Fundamental Symmetries in Laser Trapped Francium

—

Opportunities with a High-Availability Actinide Target at TRIUMF

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PREX Workshop

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

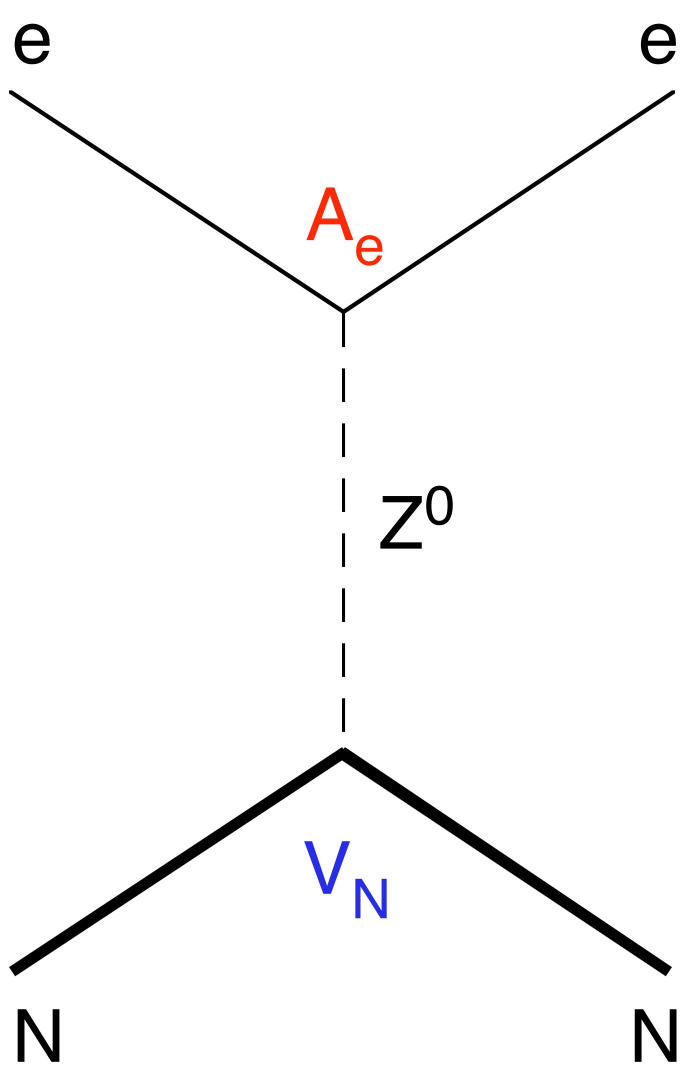
	Atom	**Nucleus**
Charged current weak interactions, β-decay	new powerful techniques (atom traps)	rich selection of spin, isospin, half-life
Neutral current weak interactions APNC anapoles	tremendous accuracy of atomic methods (lasers, microwaves) neutral (strong external fields) traps, cooling	huge enhancement 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



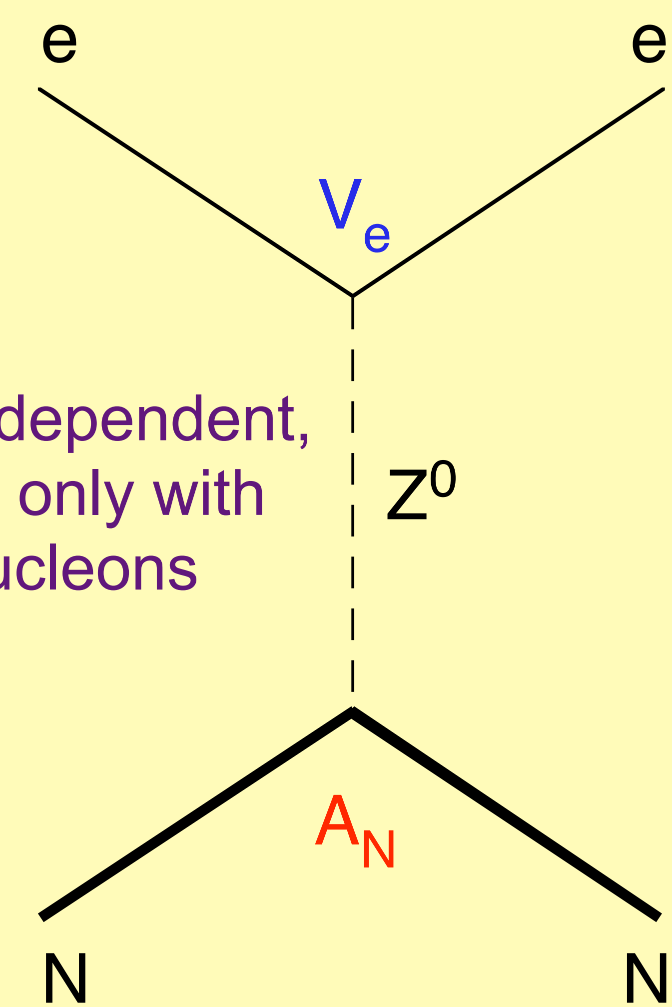
nucl. spin *independent* interaction:
coherent over all nucleons

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

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

Drive s → s E1 transition!

nucl. spin dependent,
interaction only with
valence nucleons



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 nuclear-spin independent APNC Hamiltonian for a pointlike nucleus:

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

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

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

The "nuclear weak charge" contains the weak interaction physics

$$< n'L'|H^{\rm nsi}_{\rm PNC}|nL >$$

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

$$\propto < n'L'|\frac{d}{dr}|nL > |_{r=0}$$

$$R_{nL} \approx r^L Z^{L+1/2}$$

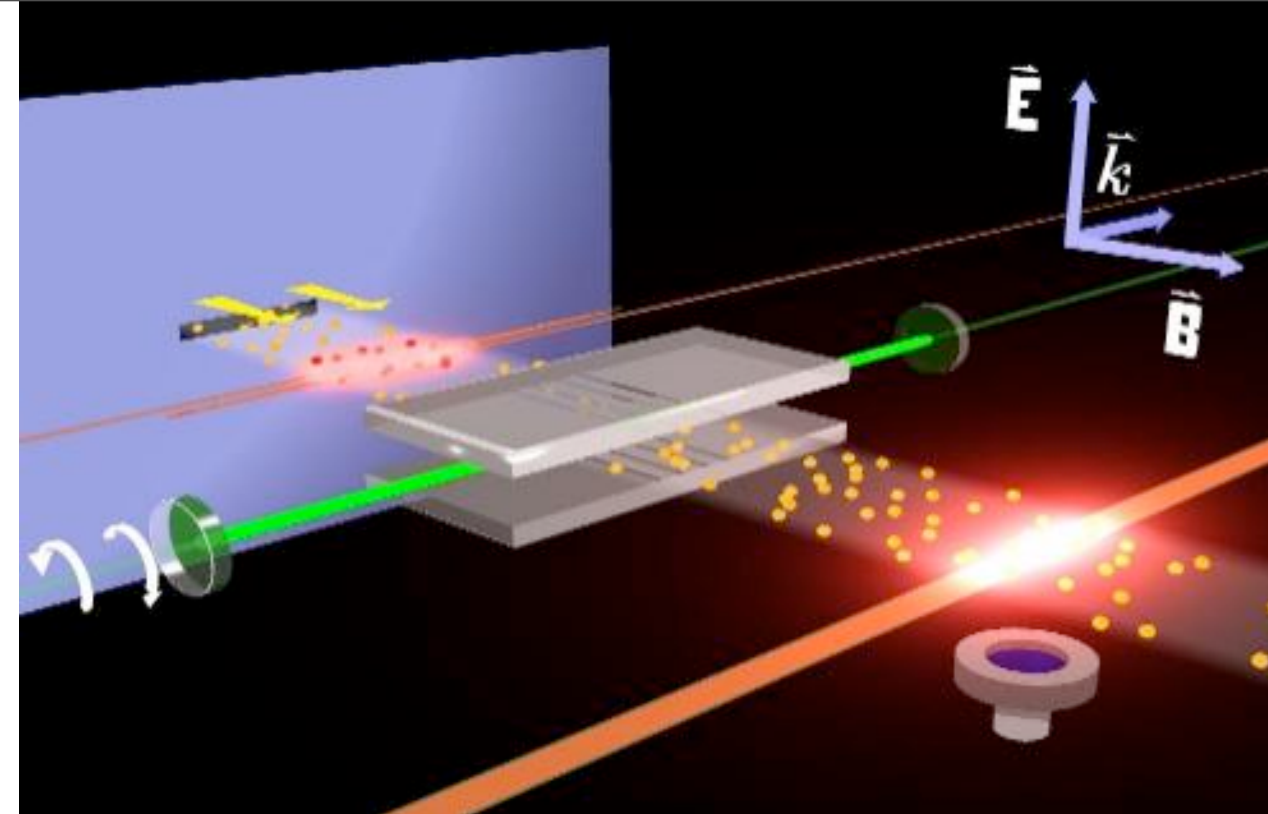
$\Rightarrow$ at $r = 0$ only R_{ns}, $\frac{d}{dr}R_{np}$ are finite

