TRIUMF
CANADA'S NATIONAL LABORATORY FOR PARTICLE AND NUCLEAR PHYSICS

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Fundamental Symmetries in Laser Trapped Francium

—

Unique Opportunities with a High-Availability Actinide Target at TRIUMF

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University of Manitoba

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LABORATOIRE NATIONAL CANADIEN POUR LA RECHERCHE EN PHYSIQUE NUCLÉAIRE ET EN PHYSIQUE DES PARTICULES

Propriété d'un consortium d'universités canadiennes, géré en co-entreprise à partir d'une contribution administrée par le Conseil national de recherches Canada

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

Atoms/nuclei provide access to fun. sym., should be viewed as complementary to high energy approaches

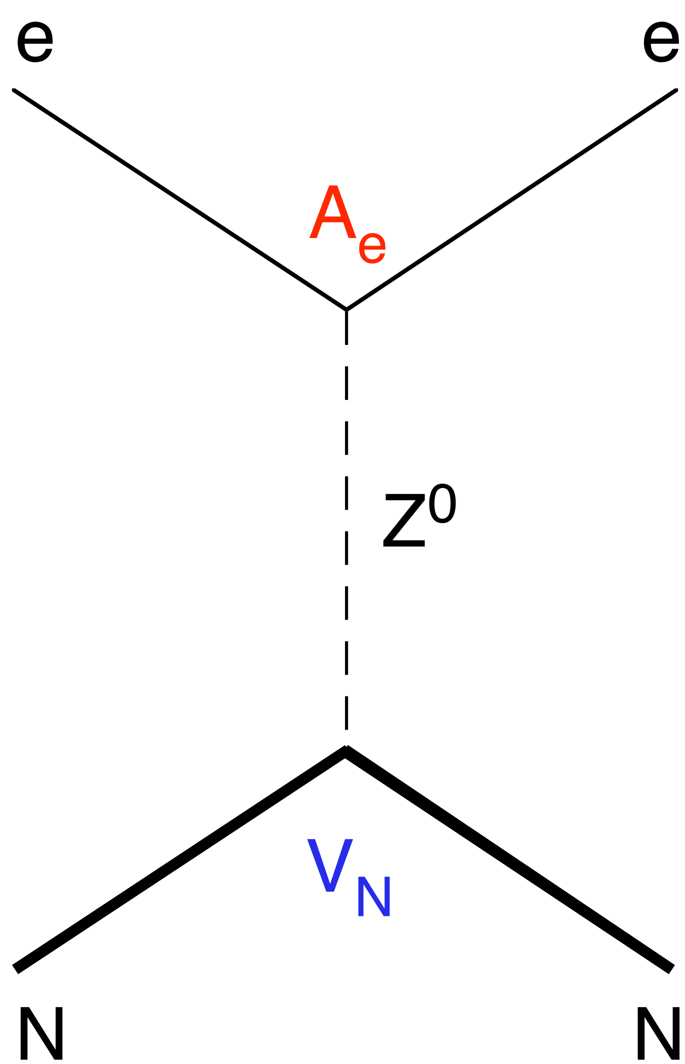
<table>
<tr><th></th><th>Atom</th><th>Nucleus</th></tr>
<tr><td>Charged current weak interactions, β-decay (JB)</td><td>new powerful techniques (atom traps)</td><td>rich selection of spin, isospin, half-life</td></tr>
<tr><td>Neutral current weak interactions
APNC
anapoles</td><td rowspan="2">tremendous accuracy of atomic methods (lasers, microwaves) neutral (strong external fields)
traps, cooling</td><td rowspan="2">huge enhancement of effects (high Z, deformation) over elementary particles
rich selection of spin, isospin, Z, N, deformation</td></tr>
<tr><td>Permanent electric dipole moments (TC)</td></tr>
<tr><td>Lorentz-symmetry & CPT violation (GG)</td><td>accuracy</td><td>selection of spin, Z, N</td></tr>
</table>

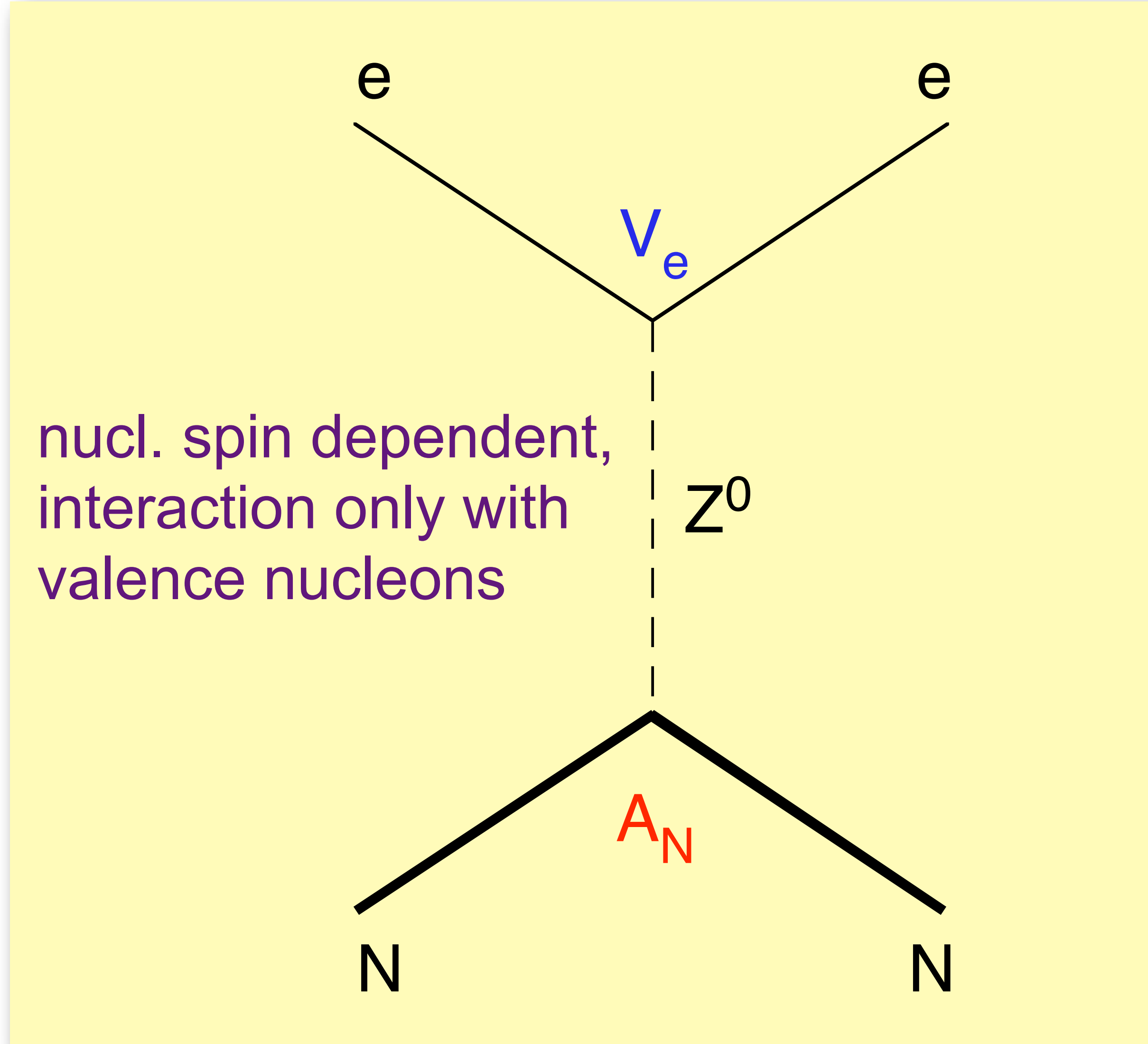
Some of most promising new candidates are heavy, radioactive systems (Rn, Fr)
Radioactive beam facilities are crucial

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

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

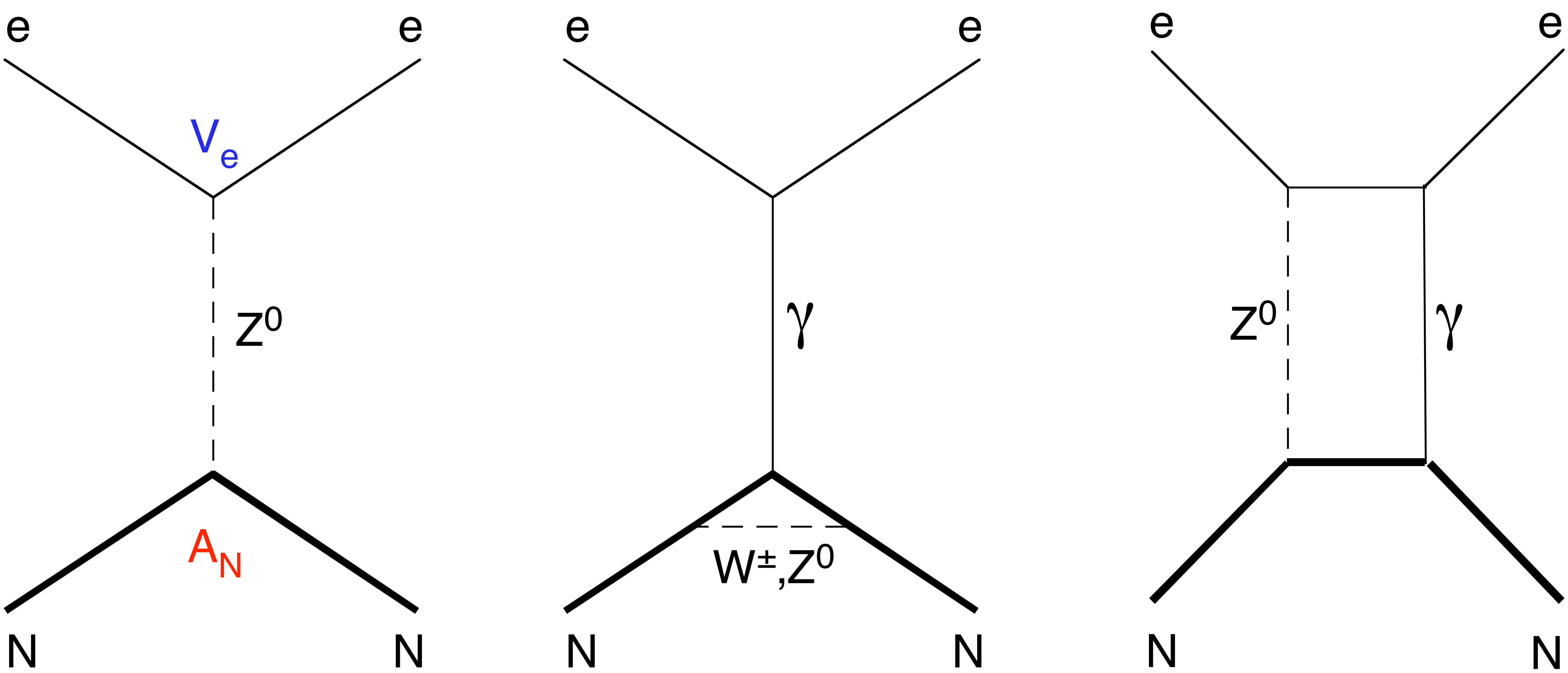
Drive s → s E1 transition!

