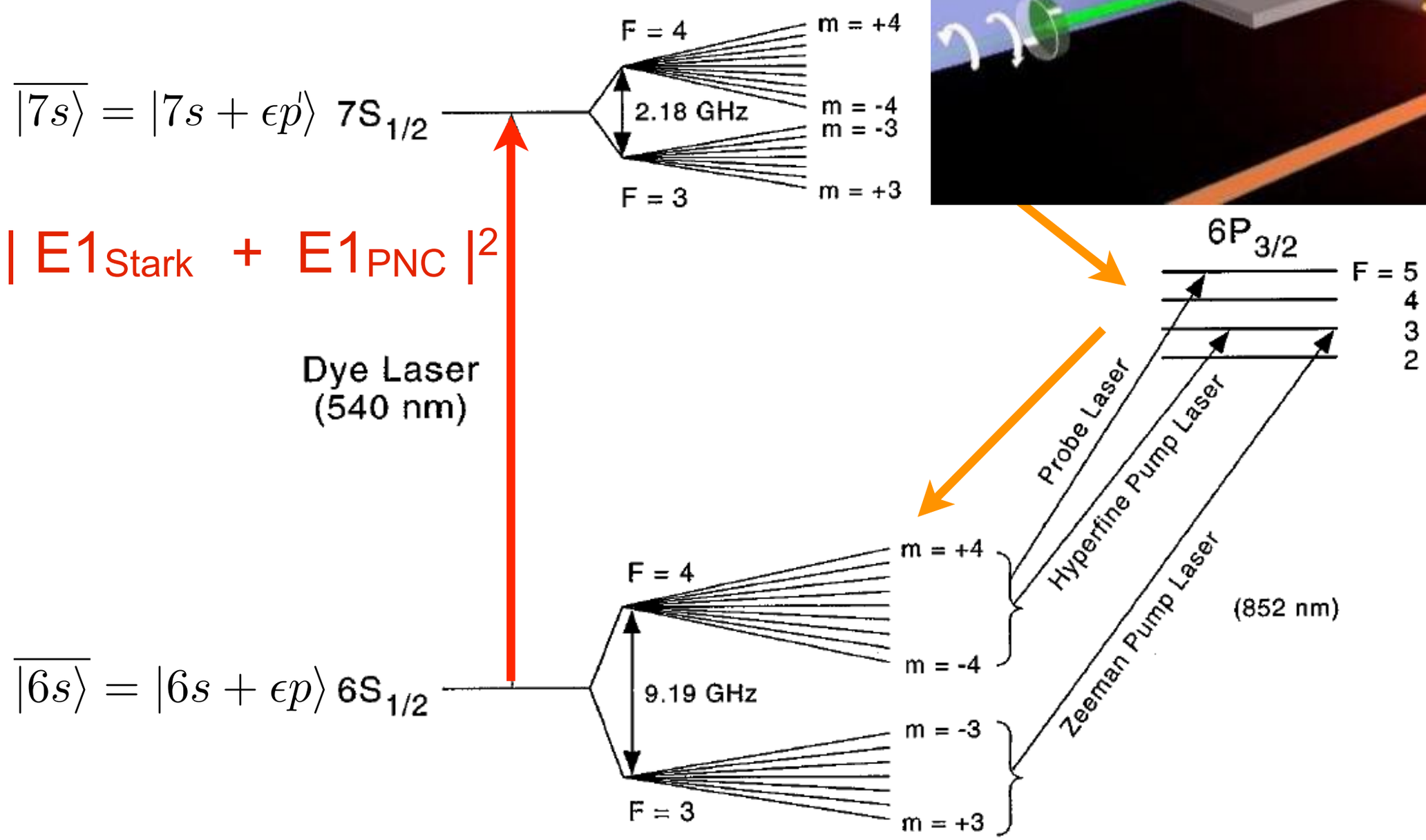
Parity violation from dark bosons [Davoudiasl PRD 89, 095006 (2014)]





The Boulder Cs Experiment (Wood, 1996)





$$\frac{\mathrm{Im}(E1_{\mathrm{PNC}})}{\beta} = \begin{array}{ll} -1.5576(77) & \mathrm{mV/cm} \\ -1.6349(80) & \mathrm{mV/cm} \end{array} \qquad \begin{array}{l} 6S\ F = 3 \rightarrow 7S\ F' = 4 \\ 6S\ F = 4 \rightarrow 7S\ F' = 3 \end{array}$$

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!

Problems: (i) no stable isotope
(ii) need to know neutron skin of Fr nucleus
(iii) need to know charge radius of Fr nucleus

Answers: (i) go to TRIUMF's actinide target to get loads of Fr, and use trap
(ii) the PREX experiment at Jefferson Lab measures the neutron radius of ^{208}Pb
(iii) new idea to measure nuclear charge radius of unstable elements

A Fr APNC experiment at TRIUMF

- Actinide target will make ISAC a great place to pursue Fr physics such as NSI APNC
- 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

➡ APNC work can start even with low current on ISAC target!

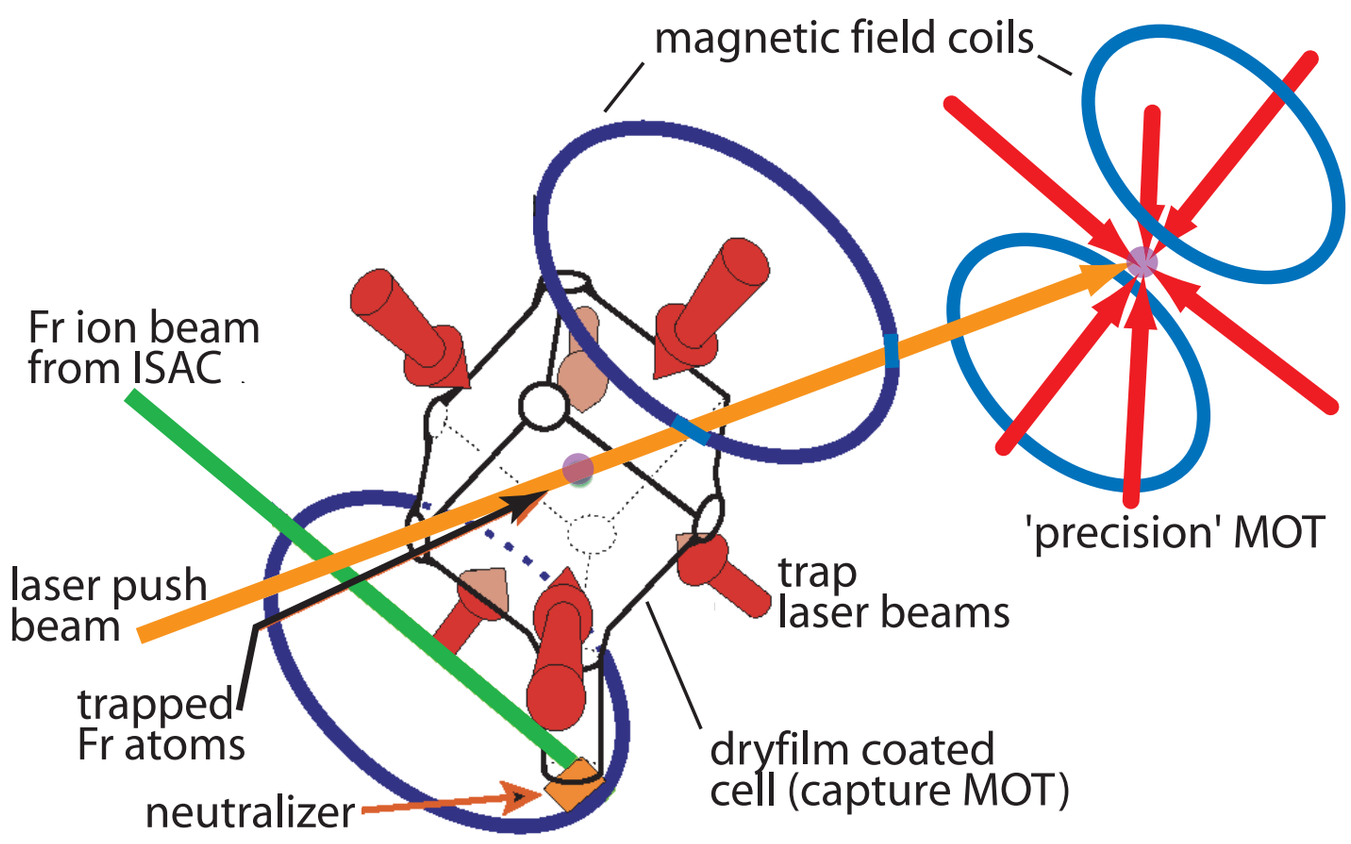
➡ But: most of the time needs to be spent on systematics. So realistically we are talking 100 days or more of beam, spread of more than a year!