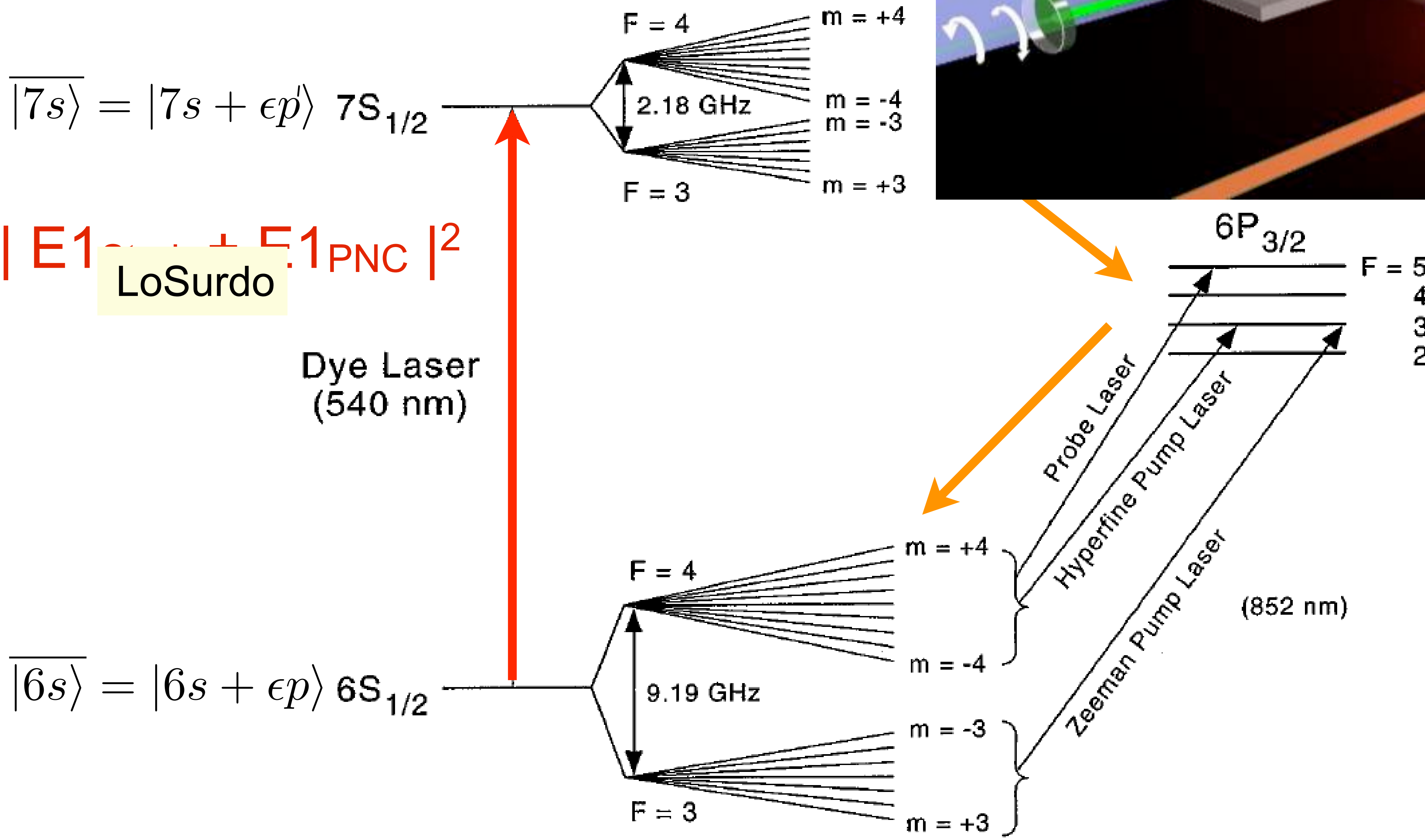
$H_{\rm PNC}$ mixes s and p states

$$< ns|H^{\rm nsi}_{\rm PNC}|n'p > \propto Z^3$$

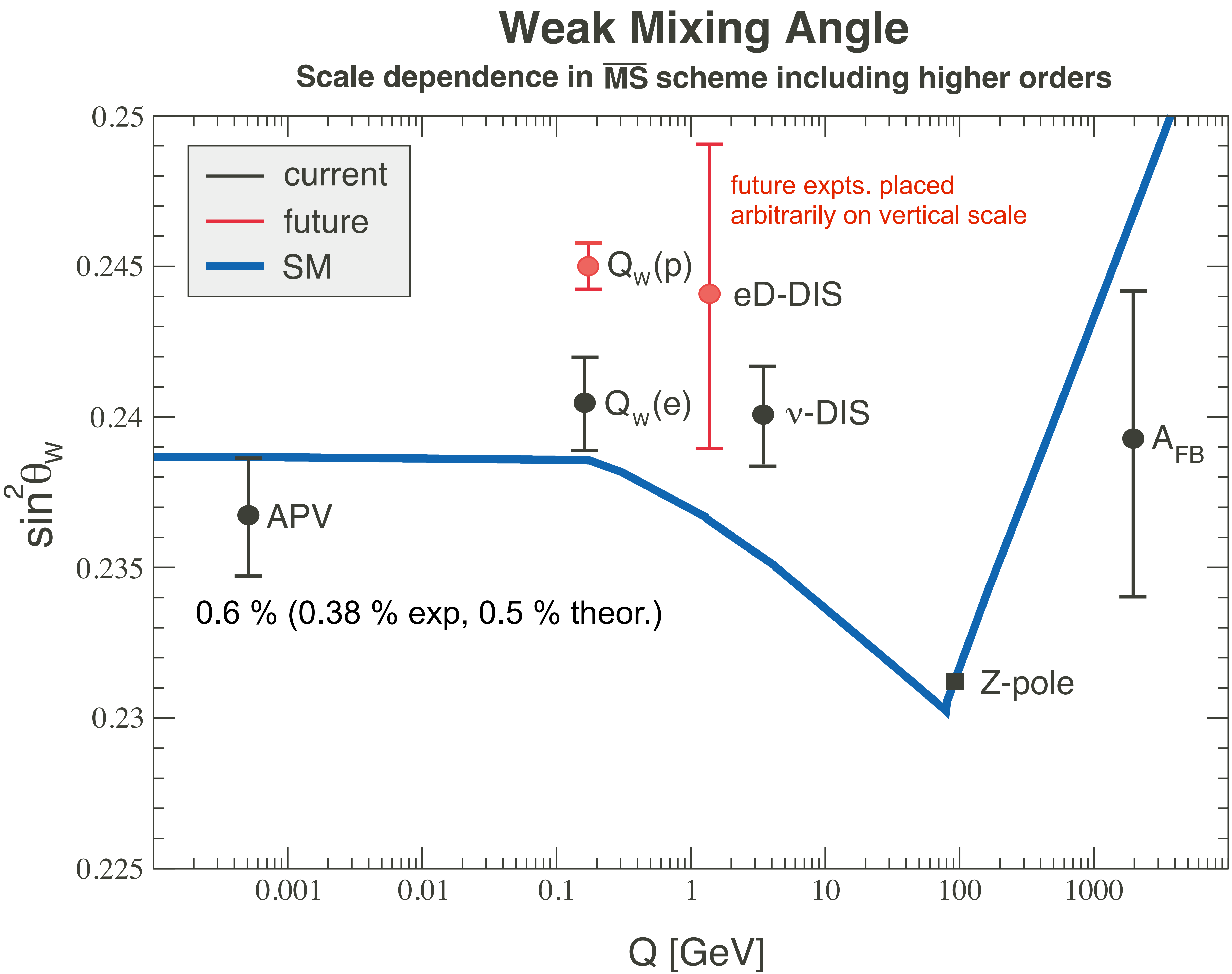
Bouchiat, 1974

The Boulder Cs Experiment (Wood, 1996)