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

use interference:

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

Nuclear spin dependent APNC



NSD Z-exchange

PV hadronic interactions
⇒ PV anapole moment
of the nucleus

hyperfine correction to
the weak neutral current

$$H_{\rm PNC} = \frac{G_F}{\sqrt{2}}\left(-\frac{Q_w}{2}\gamma_5 + \left(\frac{K}{I+1}\kappa_a + \kappa_2 + \kappa_{Q_w}\right)\frac{1}{I}\sigma_n\gamma_0\vec{\gamma}\right)\rho(\vec{r})$$

$|\kappa_2| \approx \mathcal{O}(1 - 4\sin^2\theta_w)$

$K = (-)^{I+1/2-\ell}(I+1/2)$

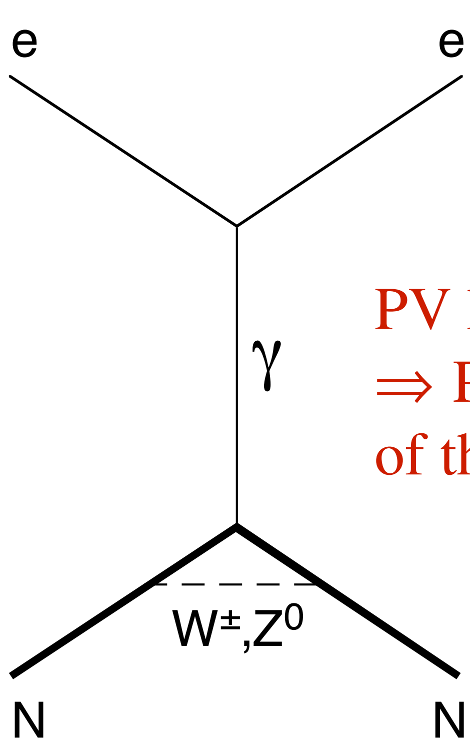
$g_p \approx 5 \qquad g_n \approx -1$

Khriplovich and Flambaum (1980)

$\kappa_a \approx 1.15\times 10^{-3} A^{2/3}\mu_n g_n$

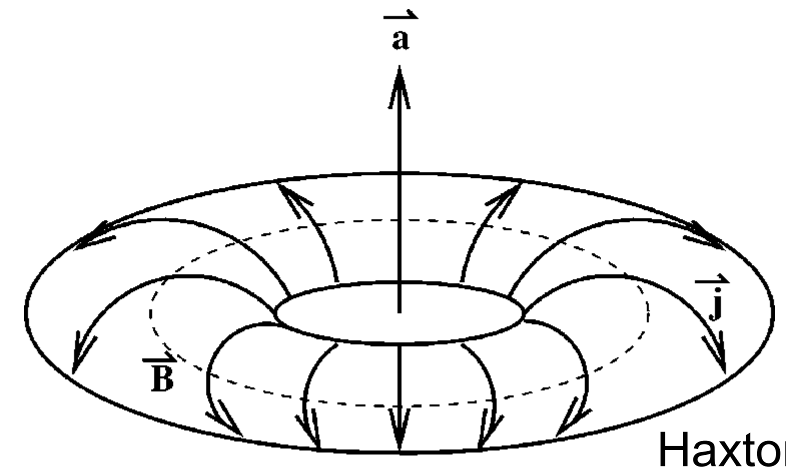
Nuclear spin dependent APNC

For A $\gtrsim$ 20 the anapole dominates the NSD part (at least for unpaired protons)



PV hadronic interactions
⇒ PV anapole moment
of the nucleus

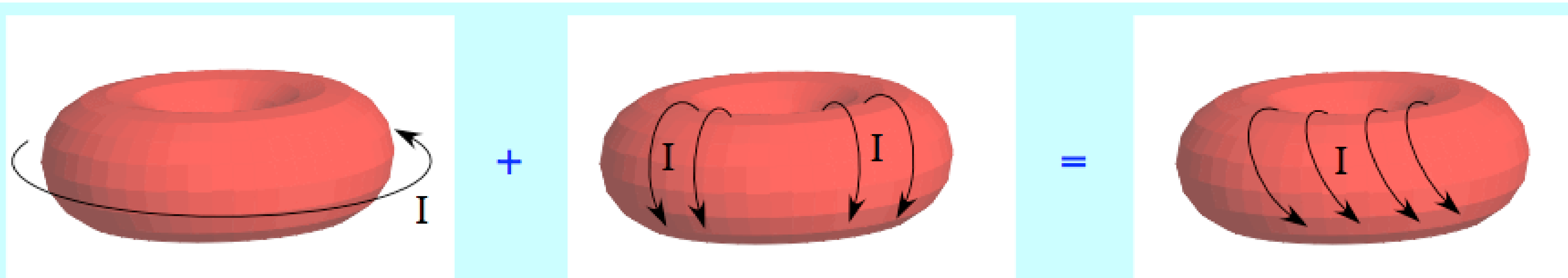
$$\mathbf{a} = -\pi \int \mathbf{j}(\mathbf{r}) r^2 d^3 r = \frac{1}{e} \frac{G}{\sqrt{2}} \frac{K\mathbf{I}}{I(I+1)} \kappa_a$$