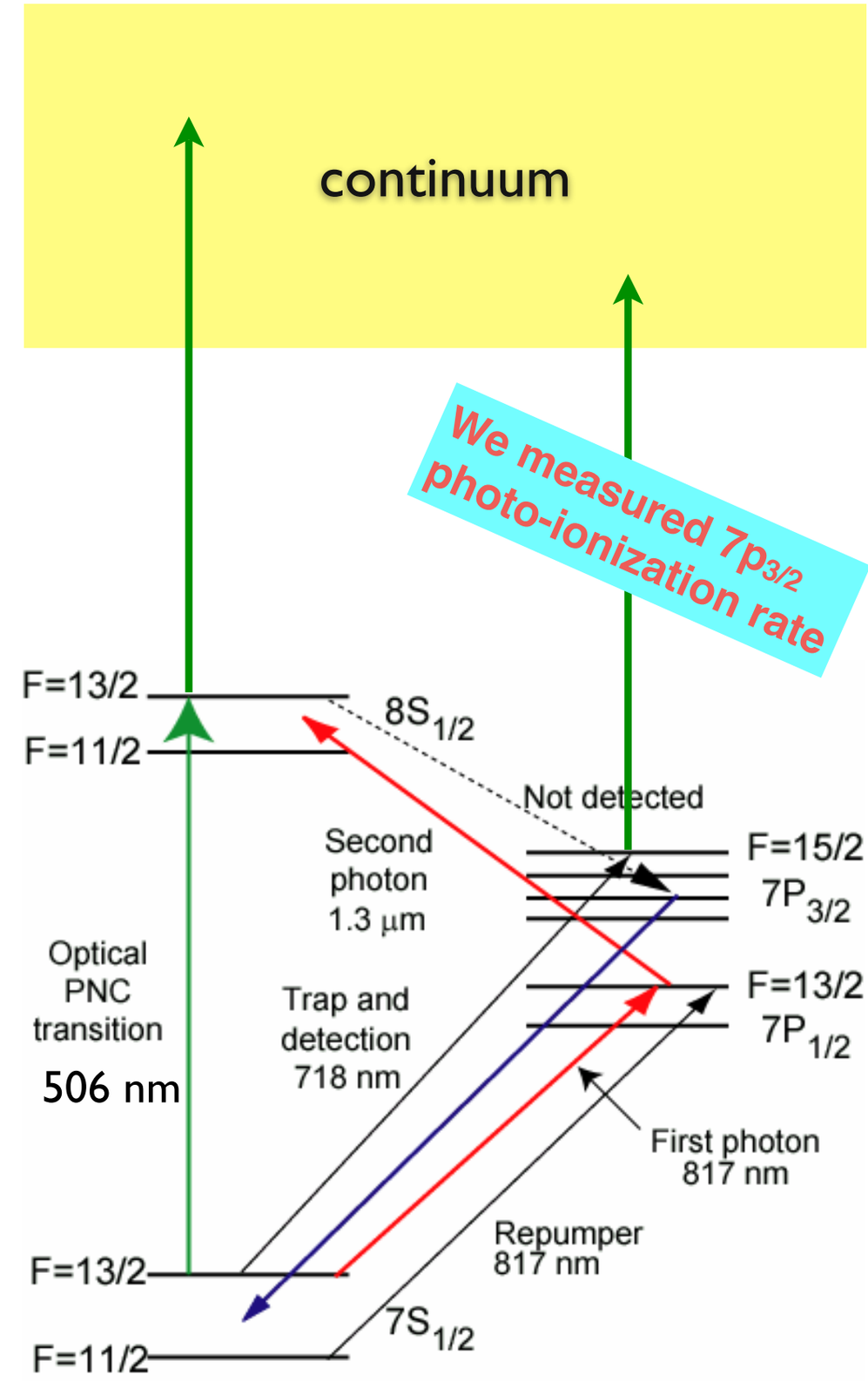
- 1% neutron radius measurement in ^{208}Pb with PREX would put a 0.2 % uncertainty on Q_w in ^{212}Fr (Sil 2005)
- atomic theory similar to Cs (0.25%), so progress in this direction required to go beyond Wood et al.
- can expect that all aspects improve over time (already happening: new Cs (alkali) APNC calculations, Porsev 2009, Dzuba 2012)

A Francium APNC Experiment at TRIUMF

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

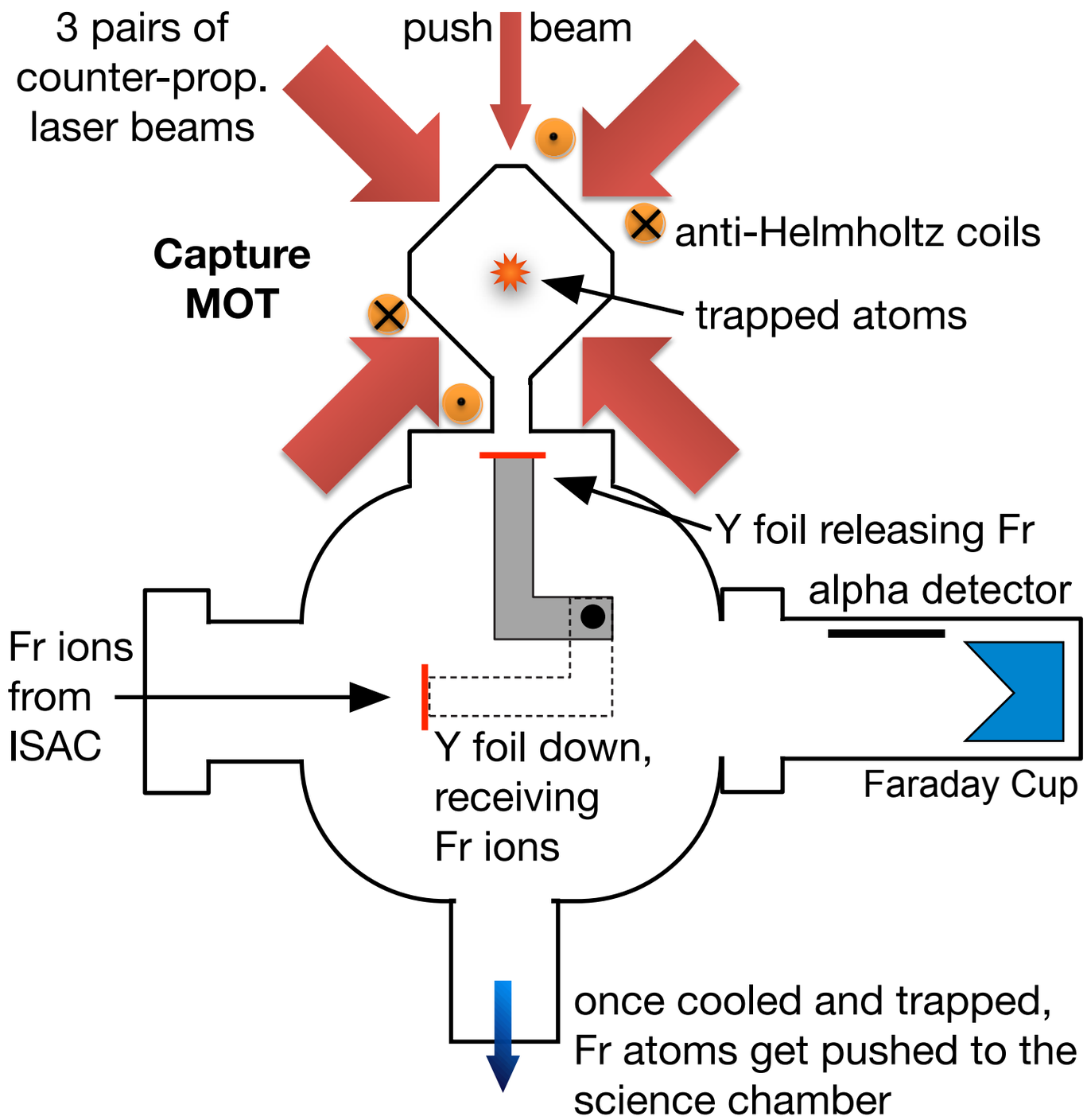
Fr trap:
excitation rate per atom: 30 s^{-1}
but asymmetry 18x larger
APNC possible with 10^6 - 10^7 atoms!