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

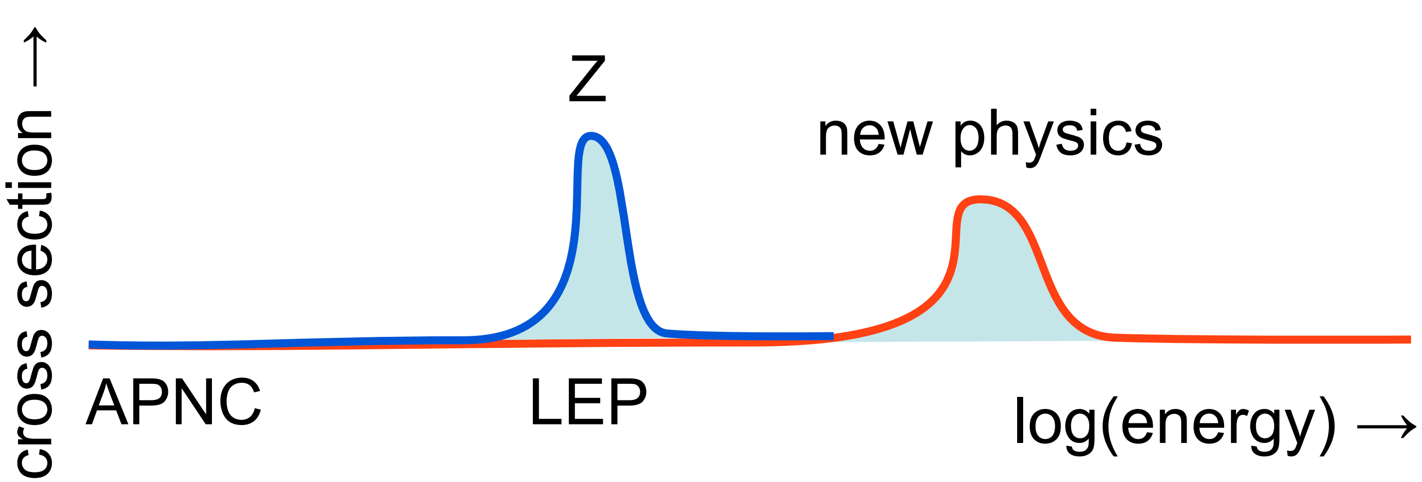


Weak Mixing Angle
Scale dependence in MS scheme including higher orders
0.25
0.245
0.24
0.235
0.23
0.225
sin²θ_W
current
future
SM
future expts. placed
arbitrarily on vertical scale
Q_W(p)
eD-DIS
Q_W(e)
ν-DIS
A_FB
APV
0.6 % (0.38 % exp, 0.5 % theor.)
Z-pole
0.001
0.01
0.1
1
10
100
1000
Q [GeV]

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

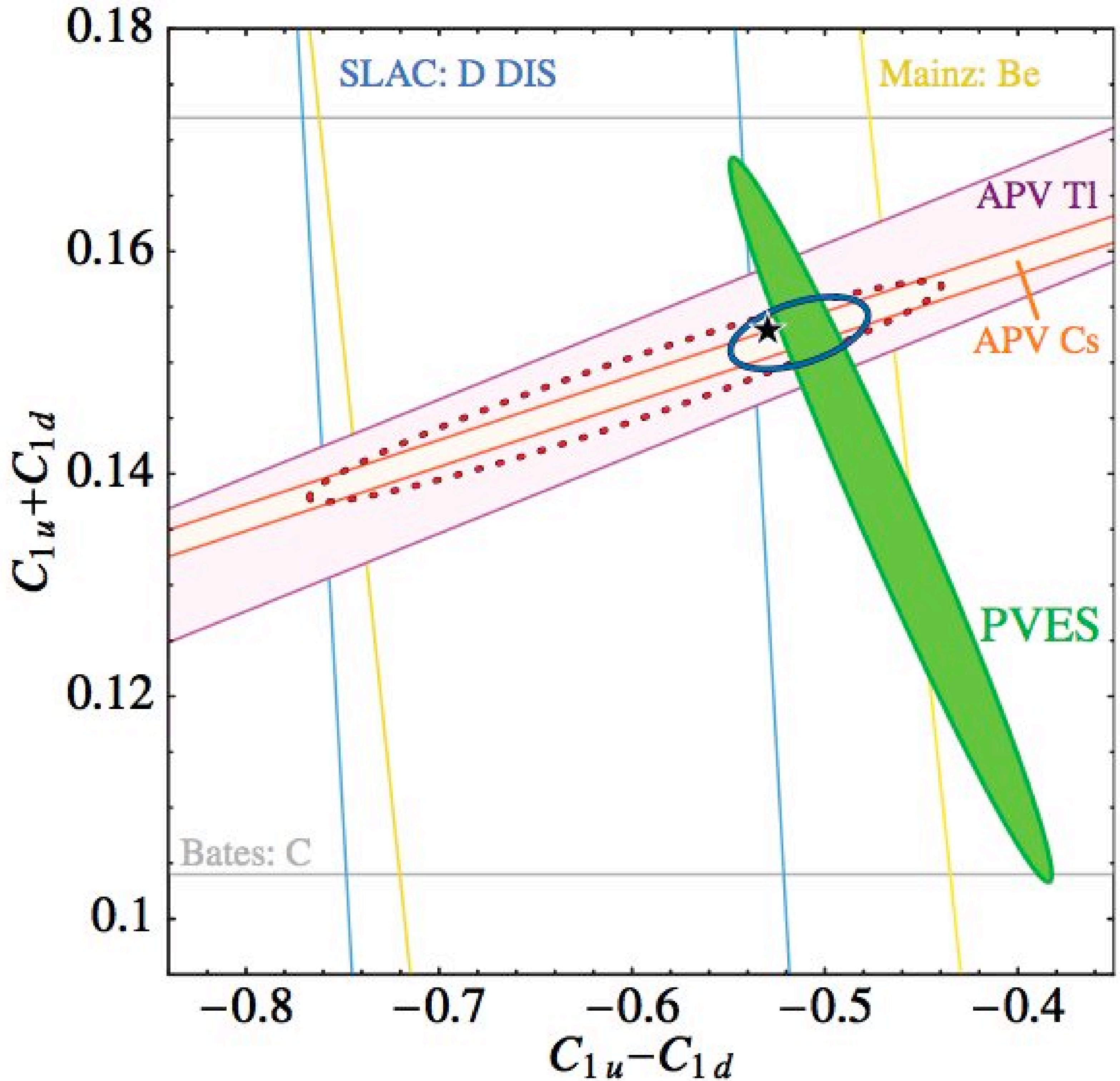
Why is APNC so sensitive?



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...

It's the heaviest, stable 'simple atom'

atomic structure factor

nuclear structure factors

$$\langle i | H_{\mathrm{PNC},1} | j \rangle = \frac{G_F}{2\sqrt{2}} C_{ij}(Z)\,\mathcal{N}$$

$$\times \left[-N q_n + Z(1 - 4\sin^2\theta_W) q_p \right]$$

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

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

$$q_p = \int \rho_p(r)\, f(r)\, d^3r\,.$$

from Pollock et al. 1992

Proposal: use francium (Z=87)

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

APNC effect 18 x larger!

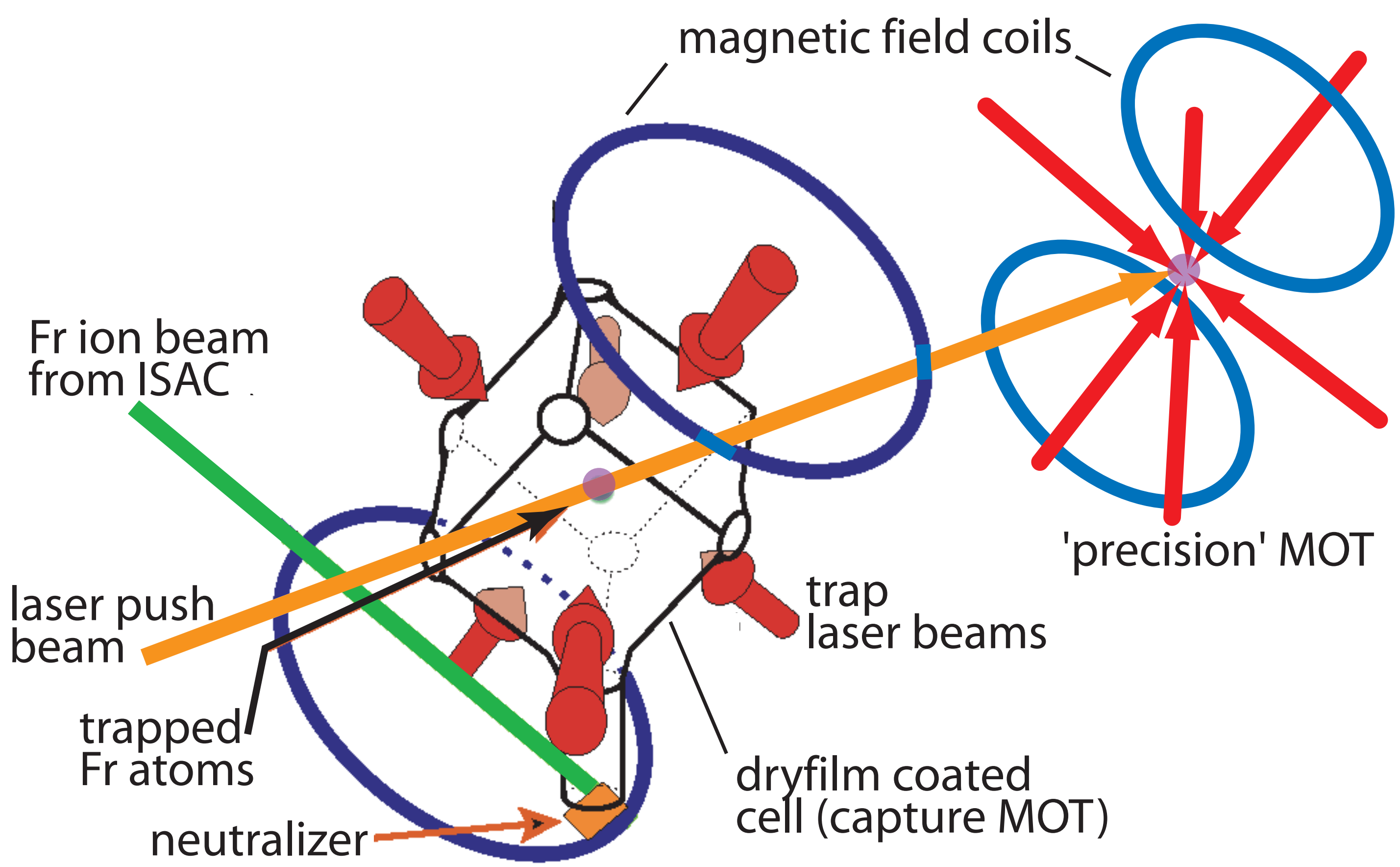
Problems: (i) no stable isotope
(ii) need to know neutron radius better than for Cs expt.