Haxton et al., PRC 2002

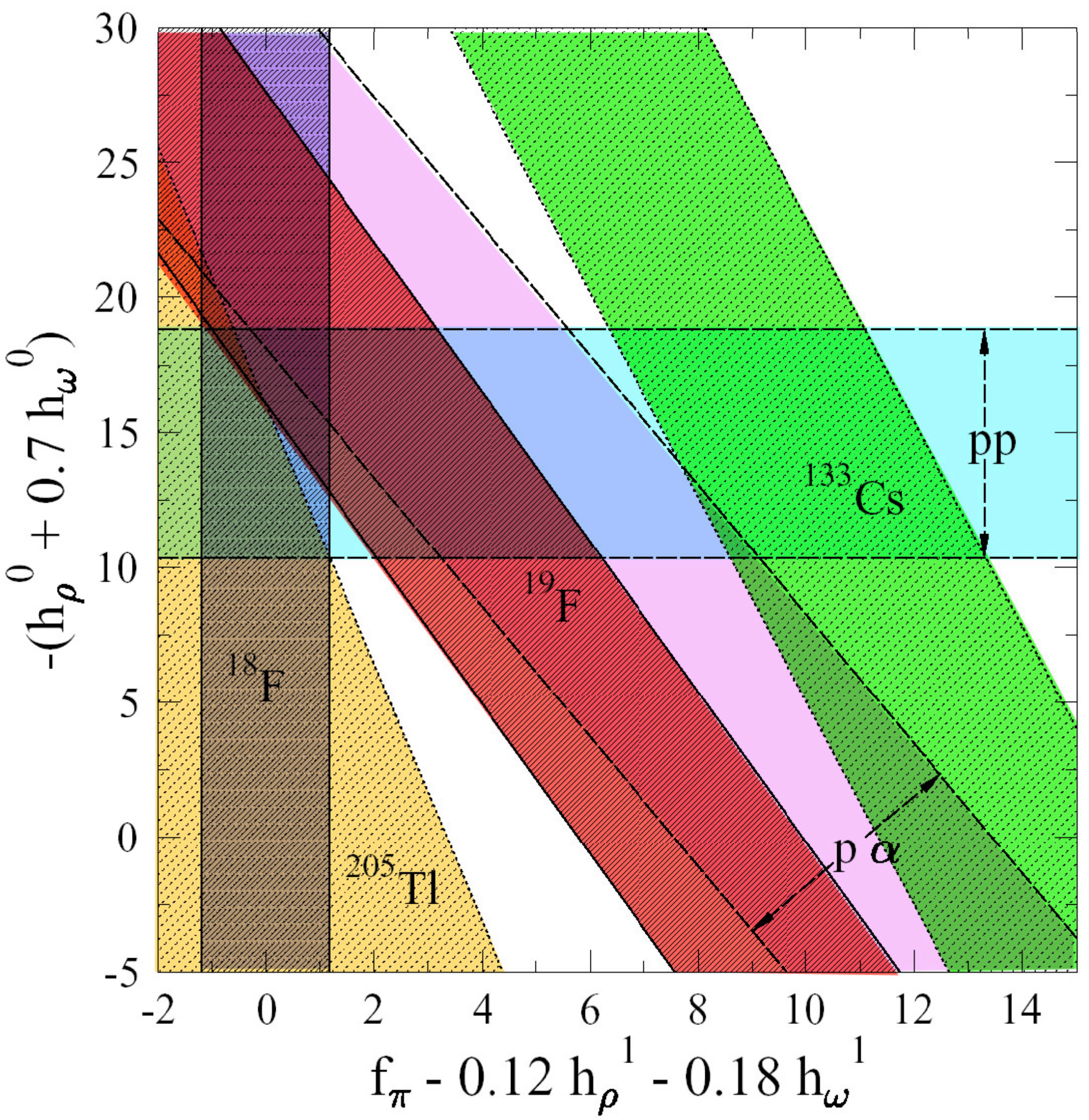
$$\kappa_a \propto A^{2/3}$$

Flambaum & Khriplovich 1980



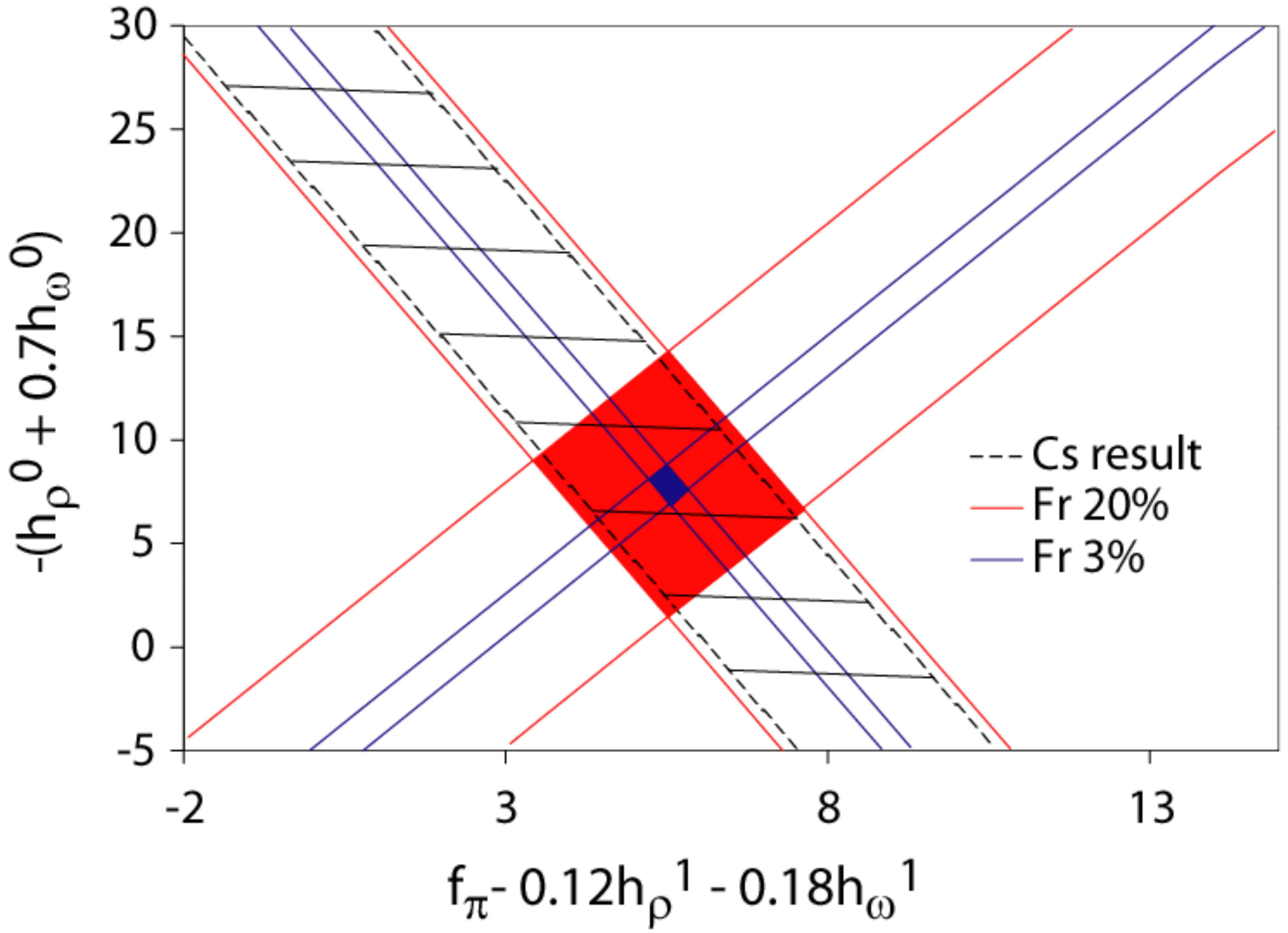
dipole current (circular current) + anapole current (toroidal current) = parity violating (helico-toroidal current)

A. Weis, U. of Fribourg,



Limits on weak nucleon coupling from various experiments

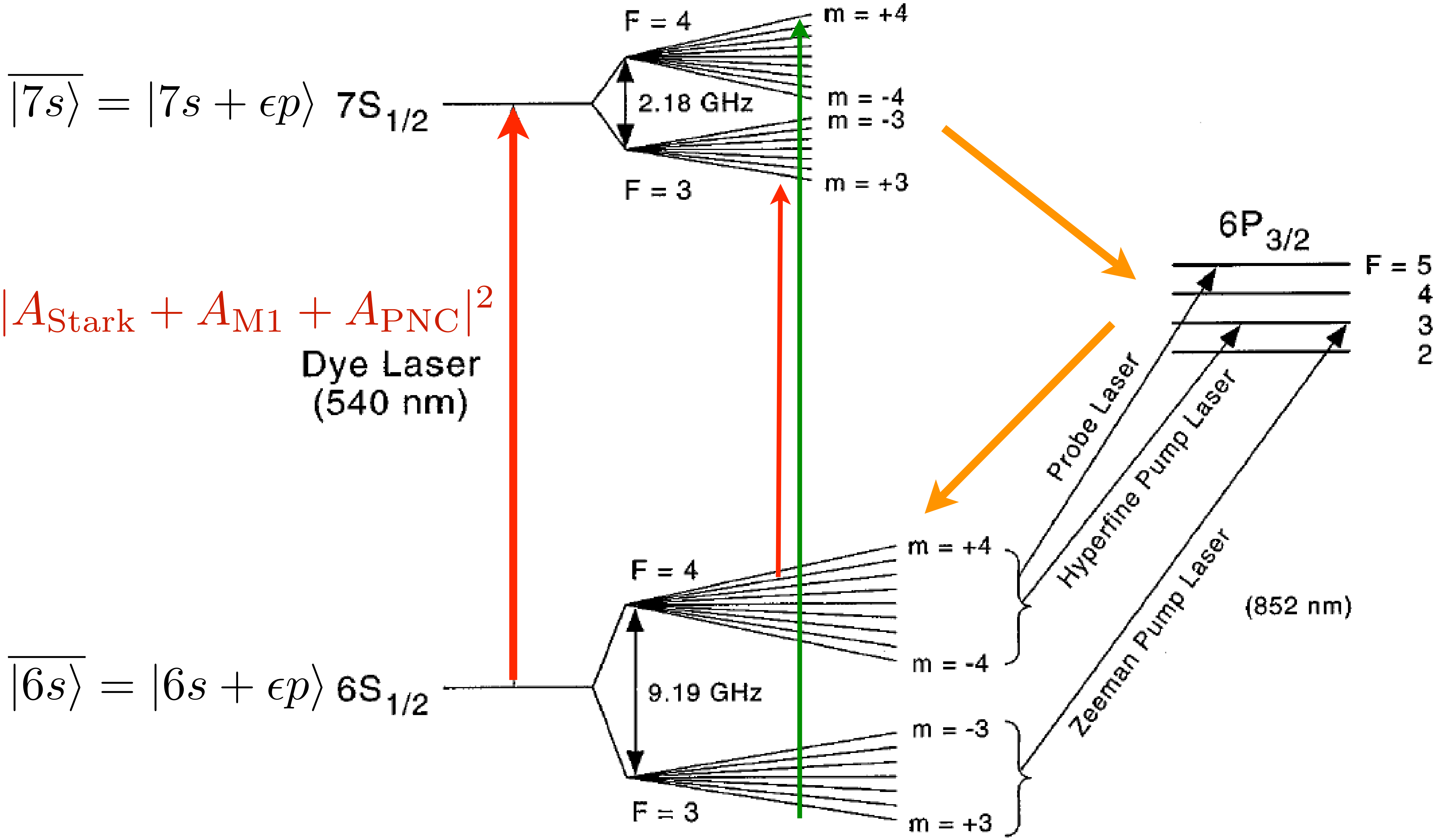
Constraints of couplings from measuring two francium isotopes
(note: the Cs band is somewhat different from the Haxton-Wieman plot due to different choices for the g_i).



Nuclear structure in heavy nuclei probably not well enough understood at this point to make reduction to meson couplings (anyway, EFT is the real deal now...)

But: Anapoles in nuclei are interesting by themselves, and data is VERY sparse. They tell us about the weak nucleon-nucleon interaction in nuclear matter.