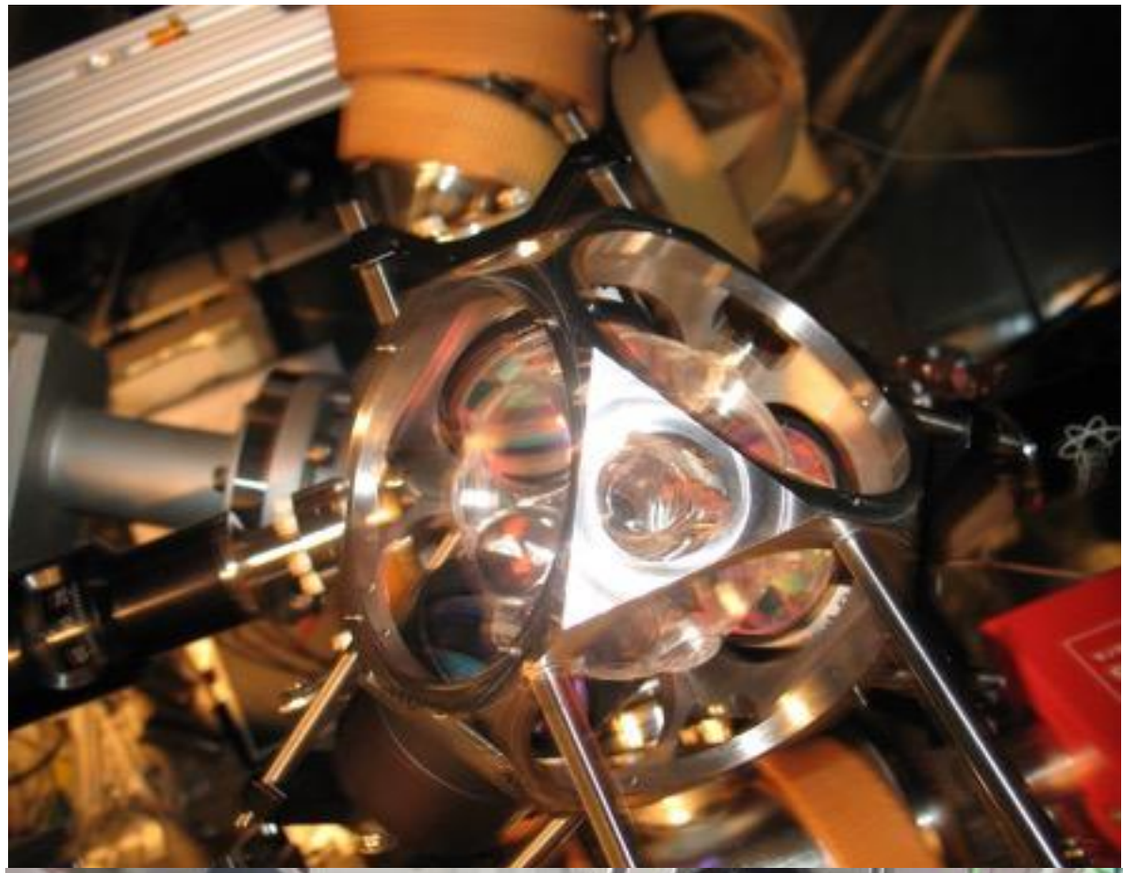


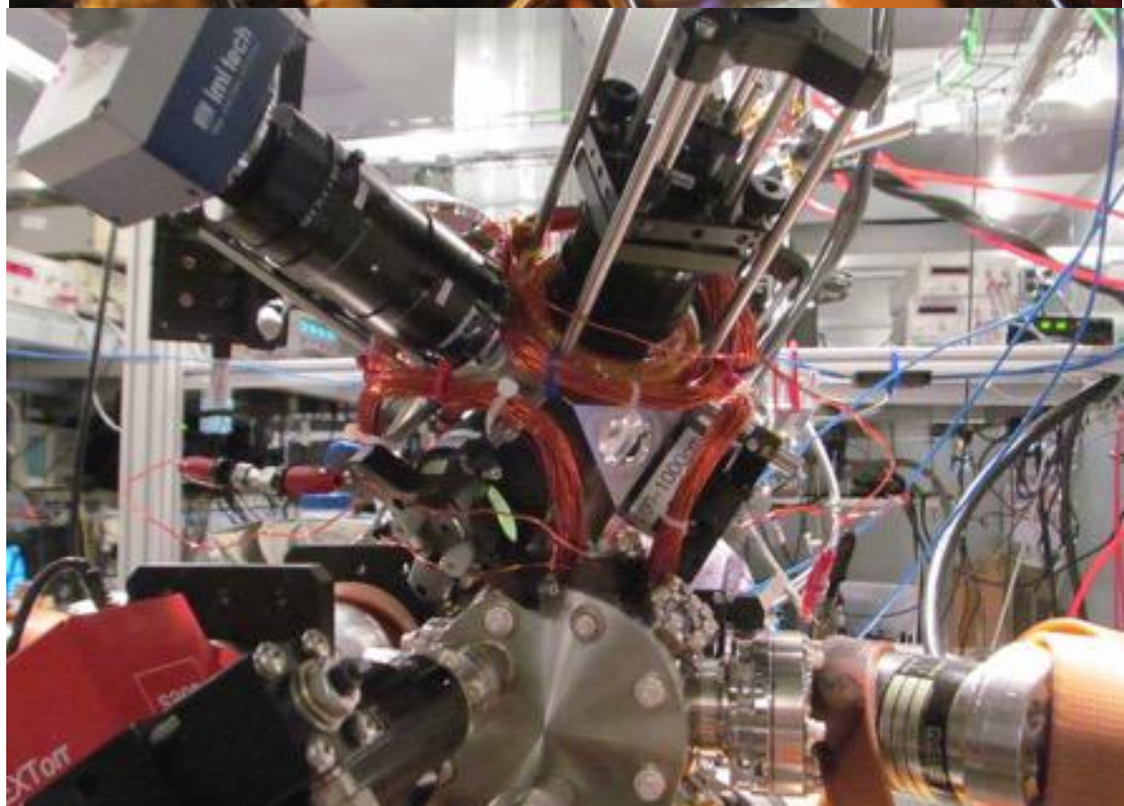


The Francium Trapping Facility at TRIUMF/ISAC

part 1: online capture trap

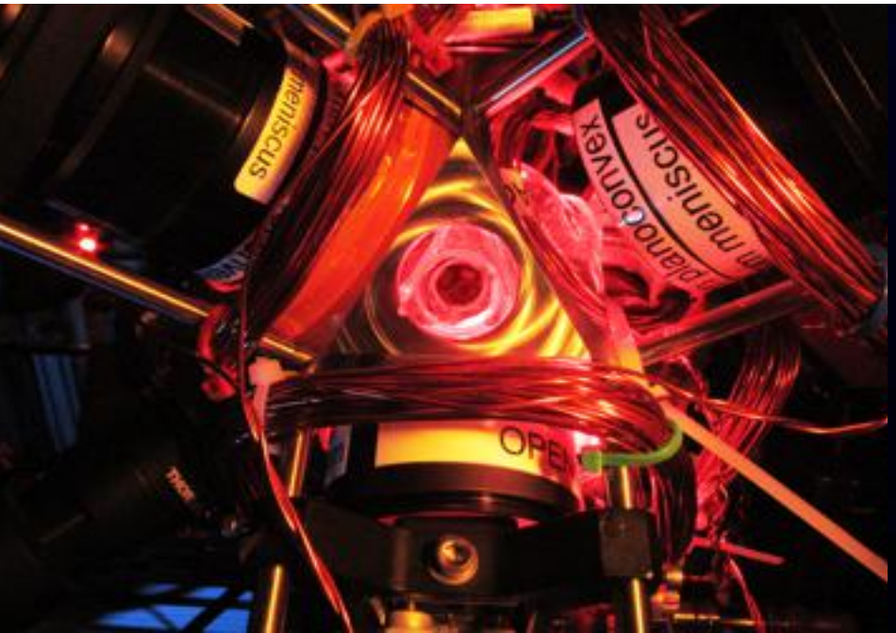


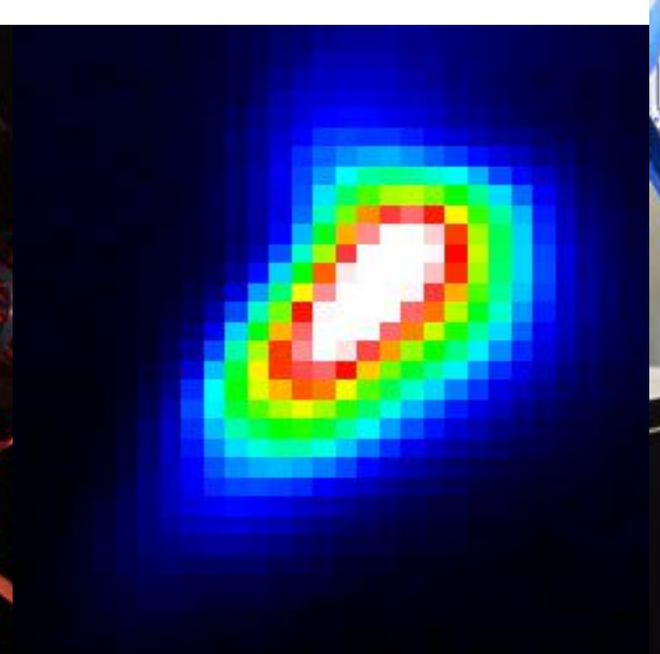




The Francium Trapping Facility

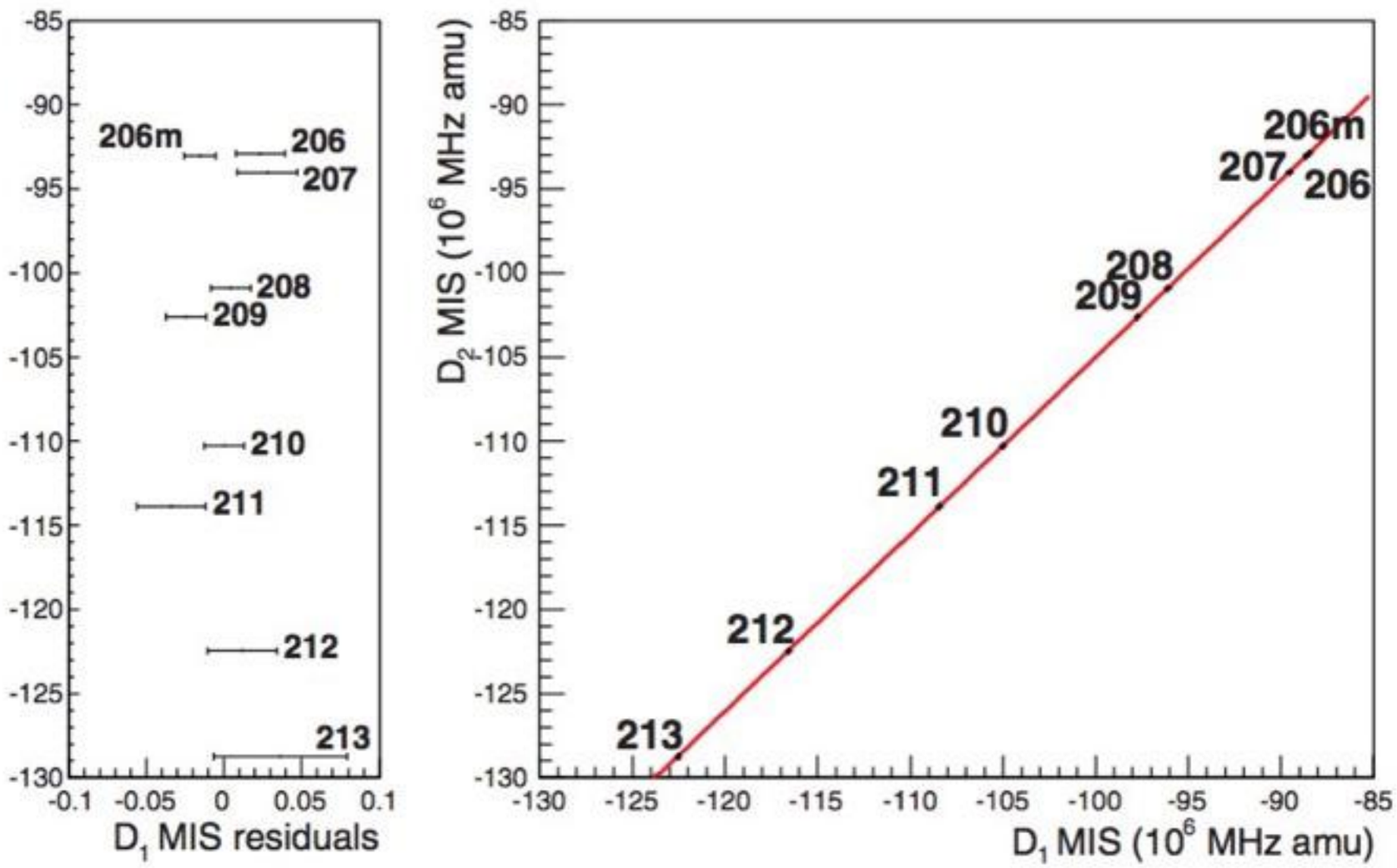