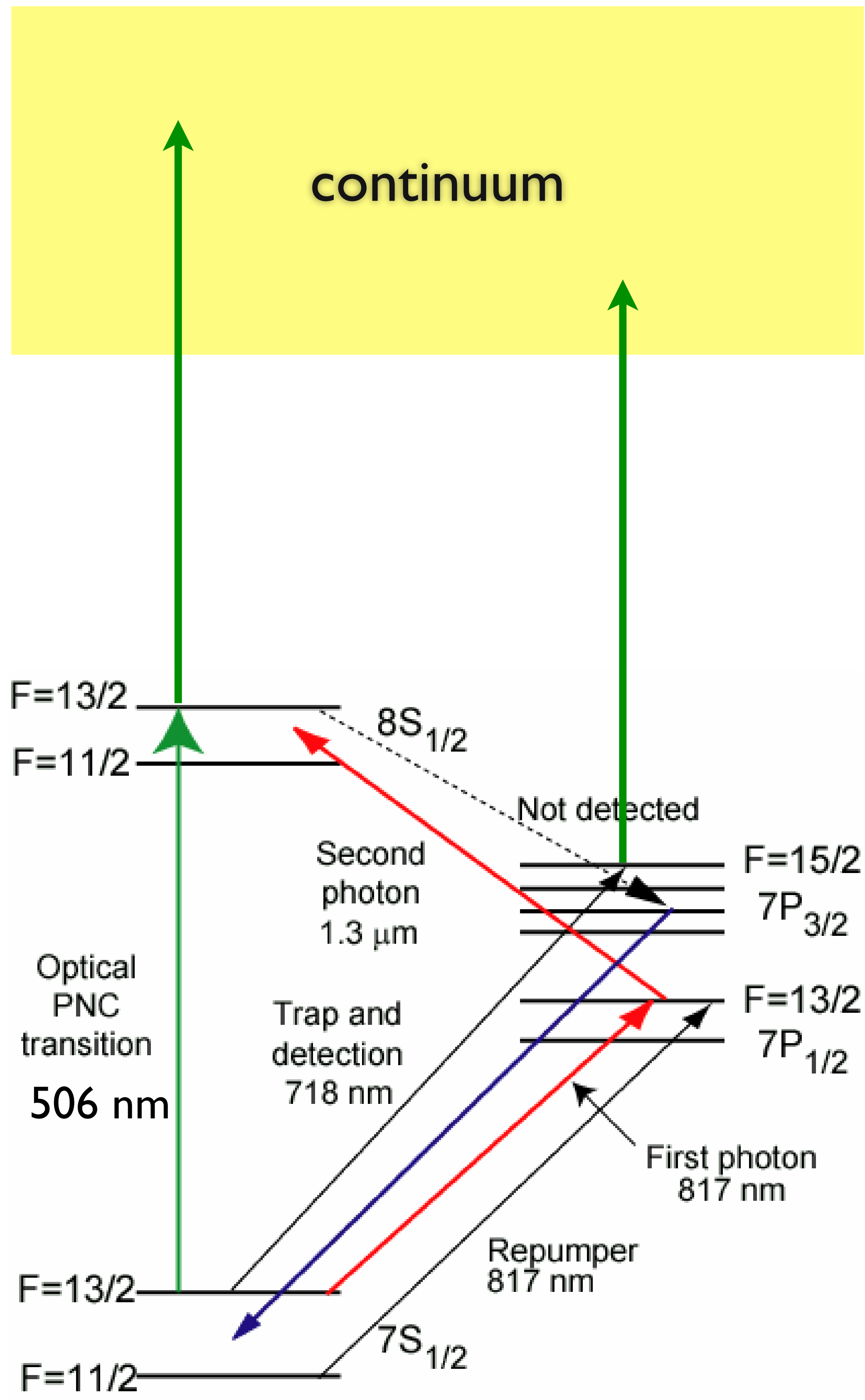
Answers: (i) go to TRIUMF's actinide target to get loads of Fr
(ii) the upcoming PREX experiment at Jefferson Lab will measure the neutron radius of ^{208}Pb

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!

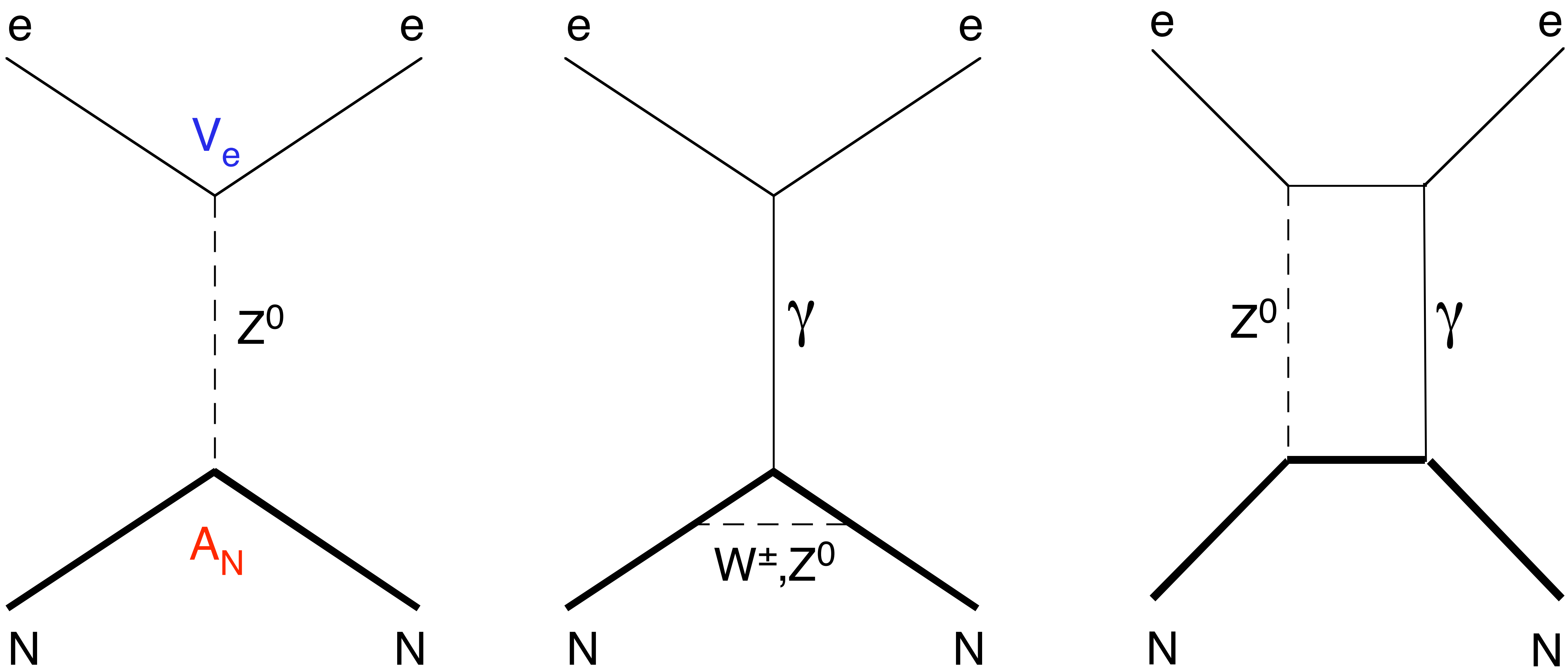
- 1% neutron radius measurement in ^{208}Pb with PREX would put a 0.2 % uncertainty on Q_W in ^{212}Fr (Sil 2005)
- atomic theory similar to Cs (0.4 - 0.5 % uncertainty), so progress in this direction required to go beyond Wood et al. (but can be expected)
- isotopic ratio will need next gen. neutron 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-the-art position control for atoms
- [particle] result