Review: the Boulder Cs experiment



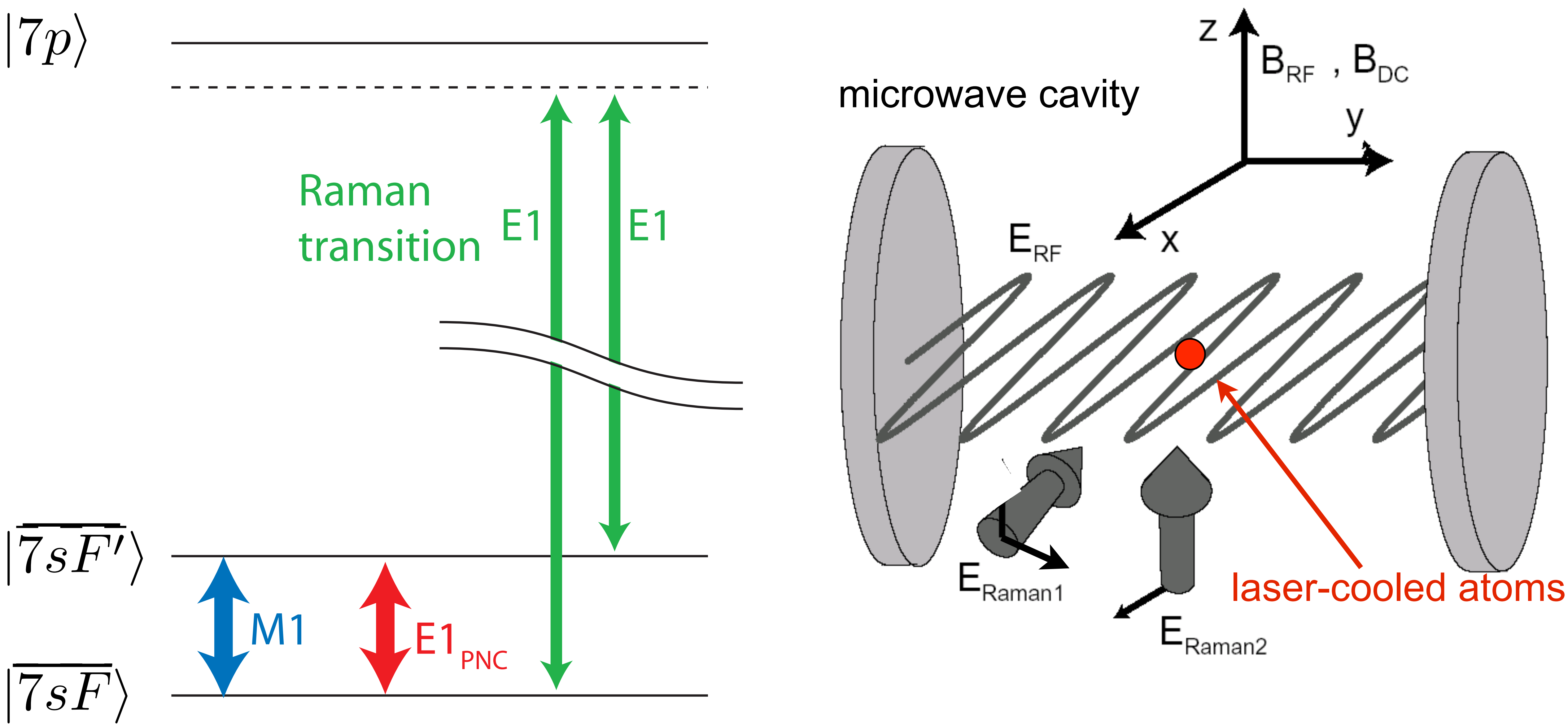
$$\frac{\mathrm{Im}(E1_{\rm PNC})}{\beta} = \begin{array}{lll} -1.5576(77) & \mathrm{mV/cm} & 6S\ F=3 \rightarrow 7S\ F'=4 \\ -1.6349(80) & \mathrm{mV/cm} & 6S\ F=4 \rightarrow 7S\ F'=3 \end{array}$$

anapole is extracted from *difference*

Interference scheme for hyperfine transitions

Drive $E1_{PNC}$ between electr. ground state hyperfine levels
⇒ NSI PNC effect absent, pure NSD APNC

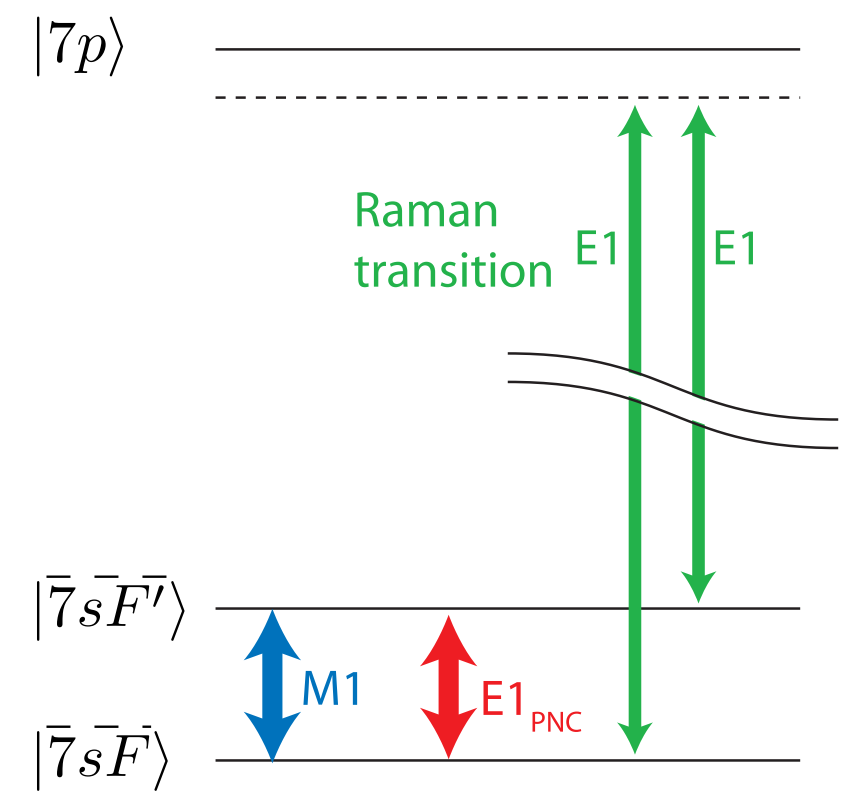
(L. Orozco, Maryland)



