FrPNC @ TRIUMF

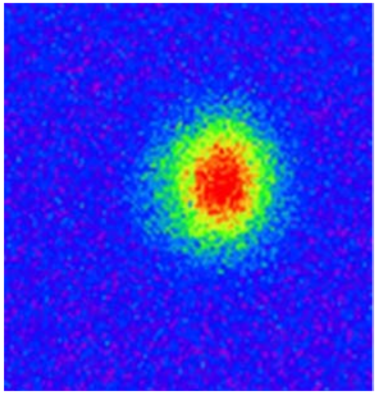
Atomic Parity Violation in Francium

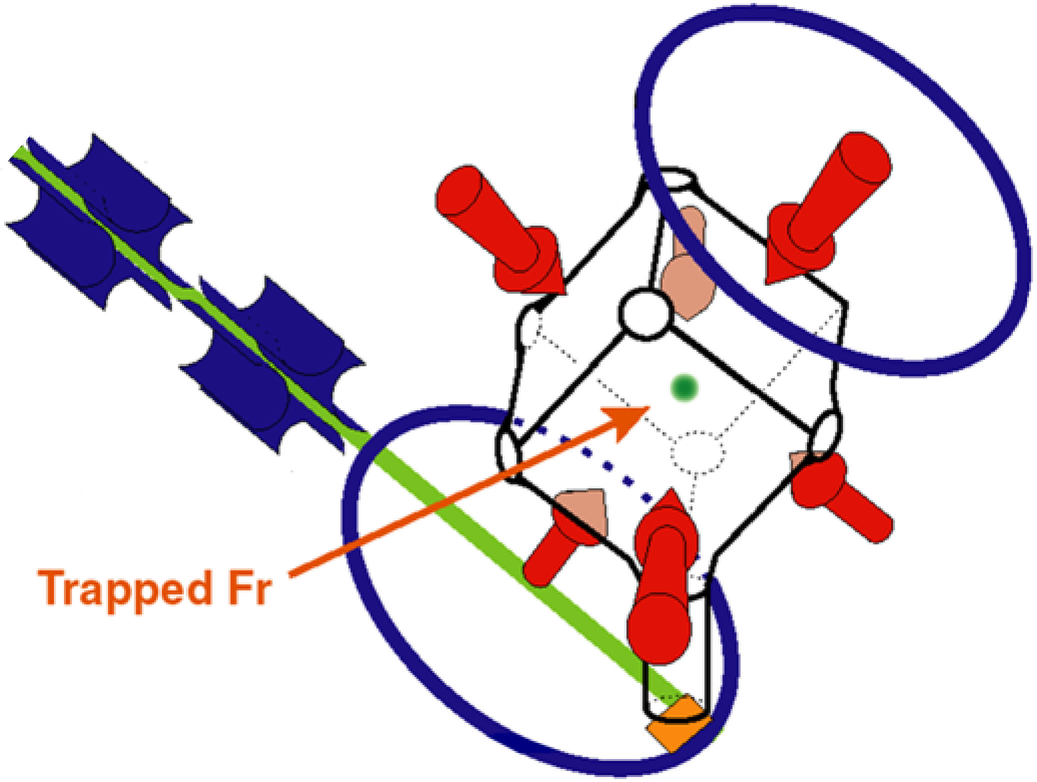
Seth Aubin

College of William and Mary

PAVI 2011 Workshop

La Sapienza University, Rome





FrPNC collaboration

S. Aubin *(College of William and Mary)*

J. A. Behr, K. P. Jackson, M. R. Pearson *(TRIUMF)*

V. V. Flambaum *(U. of New South Wales, Australia)*