Nuclear spin dependent APNC



NSD Z-exchange

PV hadronic interactions
⇒ PV anapole moment
of the nucleus

hyperfine correction to
the weak neutral current

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

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

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

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

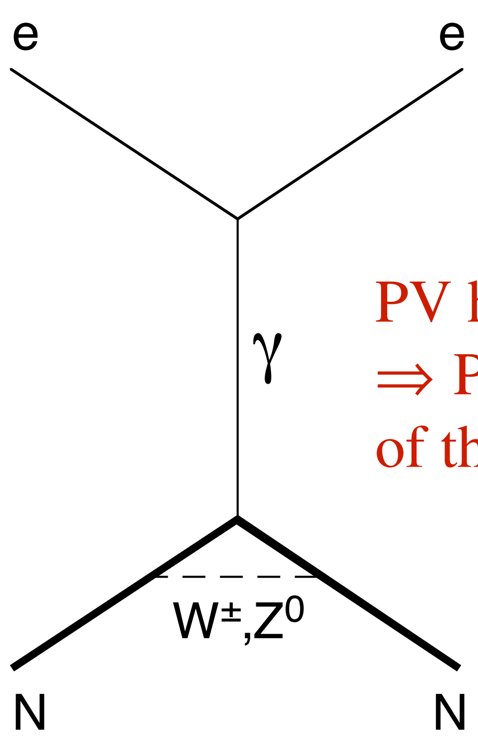
Khriplovich and Flambaum (1980)

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

Nuclear spin dependent APNC

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

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



PV hadronic interactions
⇒ PV anapole moment
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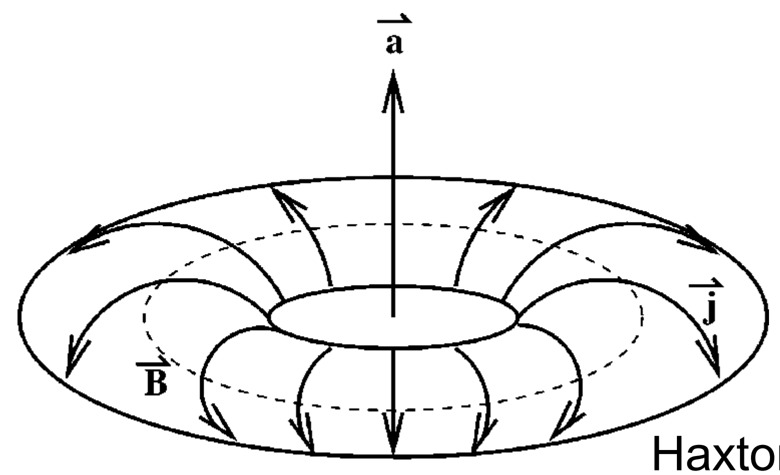
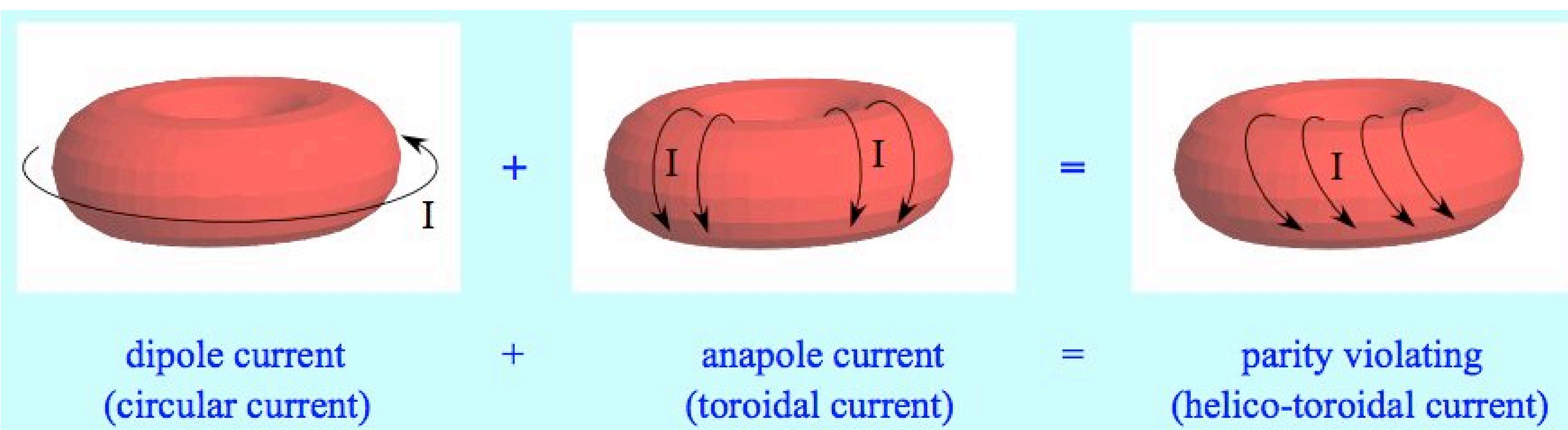