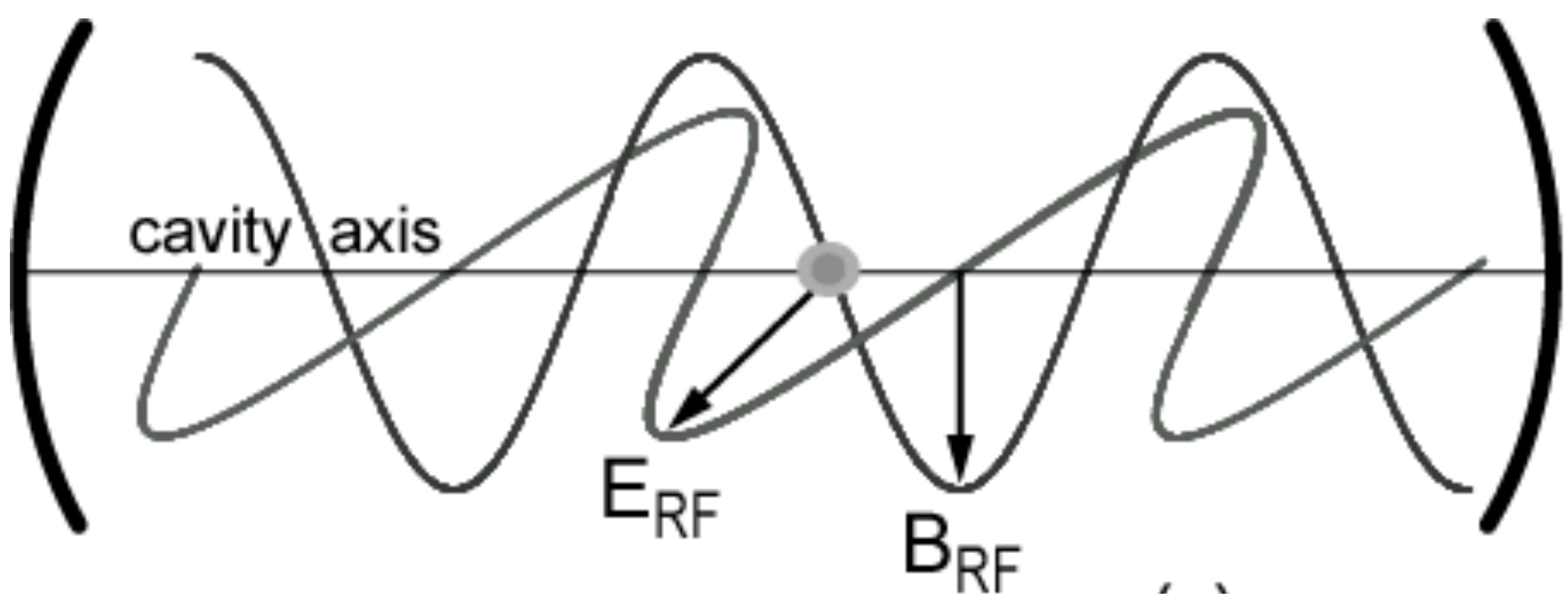
Gomez et al. PRA 2007

The big challenge: the M1 amplitude

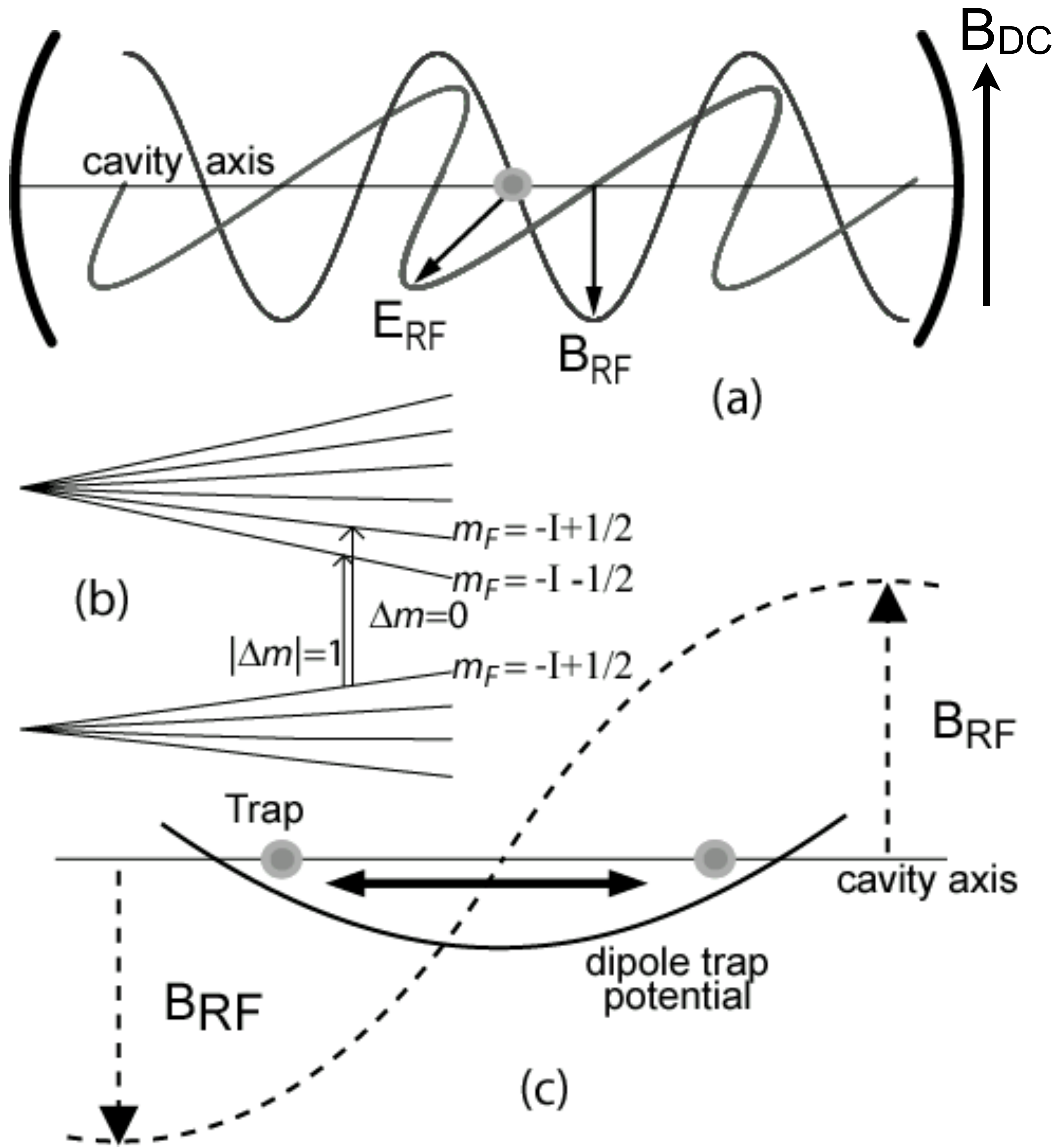
- M1 transition is allowed (unlike in optical APNC Stark experiments)
  - $|A_{E1}/A_{M1}| \sim 10^{-9}$!
  - Need some tricks to reduce the M1 amplitude



  - (1) Place atoms at the node of the magnetic field, reduction of 5×10^{-3}
    - any travelling wave component must be suppressed, bi-directional feeding of cavity



- microwave resonant for |Δm|=1 E1 transitions
    - E1 polarized along the x axis
- M1 polarized along z axis, M1: Δm=0
    - M1 tuned out of resonance, suppression of 10^{-3}
- dynamical suppression via atom movement in the trap



Signal to Noise

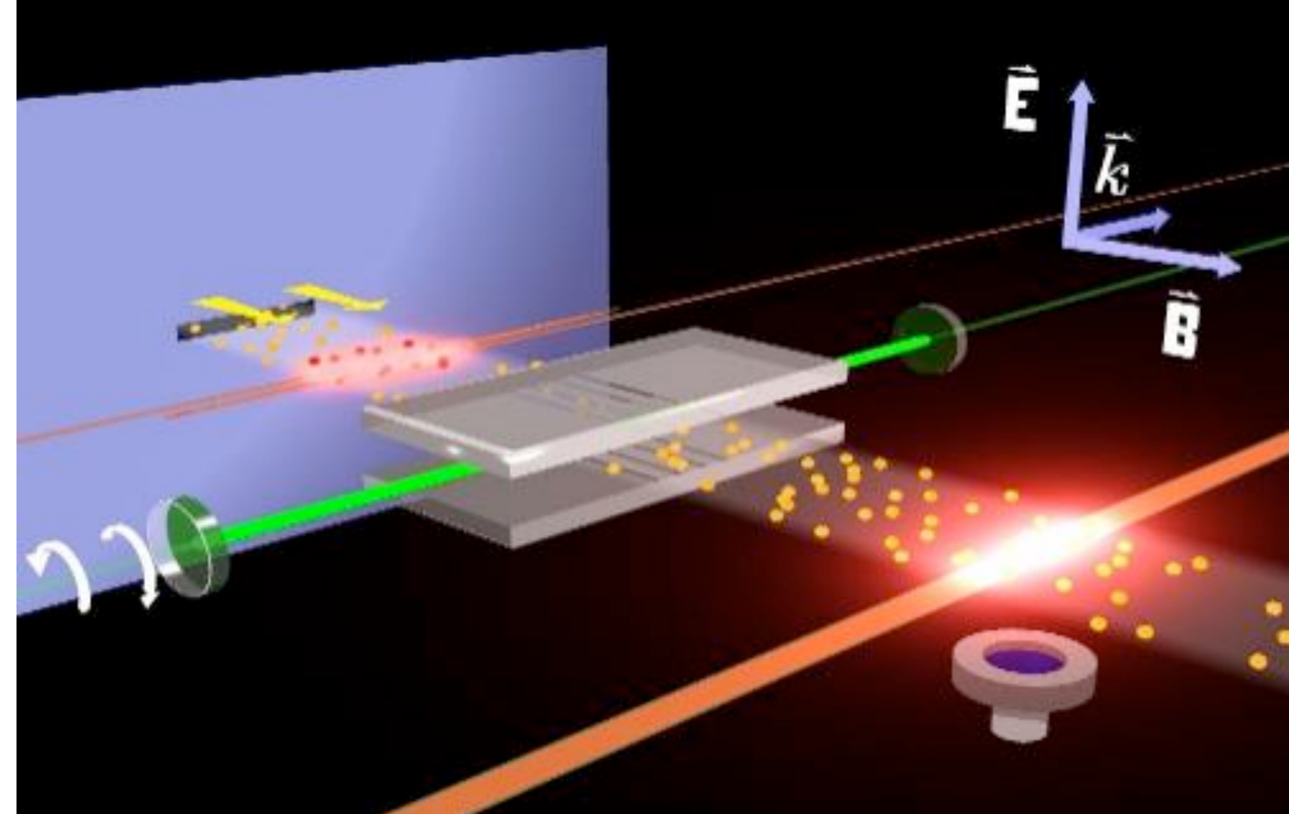
$$\frac{\mathcal{S}}{\mathcal{N}_P} = 2\frac{A_{E1}t_R}{\hbar}\sqrt{N}$$

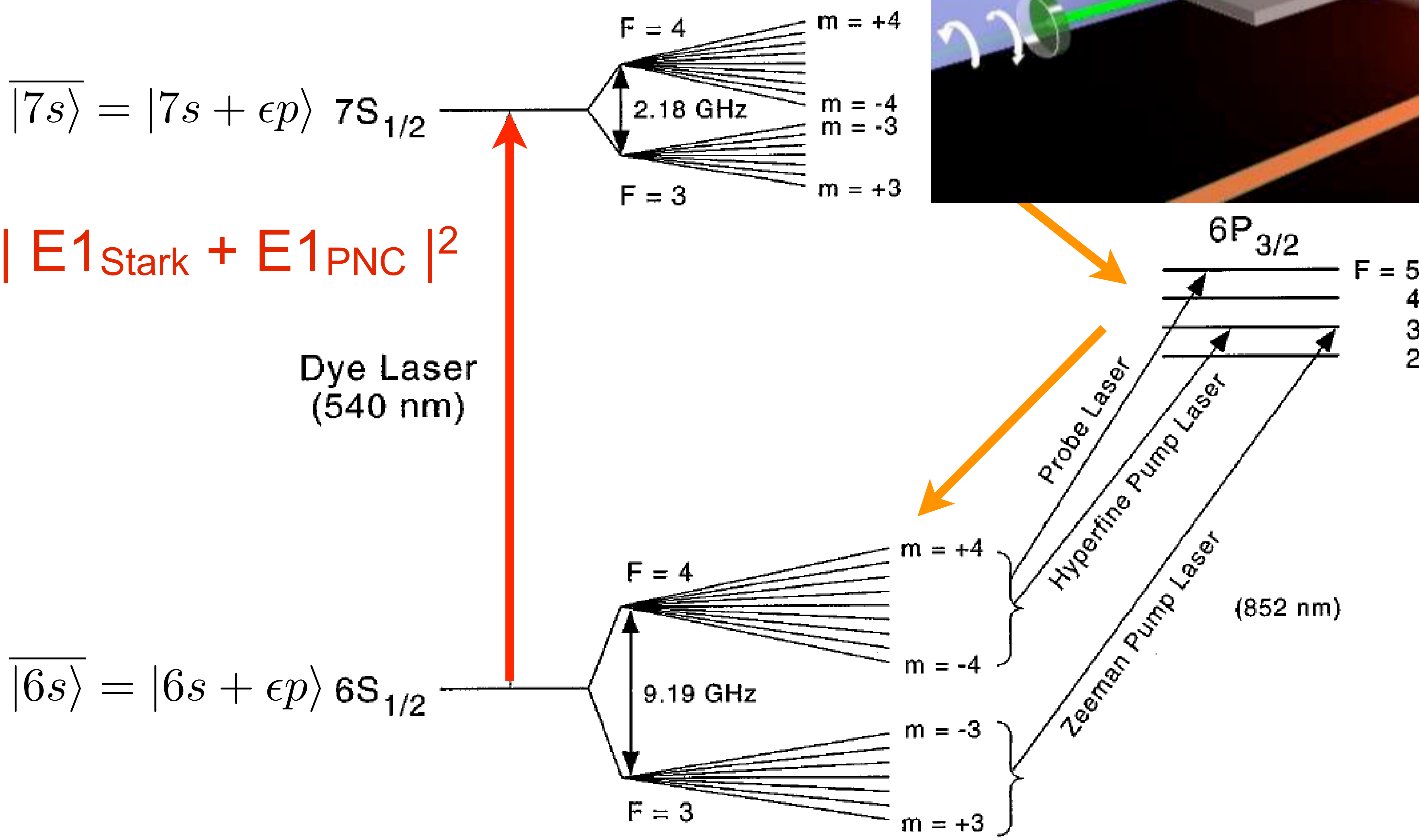
$$\mathcal{N}_P = \sqrt{N|c_e|^2(1-|c_e|^2)}$$

t_R = 1 sec, 300 atoms, 10^4 meas. cycles: 3 % measurement

10^6 atoms: S/N of 20 in 1 second

The Boulder Cs Experiment (Wood, 1996)