- Sep 2012 - Sep 2013: first beam, trapping of many isotopes: $^{206m, 206, 207\text{-}213, 221}$Fr
- Beamline and capture laser trap commissioned
- First physics measurements on allowed transitions → yielded useful info for future APNC





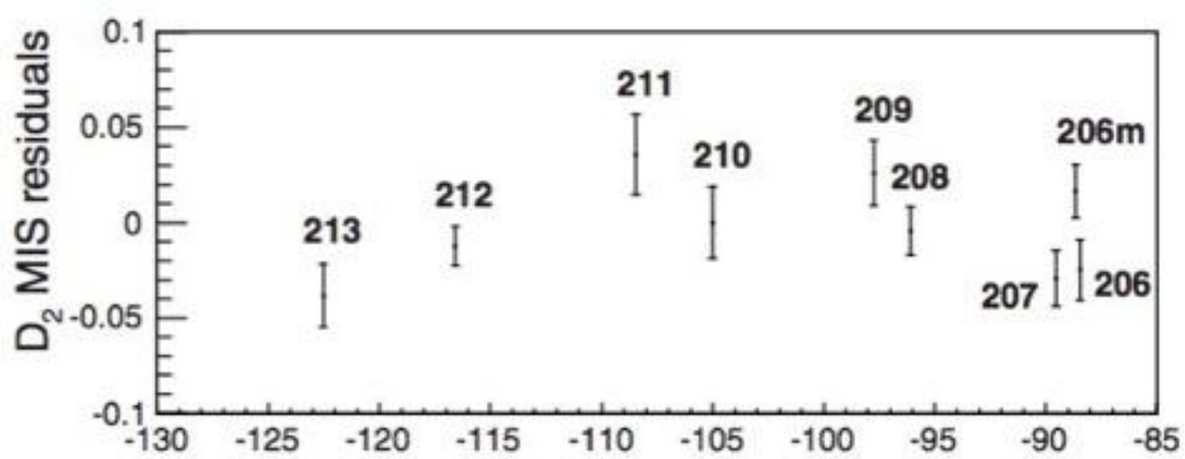
D1 isotope shifts in a string of light francium isotopes