Haxton et al., PRC 2002

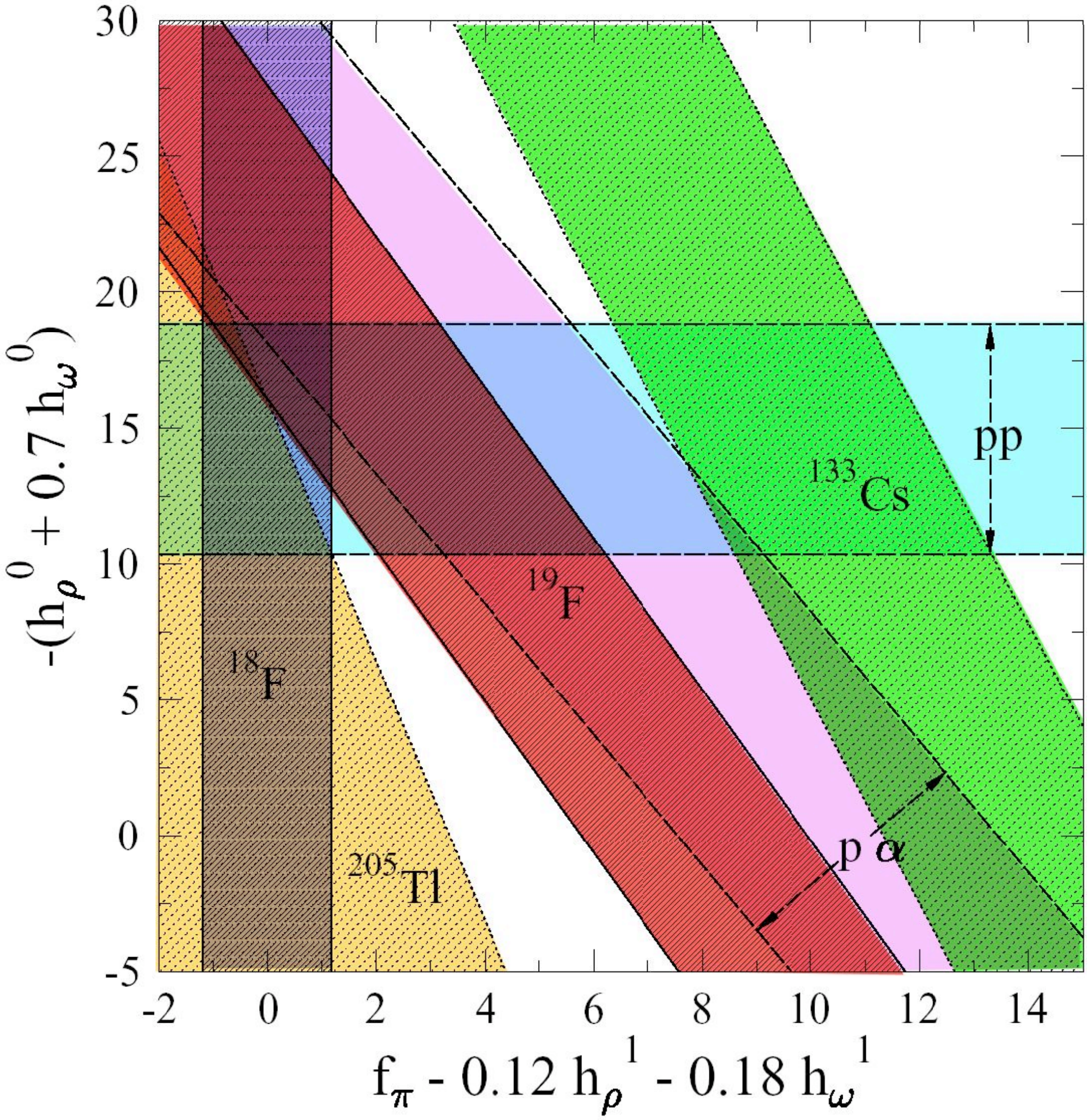
$$\kappa_a \propto A^{2/3}$$

Flambaum & Khriplovich 1980

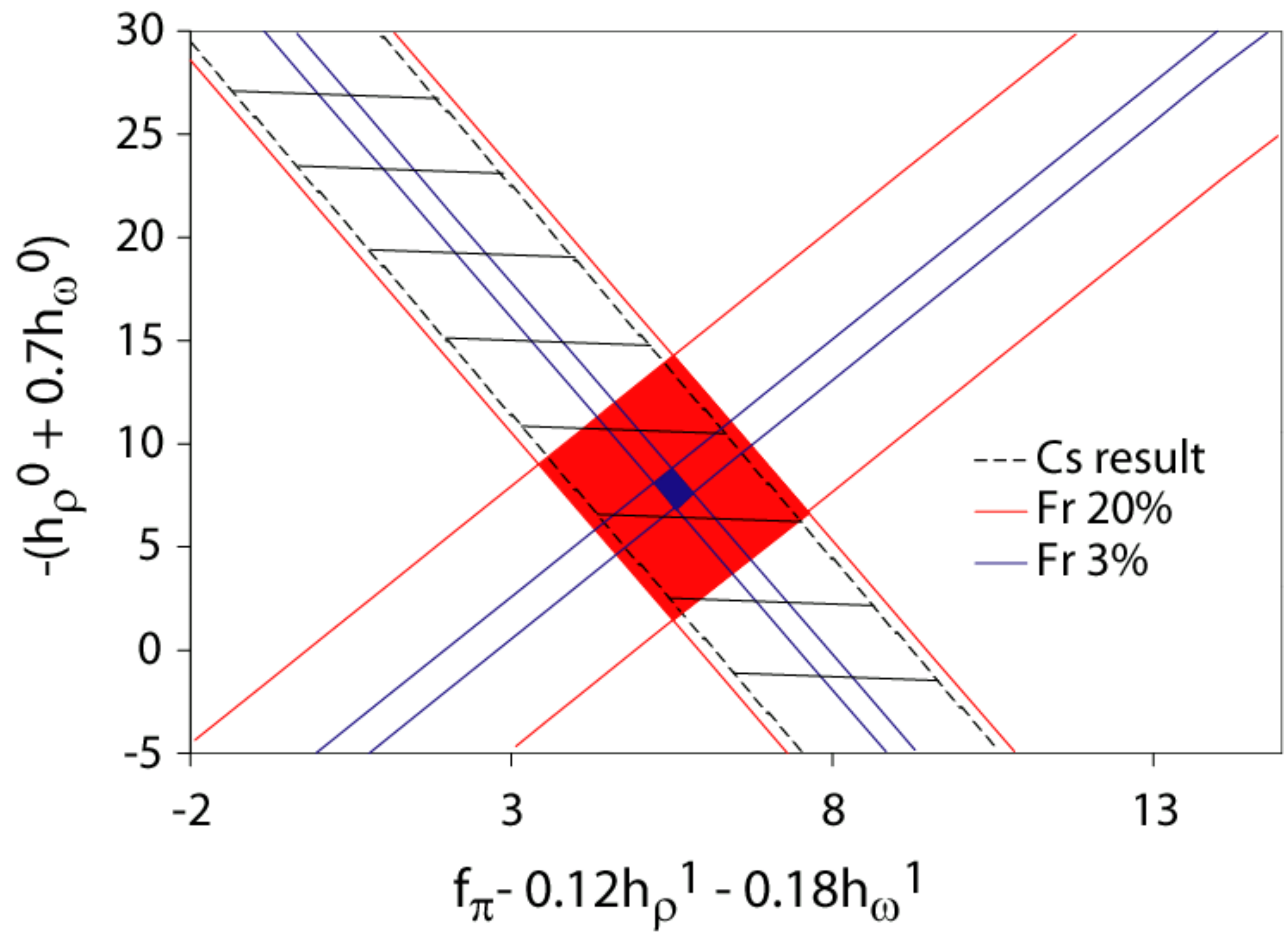


A. Weis, U. of Fribourg,

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).



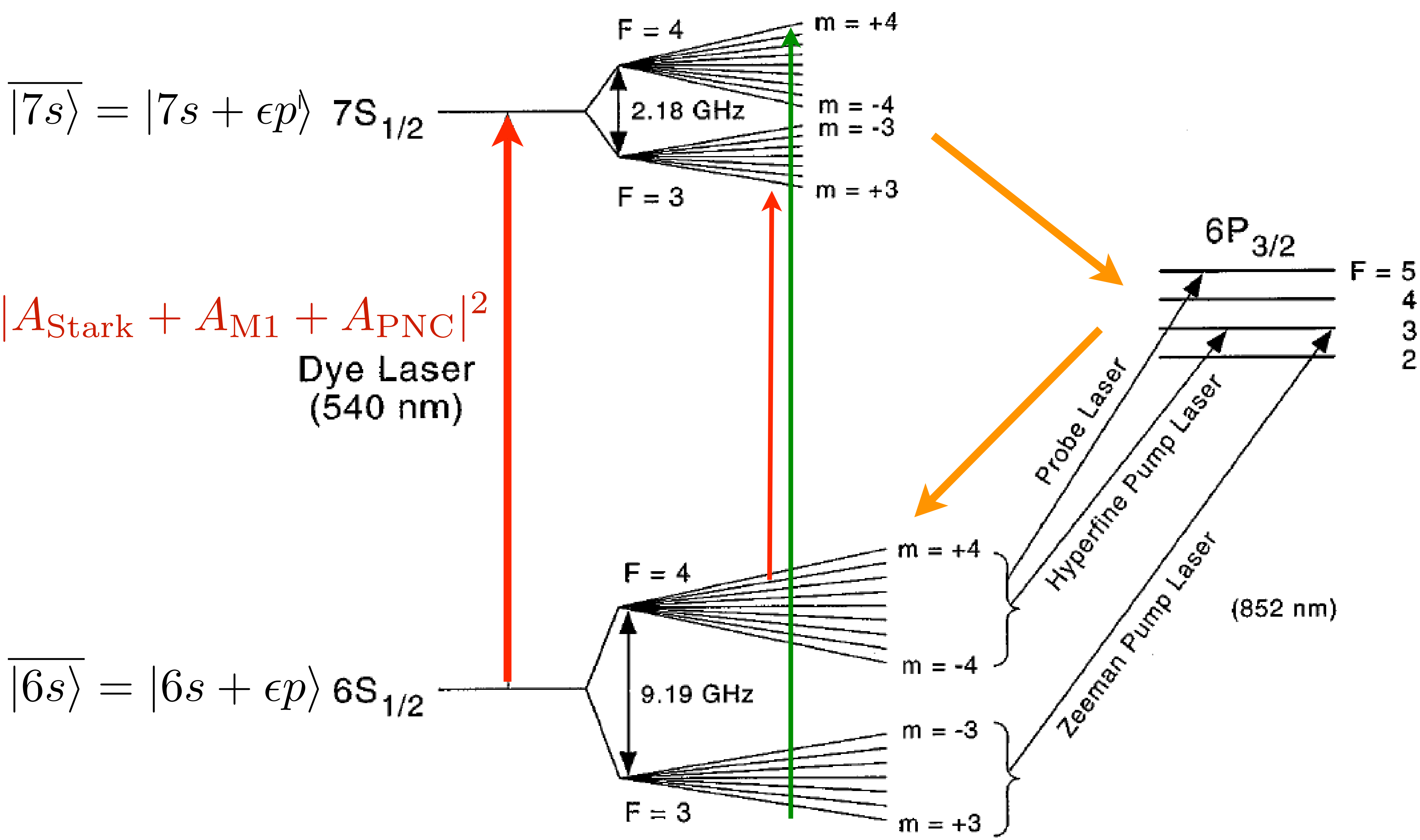
Limits on weak nucleon coupling from various experiments