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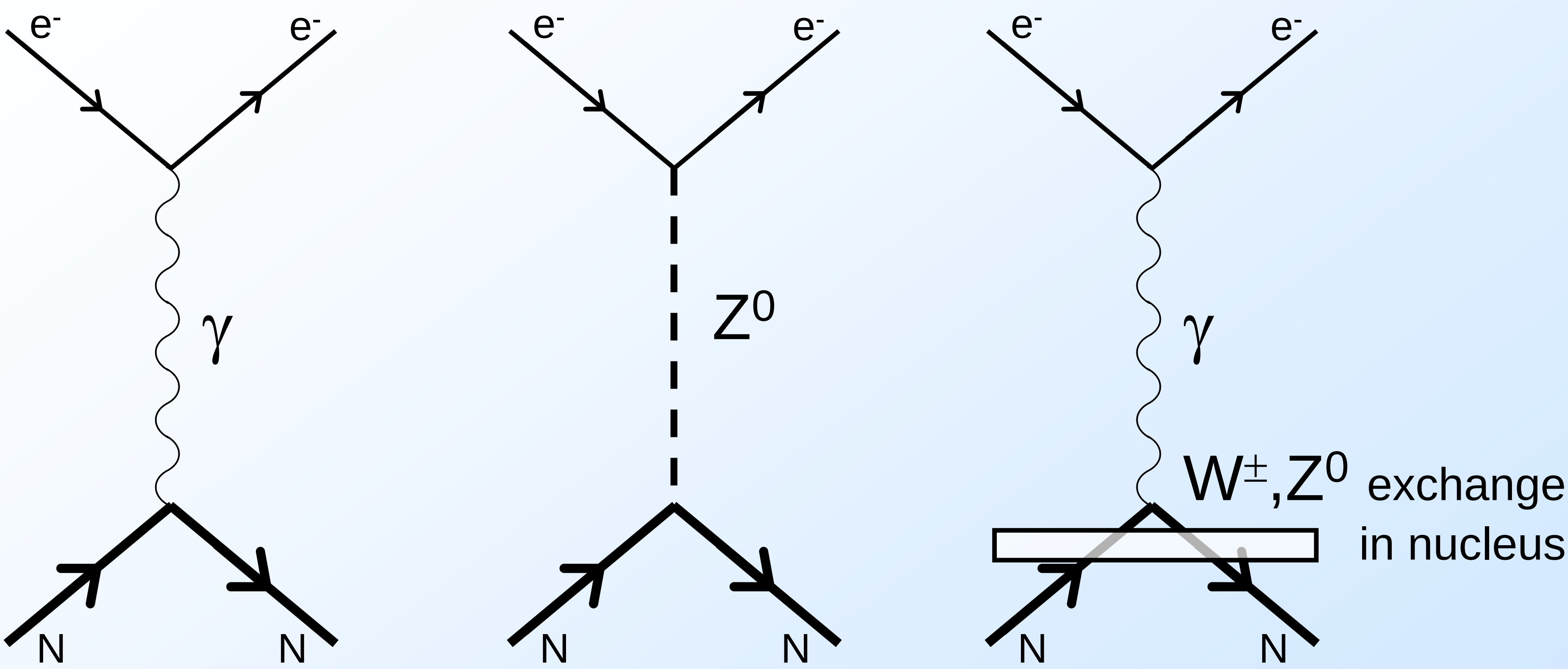
G. D. Sprouse *(SUNY Stony Brook)*

Y. Zhao *(Shanxi U., China)*

Funding

Atomic Parity Violation: Basic Processes



Standard Electromagnetic Interaction

(parity conserving)

Z^0 exchange

Electron-Nucleon PNC

(nuclear spin-independent)

Intra-nuclear PNC

Anapole moment

(nuclear spin-dependent)

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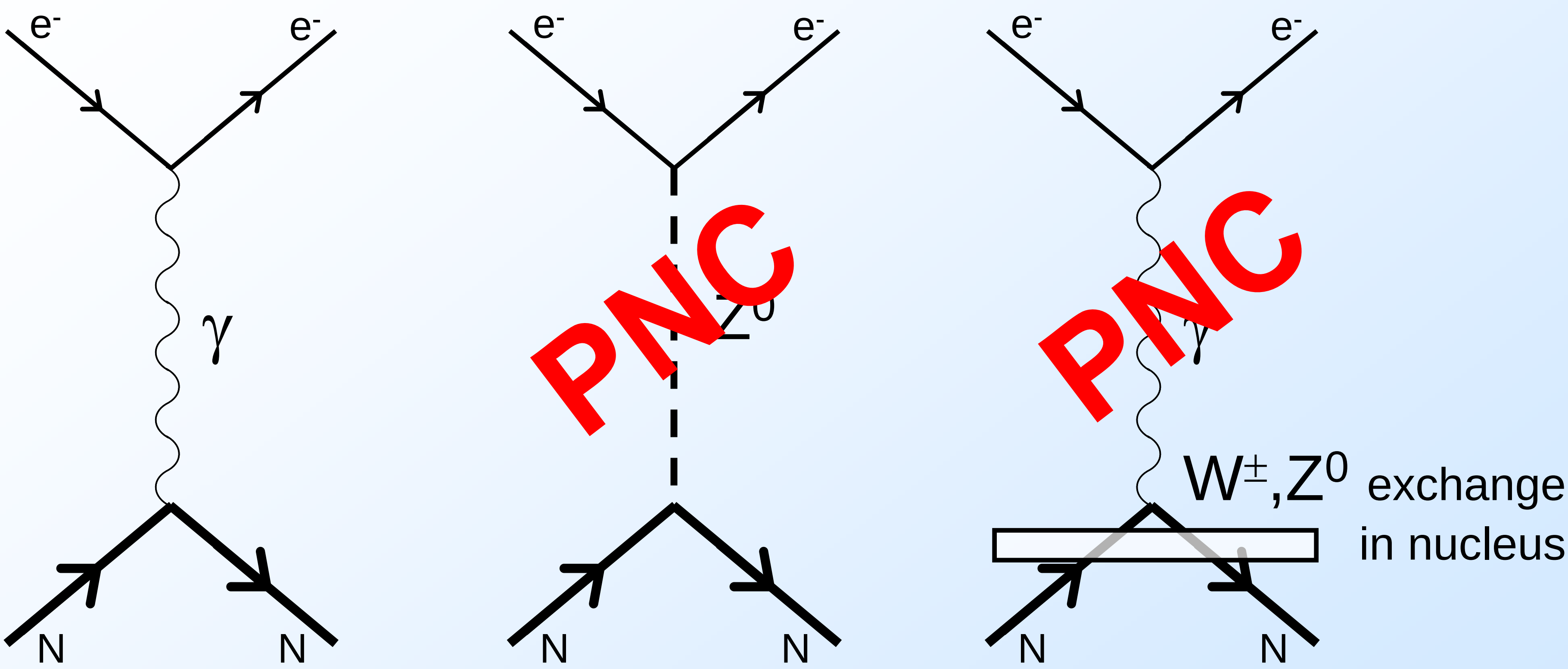