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



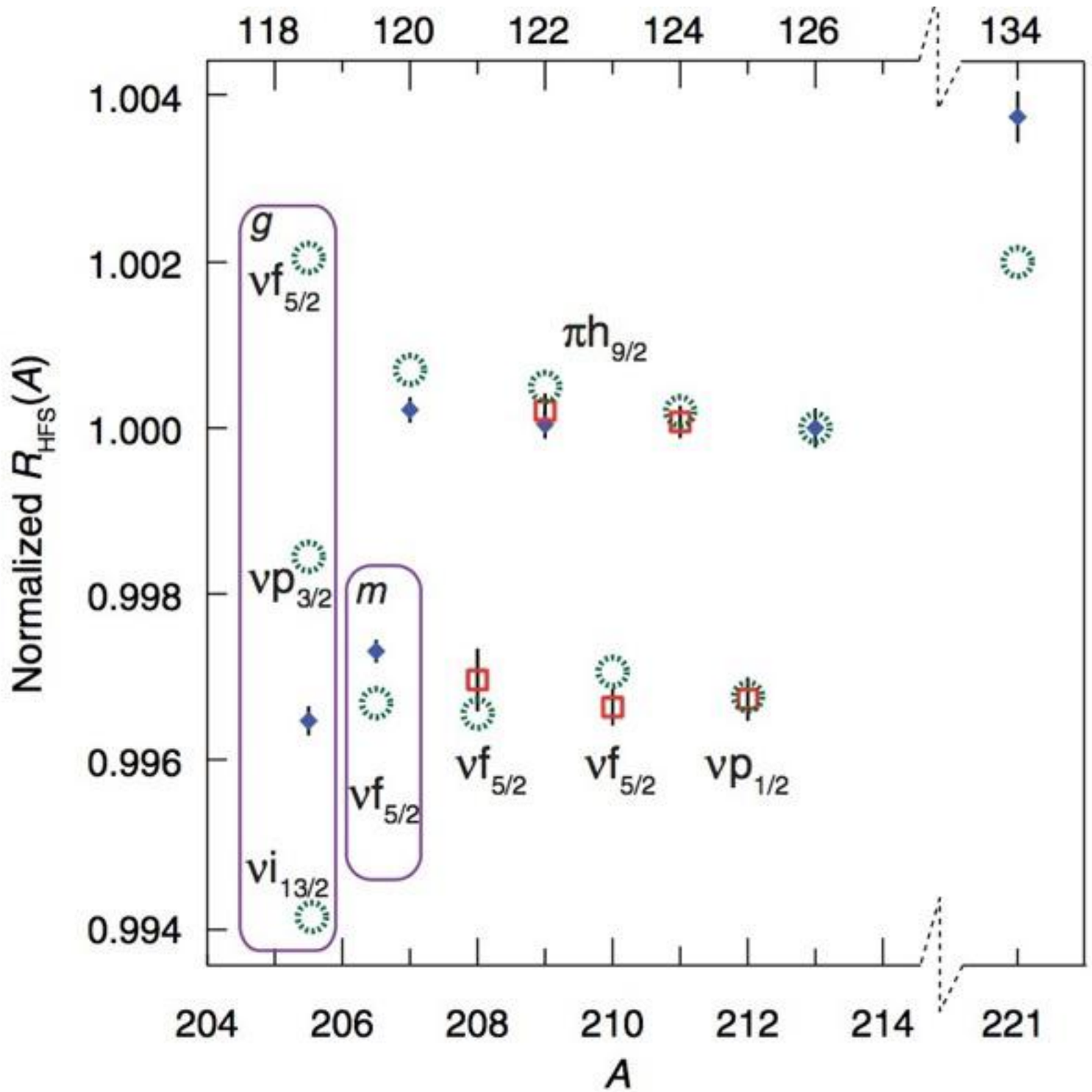
Benchmarks state-of-the-art atomic theory in Fr by Safranova and others.

Fit Results
χ^2 / ndf = 7.00094 / 7
slope = 1.0521 ± 0.0008
int = 194 ± 78 GHz amu



Hyperfine anomaly in light francium isotopes

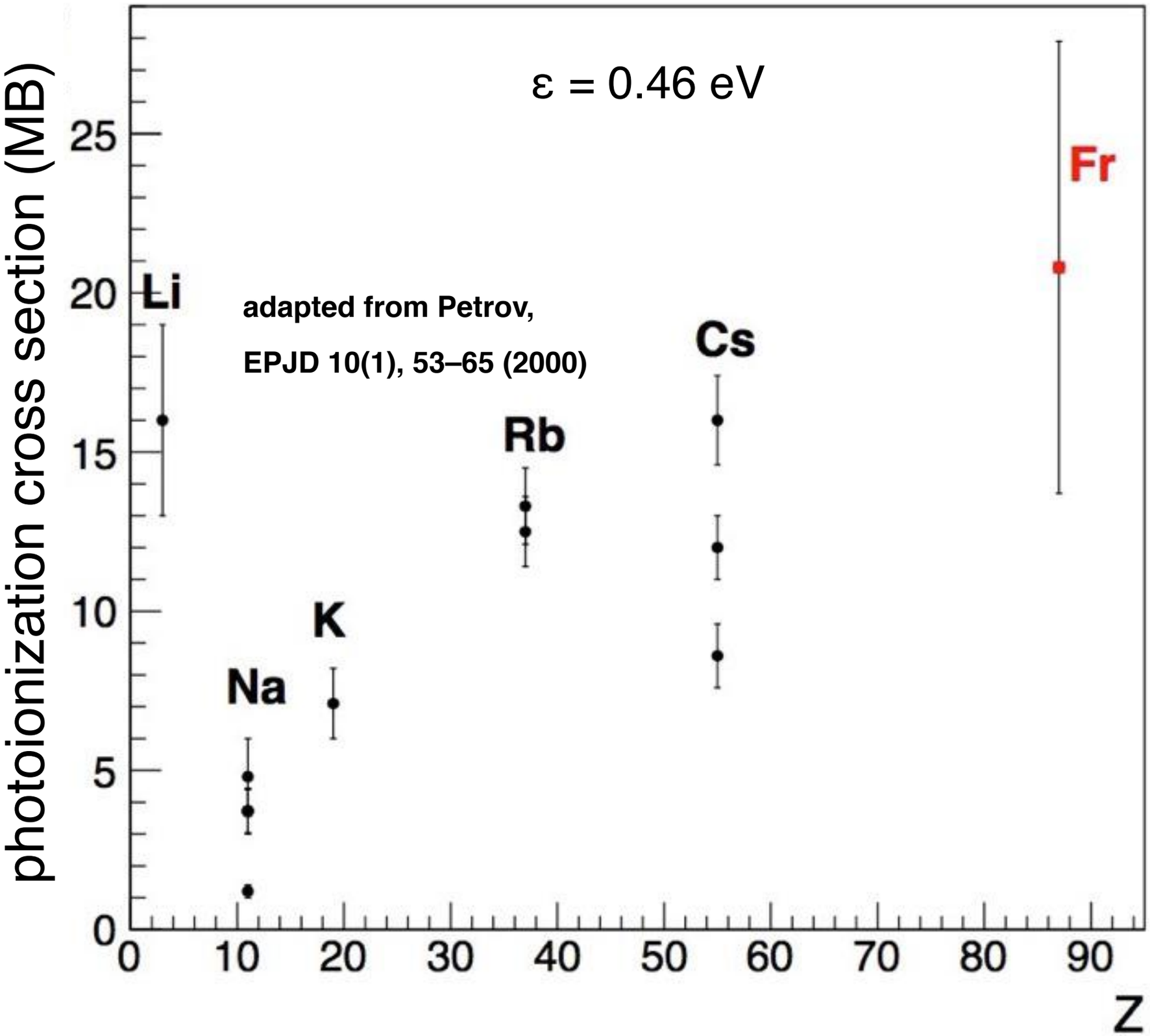
Zhang et al., Phys Rev Lett 115, 042501 (2015)



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

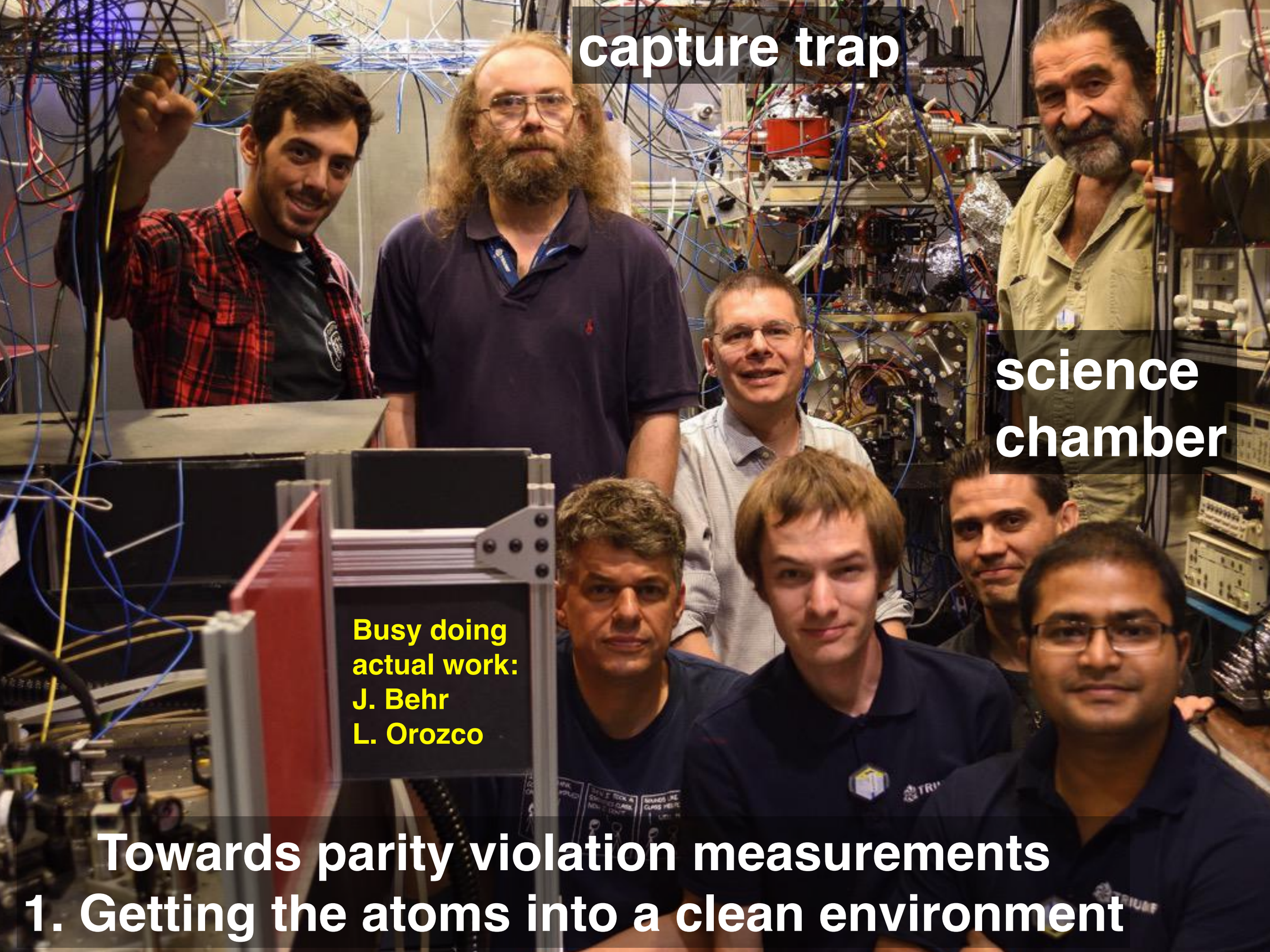
Photo-ionization cross-section of the 7p3/2 state in francium