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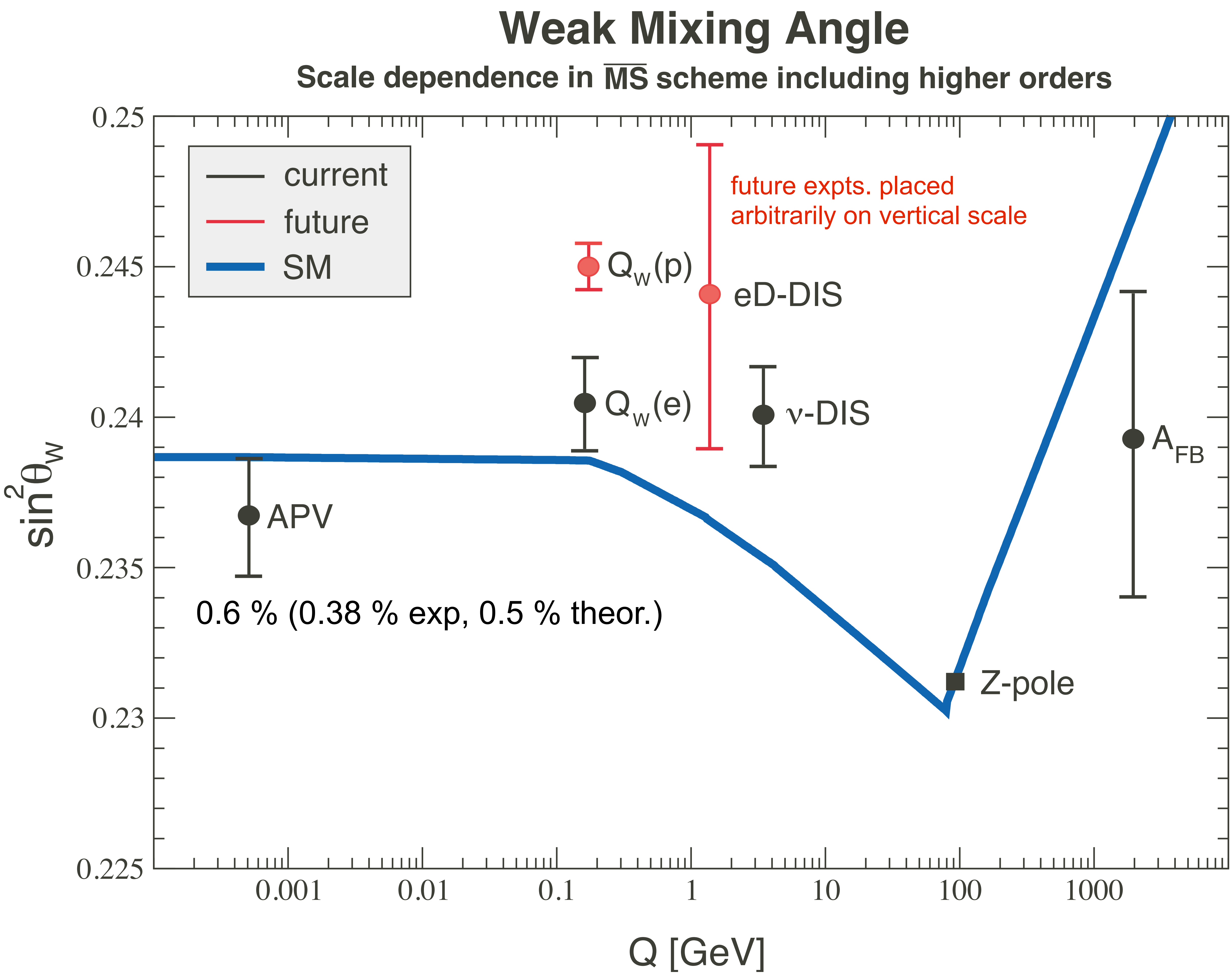
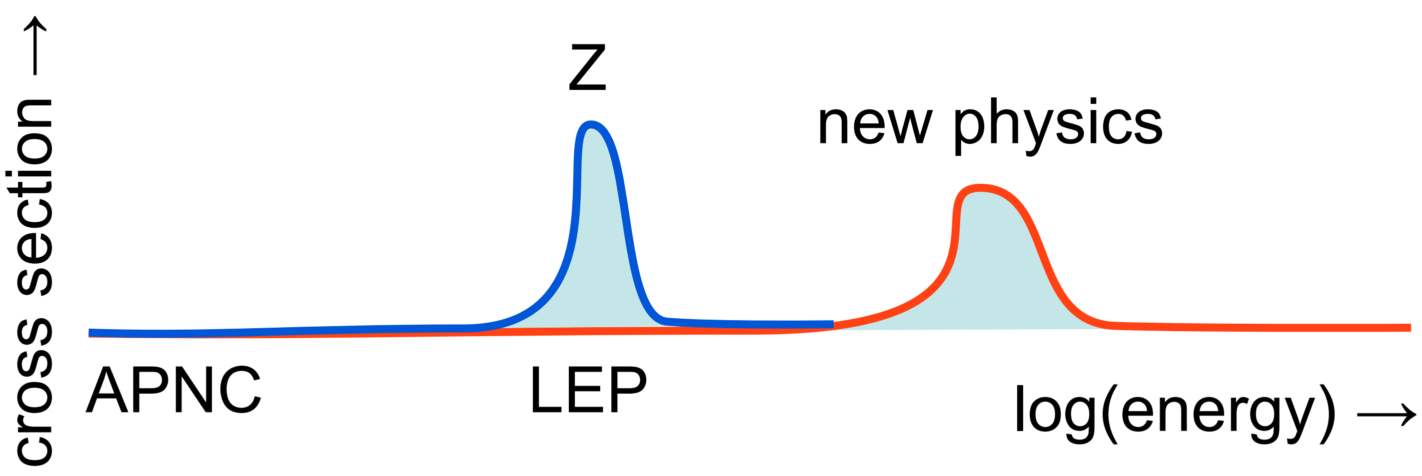

Weak Mixing Angle
Scale dependence in $\overline{MS}$ scheme including higher orders
current
future
SM
future expts. placed
arbitrarily on vertical scale
$Q_w(p)$
eD-DIS
$Q_w(e)$
ν-DIS
A_{FB}
APV
0.6 % (0.38 % exp, 0.5 % theor.)
Z-pole
$\sin^2\theta_W$
0.25
0.245
0.24
0.235
0.23
0.225
0.001
0.01
0.1
1
10
100
1000
Q [GeV]

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	$M\ (Z_x)$	>550 GeV	> 900 GeV LHC, ILC: > 5 TeV (?)
Leptoquarks	M_S	>0.7 TeV	> 256 GeV, >1200 GeV indir.
Composite Fermions	L	>14 TeV	>6 TeV

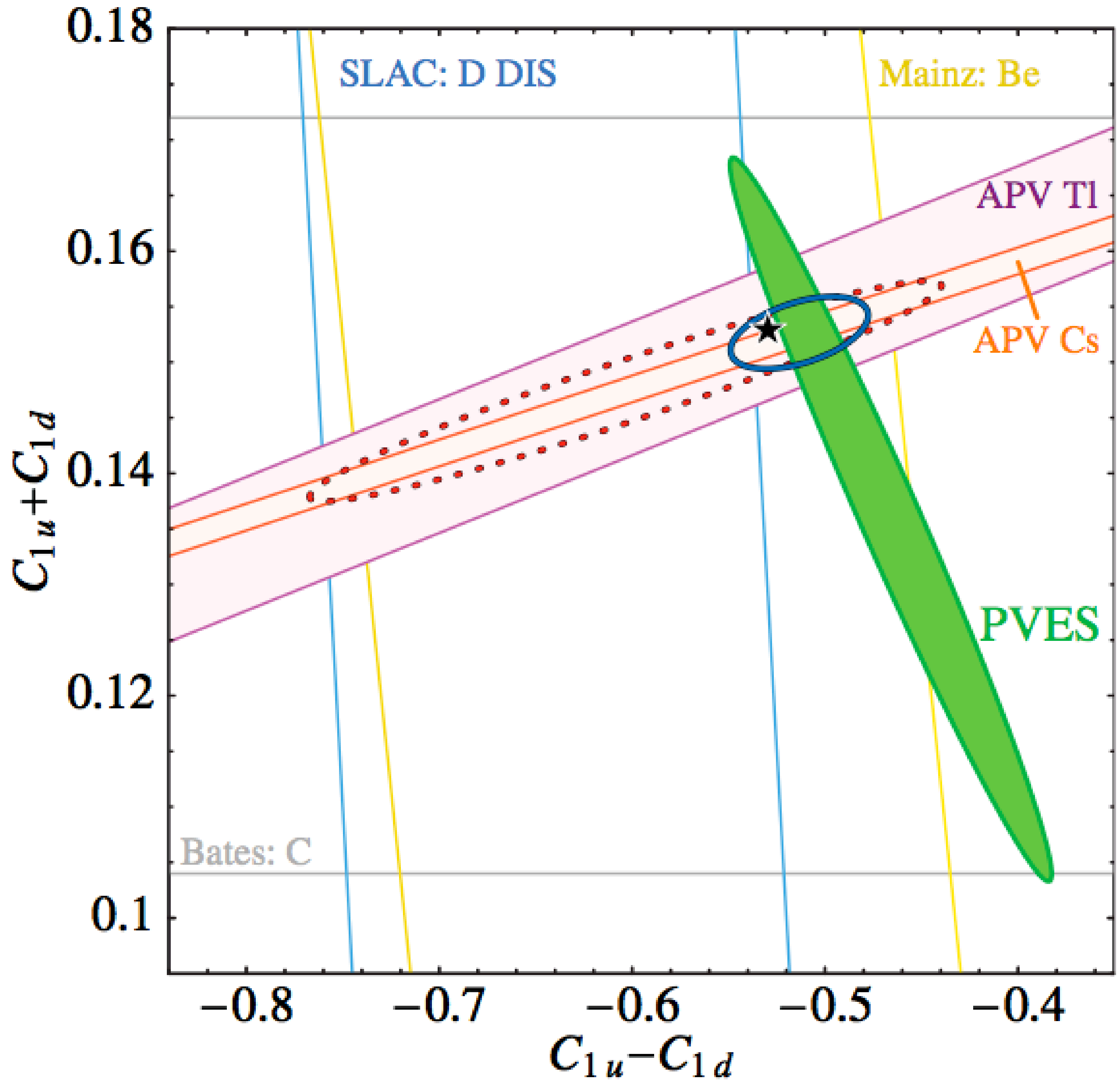
Why is APNC so sensitive?