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



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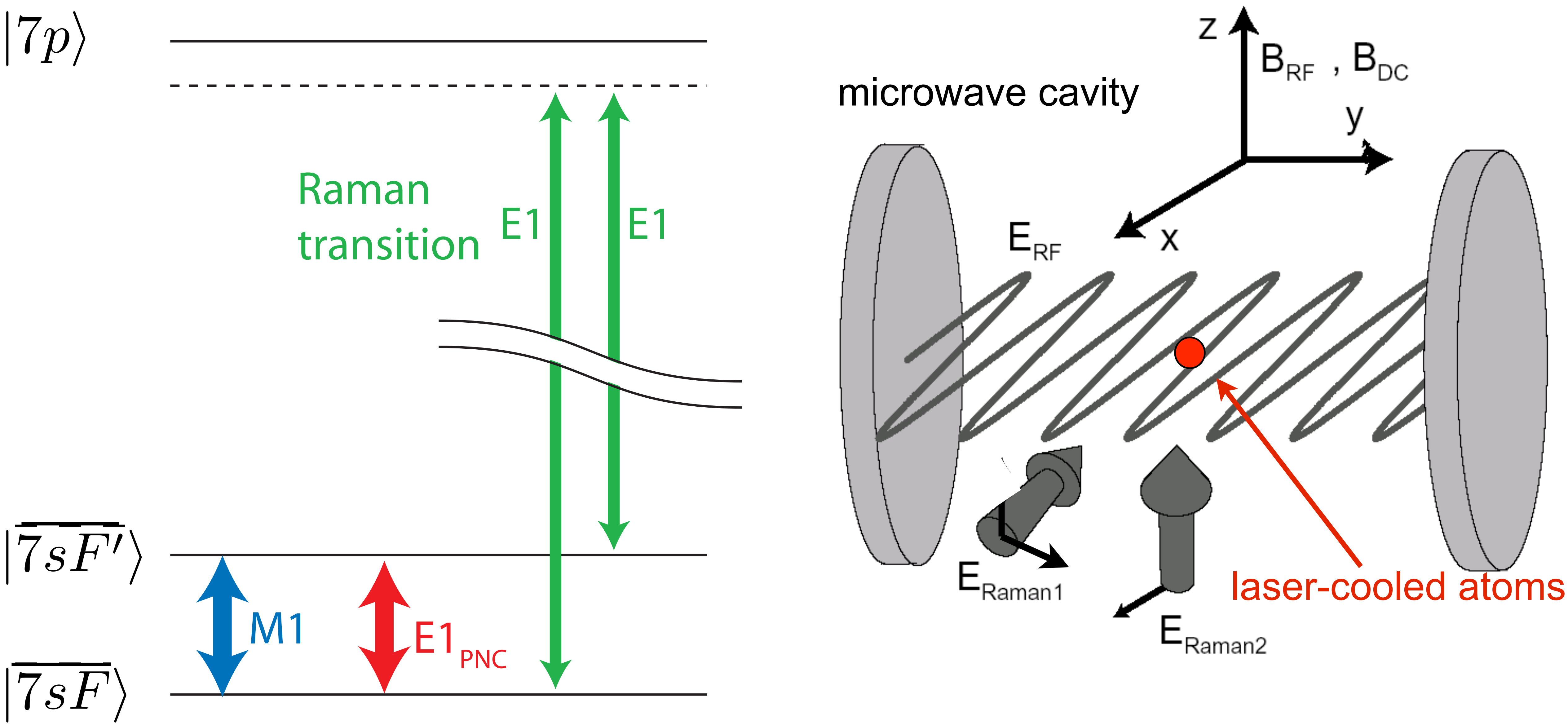
anapole is extracted from *difference*

Interference scheme for hyperfine transitions

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

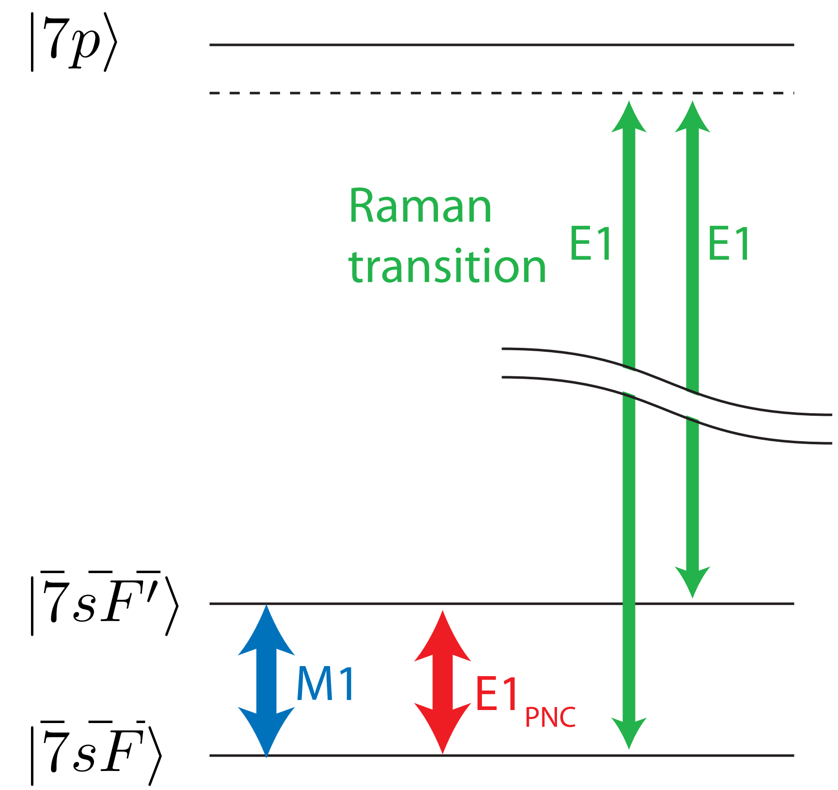
(L. Orozco, Maryland)