Collister et al., accepted for Can J Phys

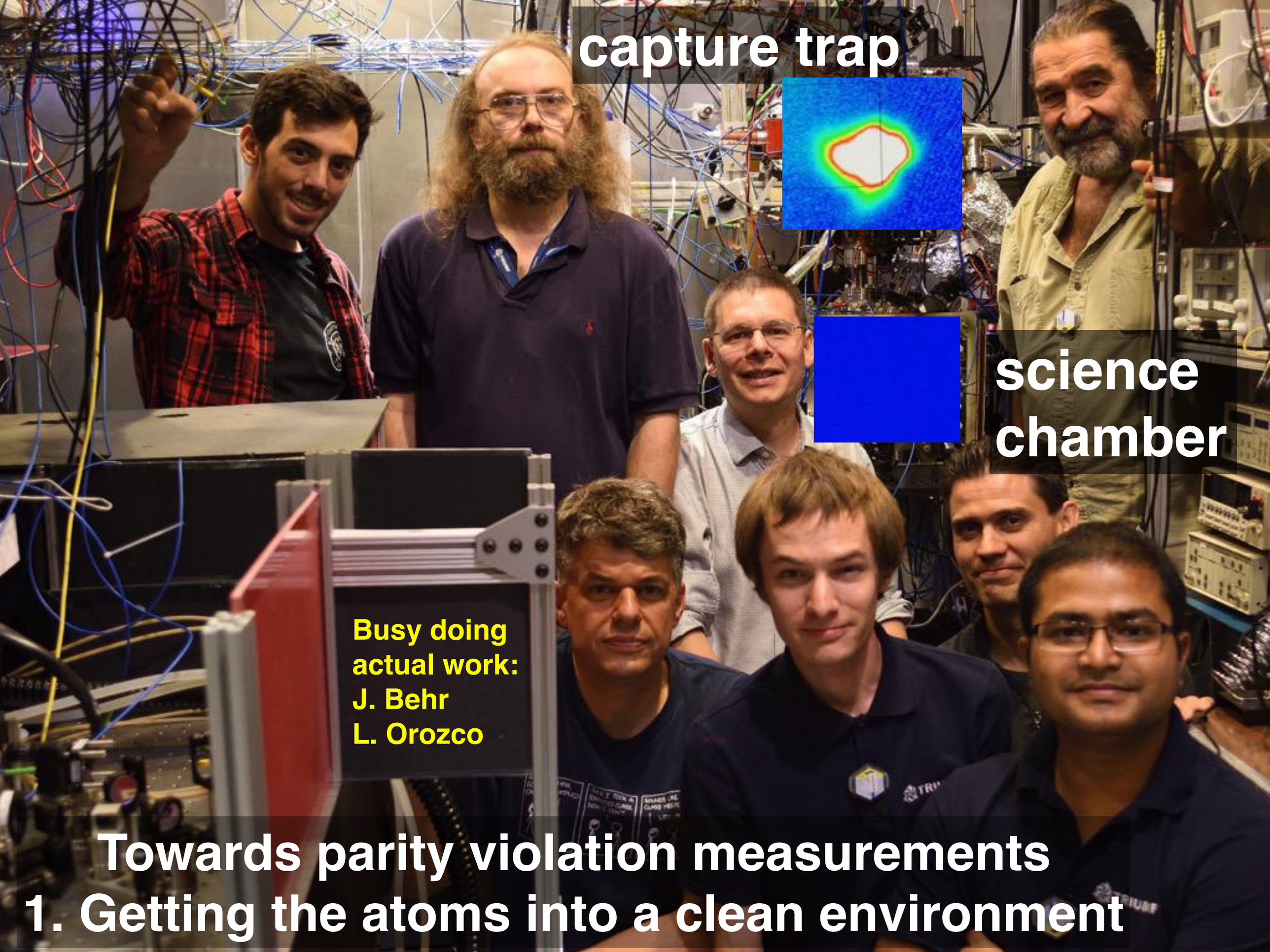


Allows us to predict the maximum 506 nm light intensity in the power buildup cavity.

Good news: This is better than the previously used conservative estimates.



Towards parity violation measurements
1. Getting the atoms into a clean environment



Towards parity violation measurements
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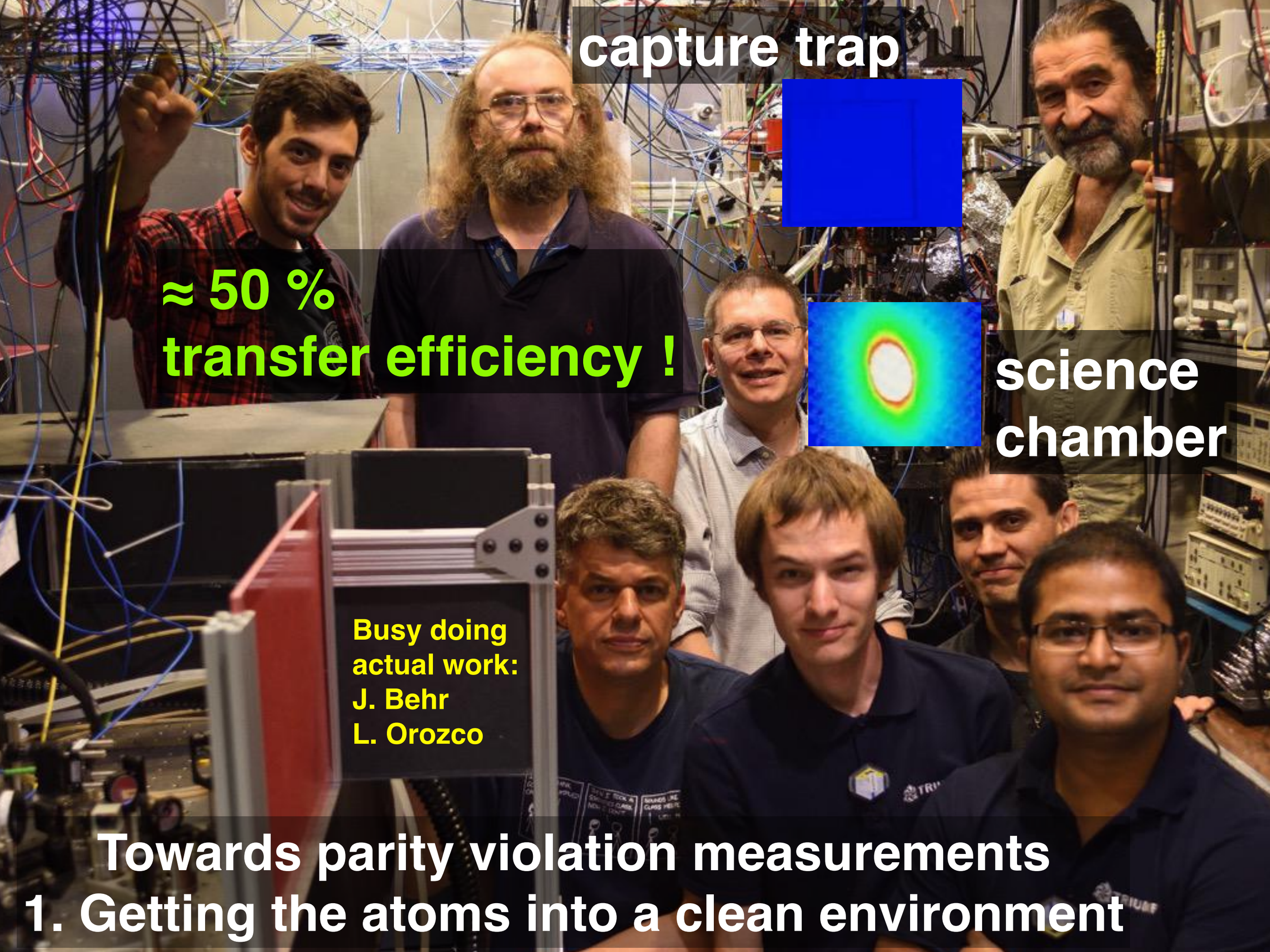