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

Young et al., PRL 2007: Dramatic recent progress from PV electron scattering for (C_{1u} - C_{1d})

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



Why Cs? Not particularly heavy...

➡ heaviest, stable, 'simple' atom
➡ lack of atomic structure knowledge in Bi, Tl, Pb

Proposal: use francium (Z=87)

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

APNC effect 18 x larger!

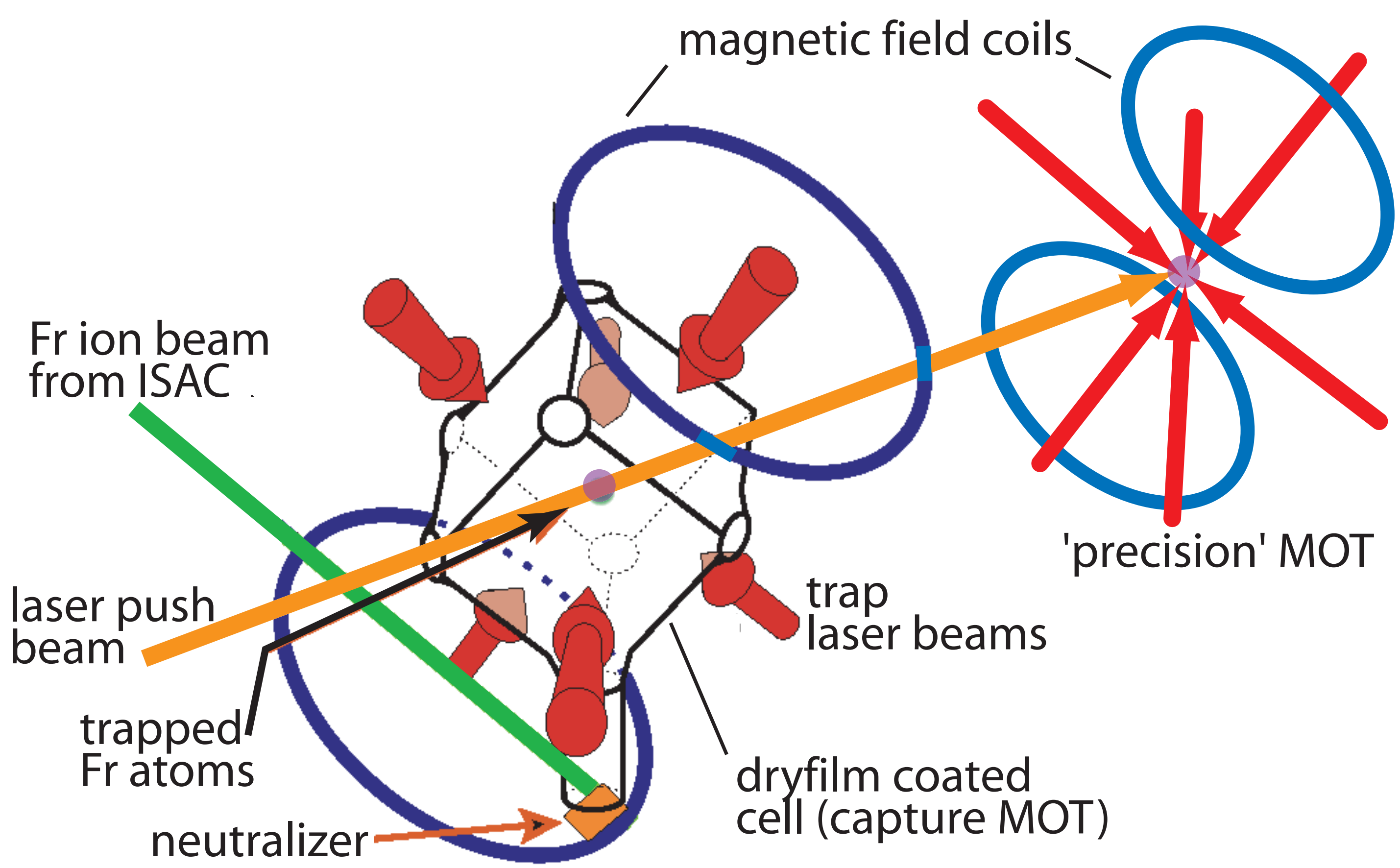
Problems: (i) no stable isotope
(ii) need to know neutron radius better than for Cs expt.

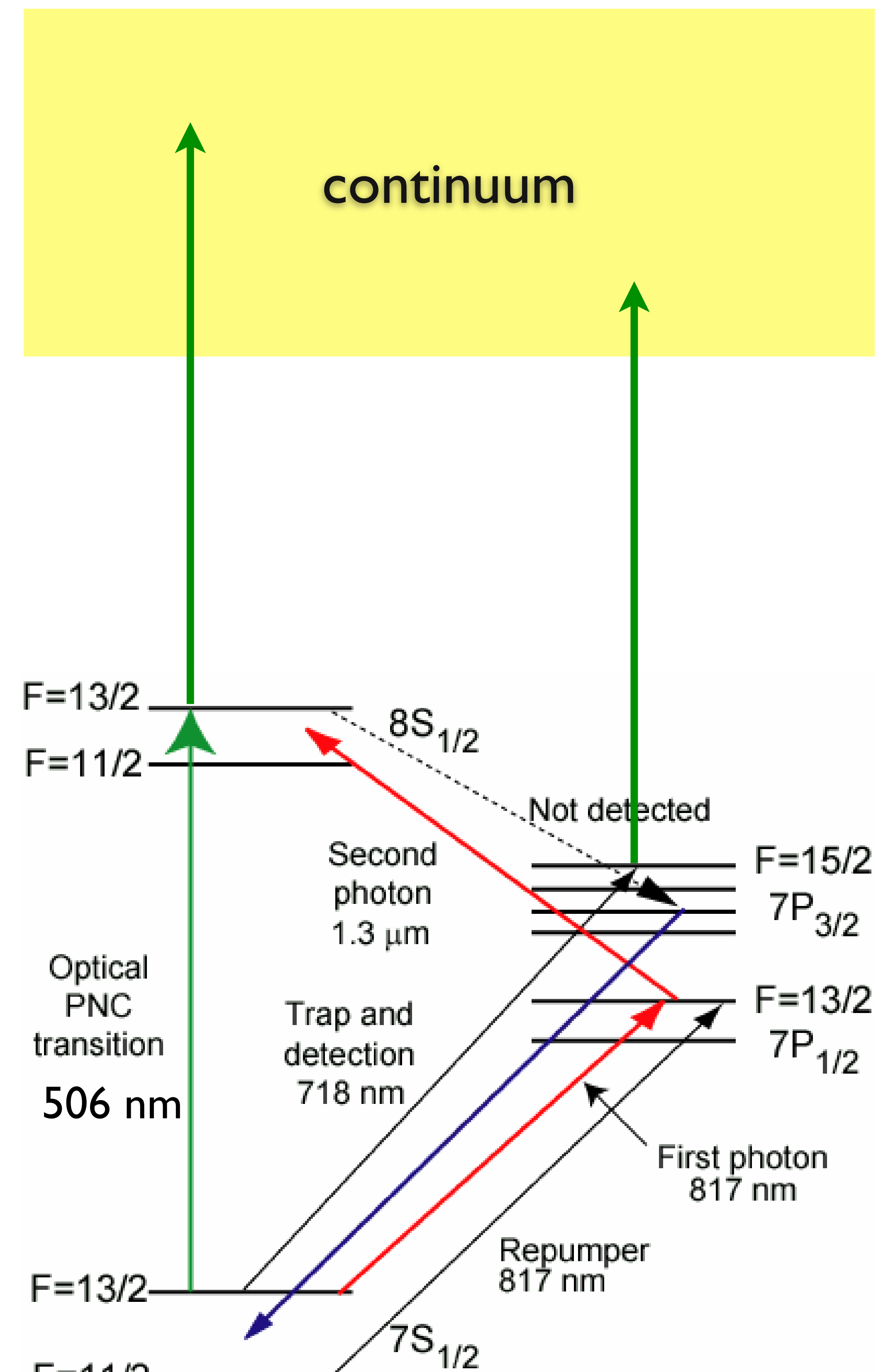
Answers: (i) go to TRIUMF's actinide target to get loads of Fr
(ii) the upcoming PREX experiment at Jefferson Lab will measure the neutron radius of ^{208}Pb

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!