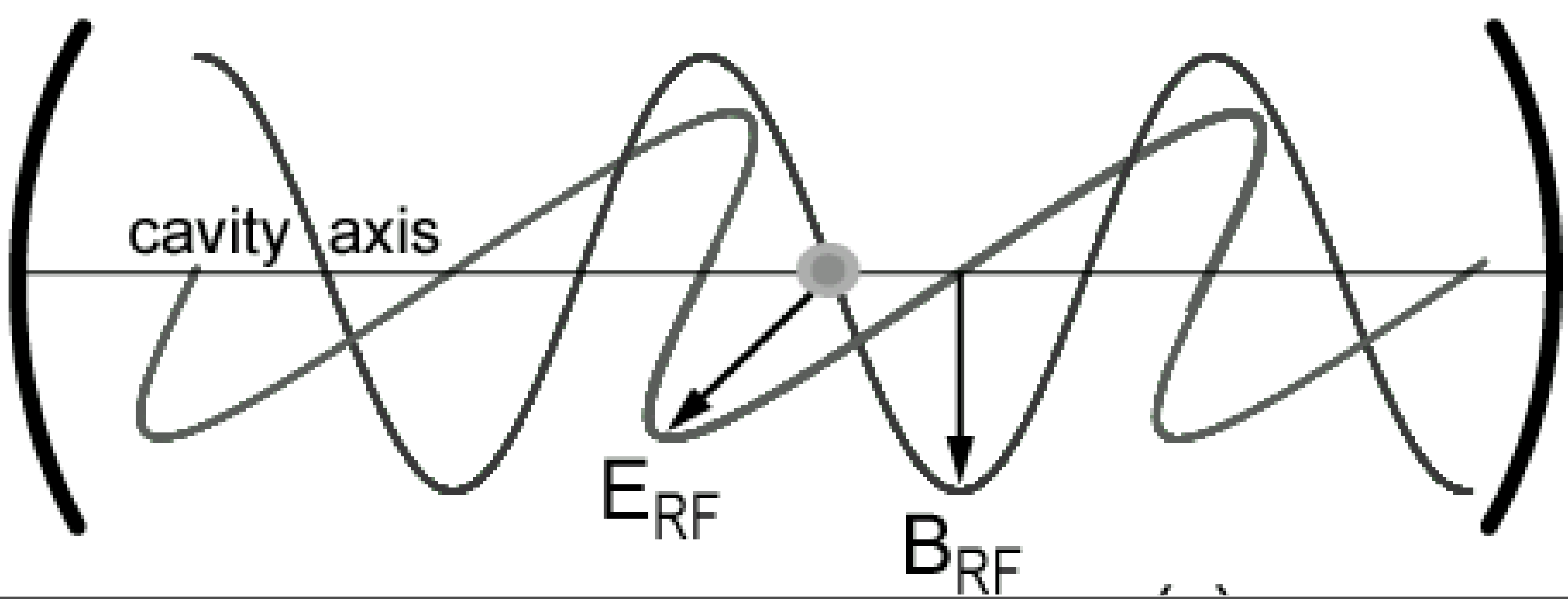
Gomez et al. PRA 2007

The big challenge: the M1 amplitude

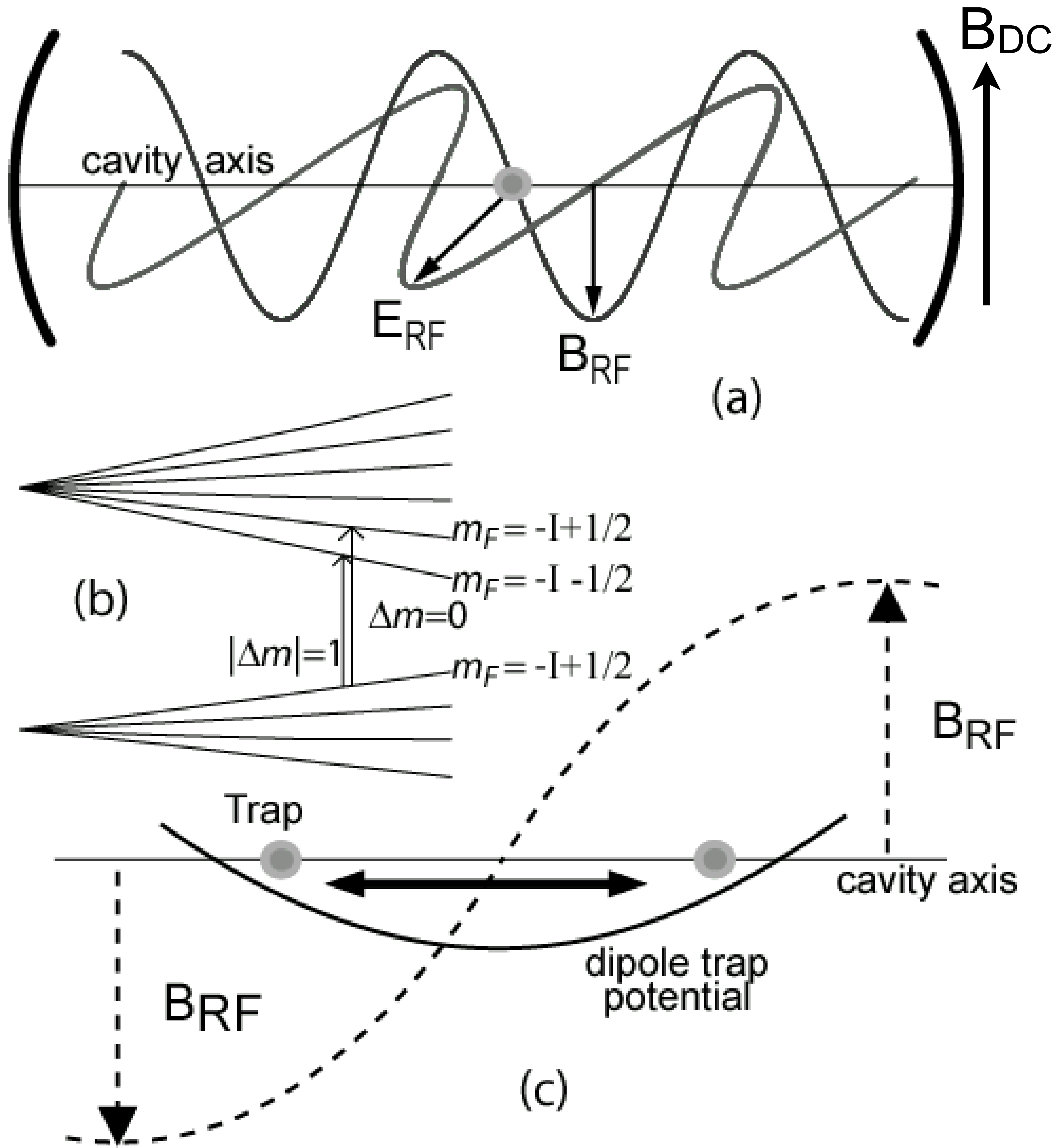
- M1 transition is allowed (unlike in optical APNC Stark experiments)



  - $|A_{E1}/A_{M1}| \sim 10^{-9}$!
  - 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



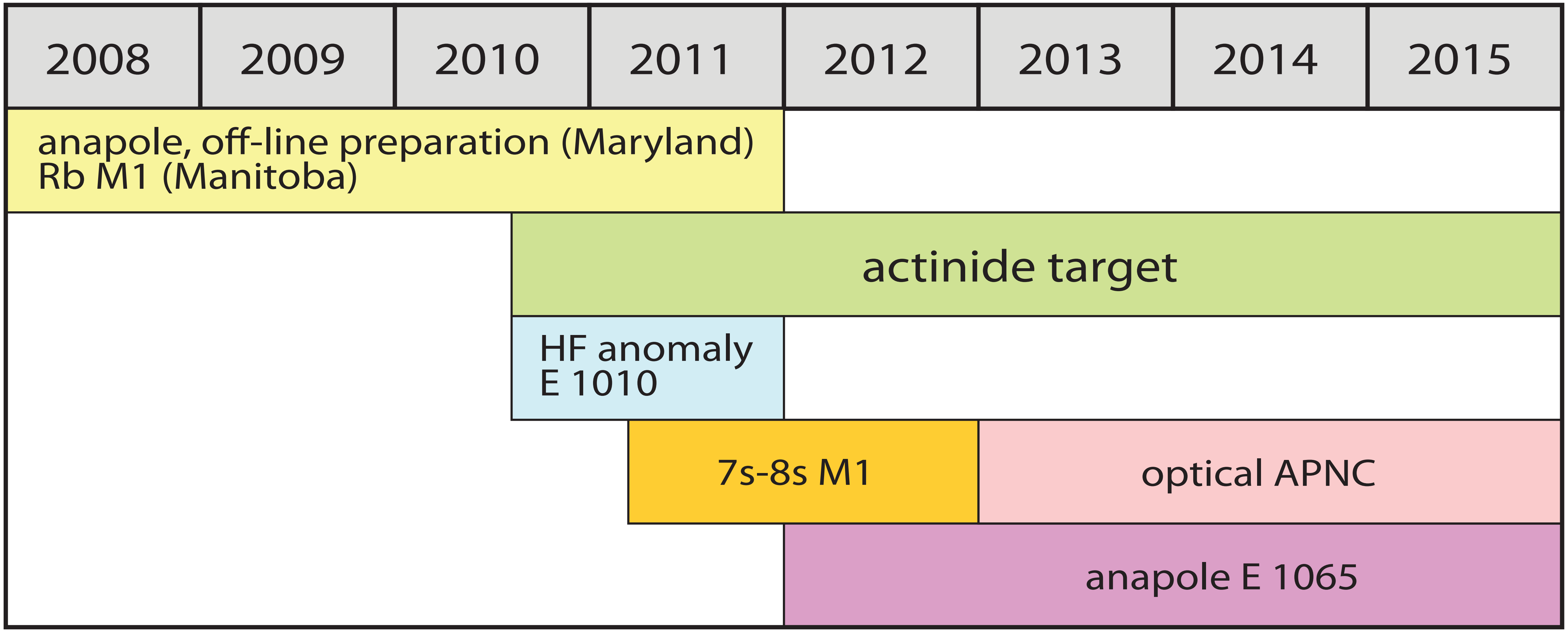
Signal to Noise

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

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

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

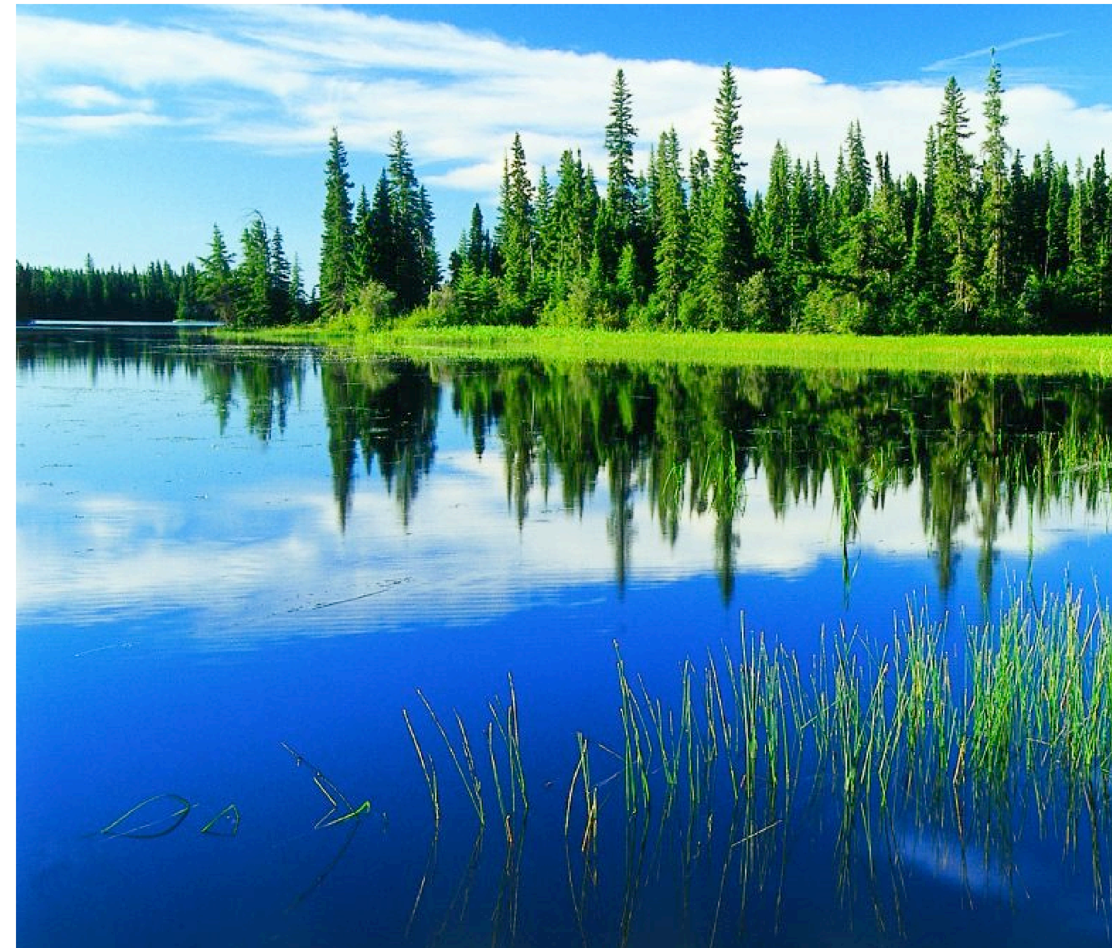
10^6 atoms: S/N of 20 in 1 second



- 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):

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V. Flambaum *(Univ. of New South Wales)*

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PRex →