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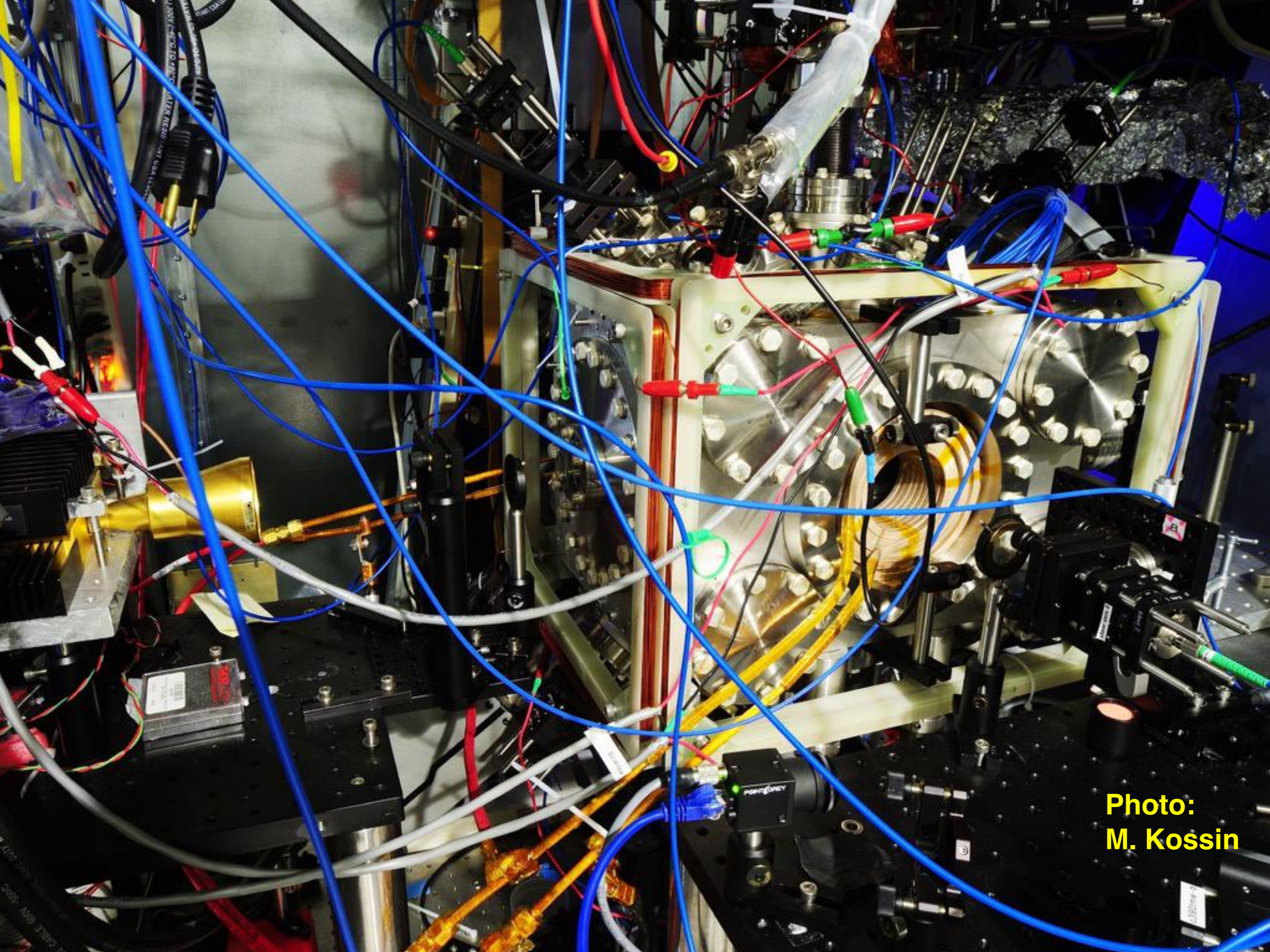
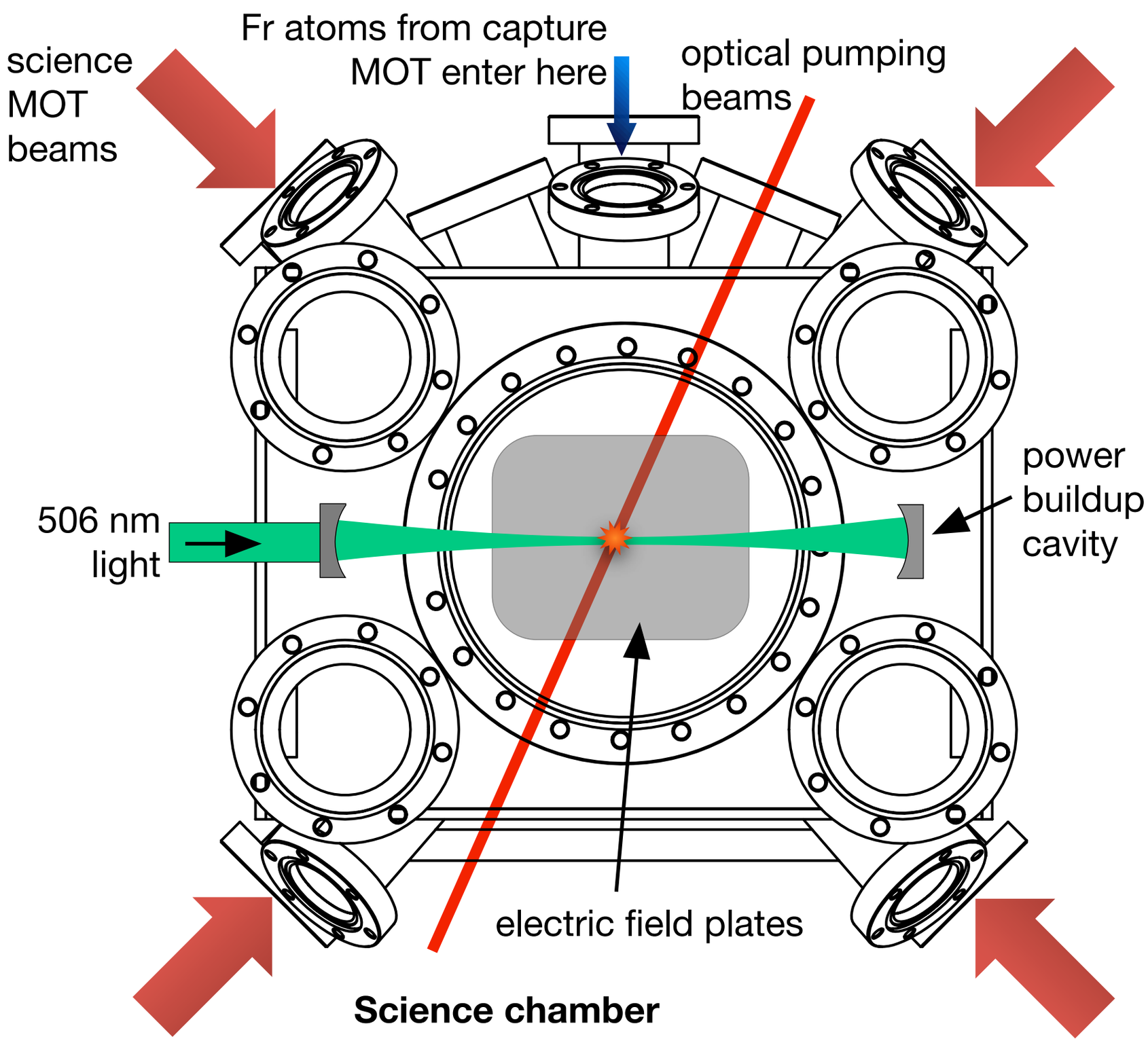