A Fr APNC experiment at TRIUMF

- Actinide target will make ISAC the best 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 (0.4 - 0.5 % uncertainty), so progress in this direction required to go beyond Wood et al. (but can be expected)
- isotopic ratio will need next gen. neutron radius experiment (also mostly sensitive to NP in proton) (Sil 2005)
- can expect that all aspects improve over time

What I like particularly about APNC measurements:

To reach sensitivity to New Physics, APNC:

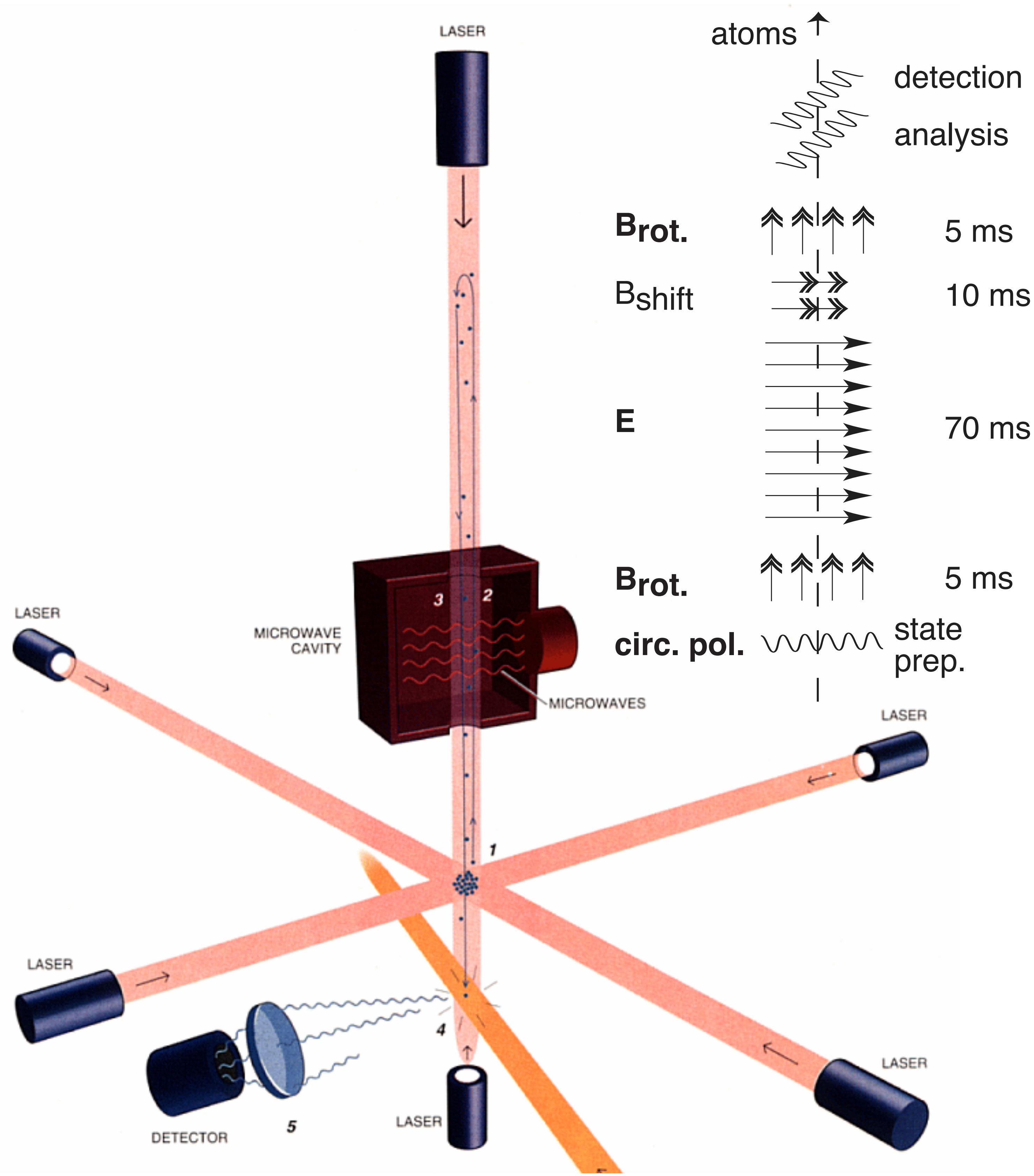
- [atomic] triggered the best atomic structure calculations in heavy atoms, truly advanced the state-of-the-art, and keeps doing so

- [nuclear] requires, and motivates the most accurate neutron skin determination (very interesting by itself)

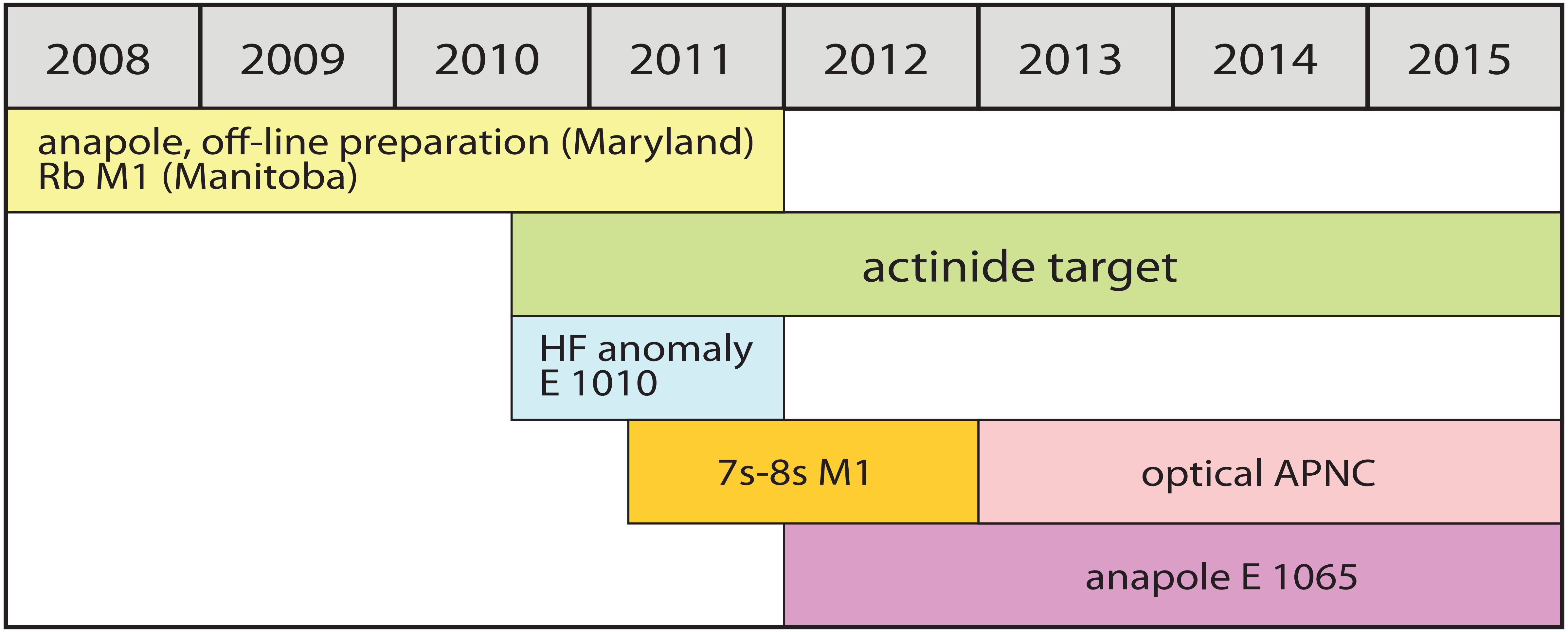
- [laser technology...] pushes experimental techniques in atomic physics
  - Cs beam: 800 kW/cm^2 narrowband light, extreme control of external fields
  - next generation trap-based expts.: frequency control of RF fields and light, new, efficient atom trapping schemes, densest samples of short-lived radioactive atoms, state-of-th-art position control for atoms

- [particle] result

Electron EDM in heavy alkalis with an atomic fountain *(H. Gould, Berkeley)*



- fountain: motional B-field much smaller, cancellation *atom by atom*
- proof of principle in Cs (Amini 2007), d <10^{-22} e cm
- believe that 'real' Cs expt can improve current limit 100 x
- e-EDM 10x enhanced in Fr rel. to Cs
- estimate: need 10^{14} interrogated atoms (just like 0.1 % APNC, hence similar time scale)



- Canadian SAP plan: high priority for francium
- Hyperfine anomalies: study of nuclear properties, tune up Fr apparatus (E 1010 approved)
- Anapole measurement (E 1065 approved)
- 7s-8s Stark/M1: precursor to optical APNC (in preparation)
- Optical APNC (future EEC proposal)

- e-EDM: letter of intent by H. Gould (LBNL)

Weak Nucleon-Nucleon Interactions by Parity Nonconservation Measurements in Francium (E 1065)

by the FrPNC collaboration (in fairly arbitrary order):
G. Gwinner (Manitoba)
E. Gomez (Univ. Autonoma San Luis Potosi, Mexico)
G.D. Sprouse *(Stony Brook)*
J.A. Behr, K.P. Jackson, M.R. Pearson *(TRIUMF)*
L.A. Orozco *(Univ. of Maryland)*
V. Flambaum *(Univ. of New South Wales)*
S. Aubin *(College of William and Mary)*

good mix of in-house & external scientists
experts: radioactive beams/nuclear physics
fundamental symmetry measurements
quantum optics

Fractional stability required for a 3% measurement. The observable associated with each constraint is also included

Observable	Constraint	Set value	Stability
$A_{Ry}A_{E1}$	Microwave amplitude	476 V/cm	0.03
$A_{Ry}A_{Ry}$	Raman amplitude	121 rad/s	2.5×10^{-4}
$(\hbar\delta)^2$	Microwave frequency	45 GHz	10^{-11}
	Dipole trap Stark shift	6.3 Hz	0.07
	dc magnetic field	1500 G	4.7×10^{-5}
$A_{Rx}A_{Rx}$	Raman polarization	0 rad	10^{-3} rad
$A_{Ry}A_{Miy}$	Mirror separation	13 cm	7.7×10^{-7}
	Antenna power	57 mW	0.02
	Antenna phase	0 rad	0.01 rad
$A_{Ry}A_{Mox}$	Mirror birefringence	0 rad	1×10^{-4} rad
	Trap displacement	0 m	3×10^{-11} m