Photo:
M. Kossin


science
MOT
beams
Fr atoms from capture
MOT enter here
optical pumping
beams
power
buildup
cavity
506 nm
light
electric field plates
Science chamber

Current developments

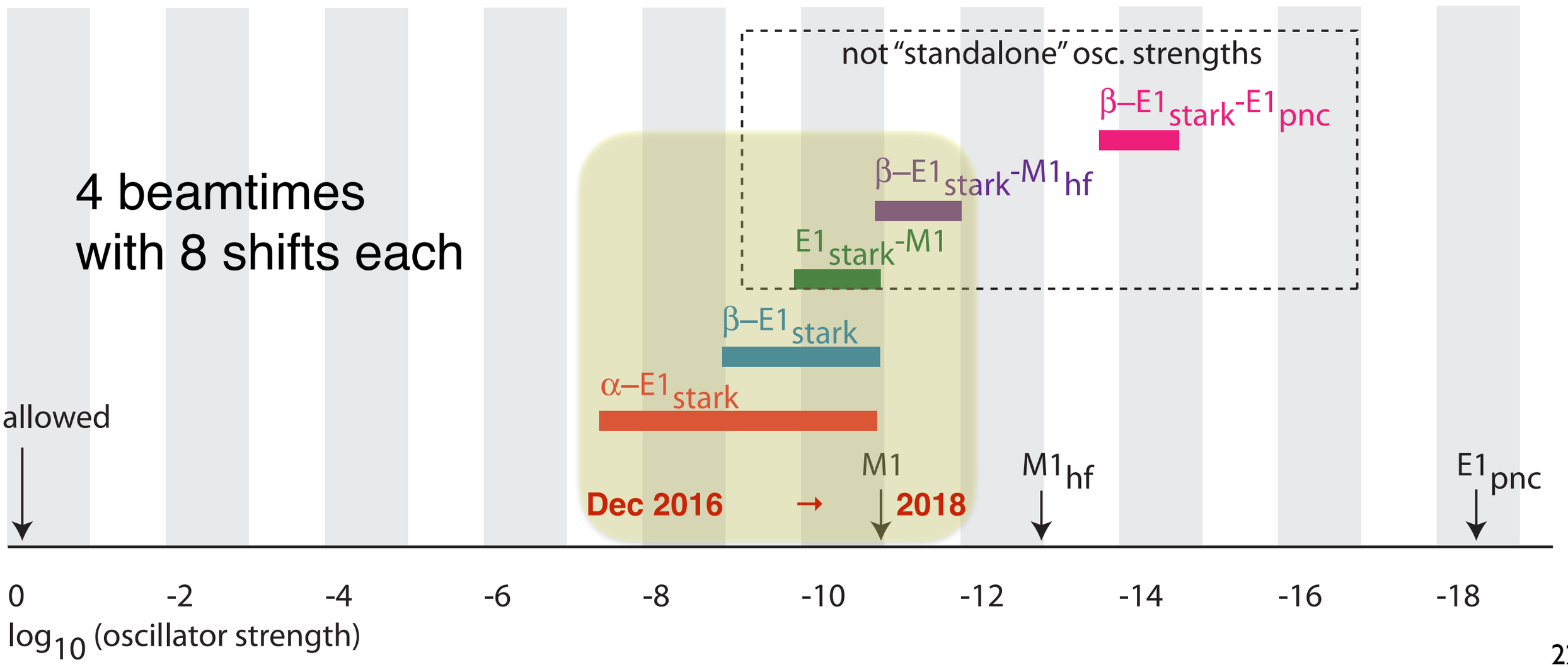
- August 2016
  - Observed for first time 7s - 8s using two-photon spectroscopy
  - Measured DC Stark shift of the 7s - 8s transition

- In development
  - reliable laser sources at 506 nm (Fr) and 496 nm (Rb)
  - ultra-stable (100 kHz) ULE cavity to lock those lasers
  - transparent field plates for internal operation of MOT

- Starting soon
  - UHV-compatible power-buildup cavity to enhance laser power for 7s - 8s spectroscopy

$$A_{7s\to 8s} = E1_{\mathrm{stark}} + M1 + E1_{\mathrm{pnc}}$$

- One of the faintest transitions observed in atoms
- $M1_{rel}$ hard to calculate (20-30 % discrepancy to expt. in Cs)
- "Most sensitive transition to the accuracy of the relativistic description of an atomic system" (Savukov et al, PRL 1999)
- So far, only measured in Cs, in context of APNC measurements



FrPNC collaboration

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TRIUMF via NRC

USA:
NSF, DOE

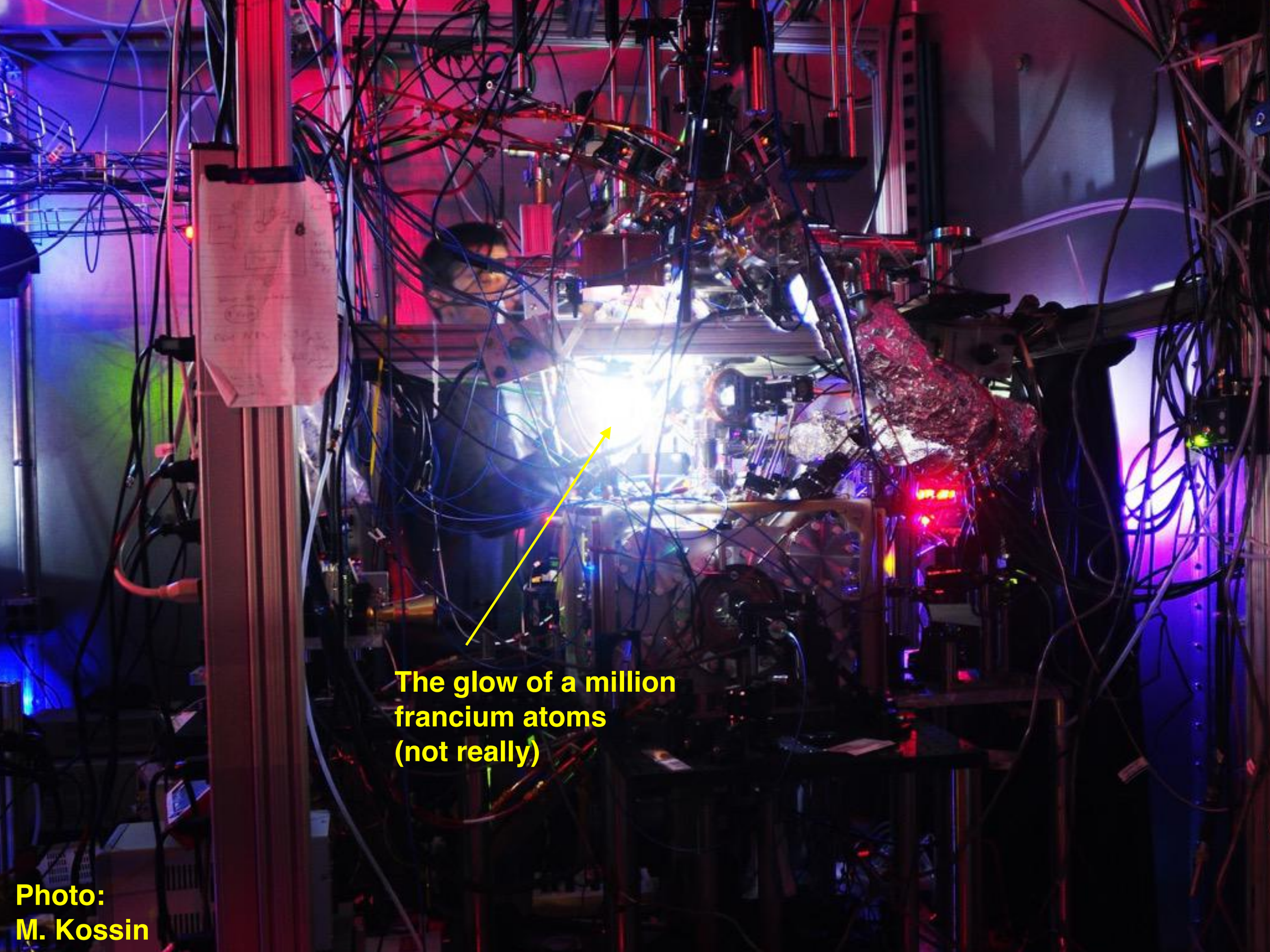

Photo:
M. Kossin