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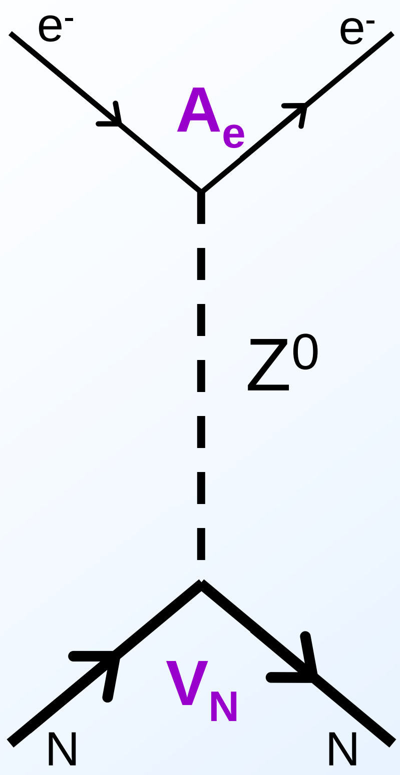
Motivation 1: Nuclear Spin-Independent PNC



Z^0 exchange

Electron-Nucleon PNC

(nuclear spin-independent)

The Hamiltonian for this interaction:

(infinitely heavy nucleon approximation)

$$H_{PNC,\,nsi} = \frac{G}{\sqrt{2}} \kappa_1 \gamma_5\, \delta(\vec{r})$$

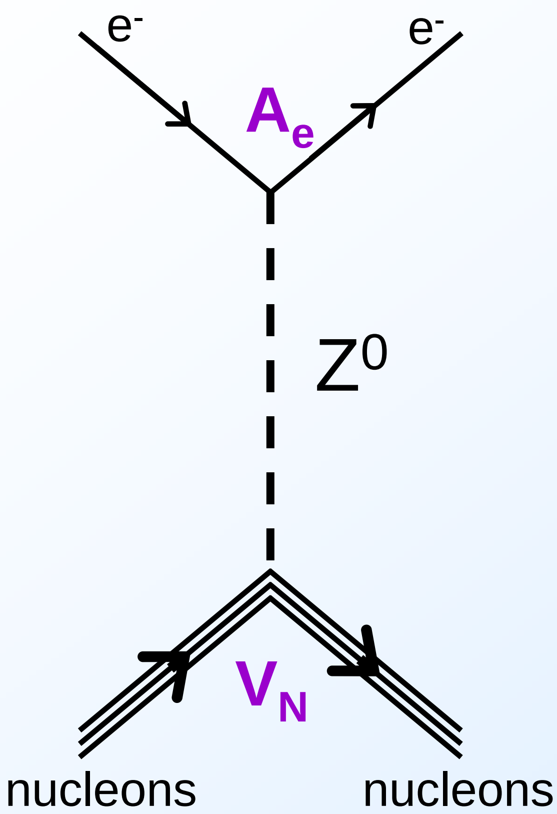
G = Fermi constant = $10^{-5}/m_p^2$

Proton: $\kappa_{1,p} = \frac{1}{2}\left(1 - 4\sin^2\theta_W\right) \approx 0.04$

Neutron: $\kappa_{1,n} = -0.5$

[Standard Model values for $\kappa_{1,\,(p,n)}$]

Motivation 1:
Nuclear Spin-Independent PNC



Z^0 exchange
Electron-Nucleons PNC
(nuclear spin-independent)

For a **nucleus** with Z protons and N neutrons:

$$H_{PNC,\,nsi} = \frac{G}{\sqrt{2}} \frac{Q_{weak}}{2} \gamma_5 \, \rho(\vec{r})$$

Q_{weak} = *weak charge of nucleus* $\approx$ *-N*

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

$$\rho(\vec{r}) = \text{nucleon distribution}$$

Motivation 1: Testing and Probing the Weak Interaction

Parity Violation = Unique Probe of Weak Interaction

Atomic PNC (APV) experiments **test** and **constrain** the Standard Model

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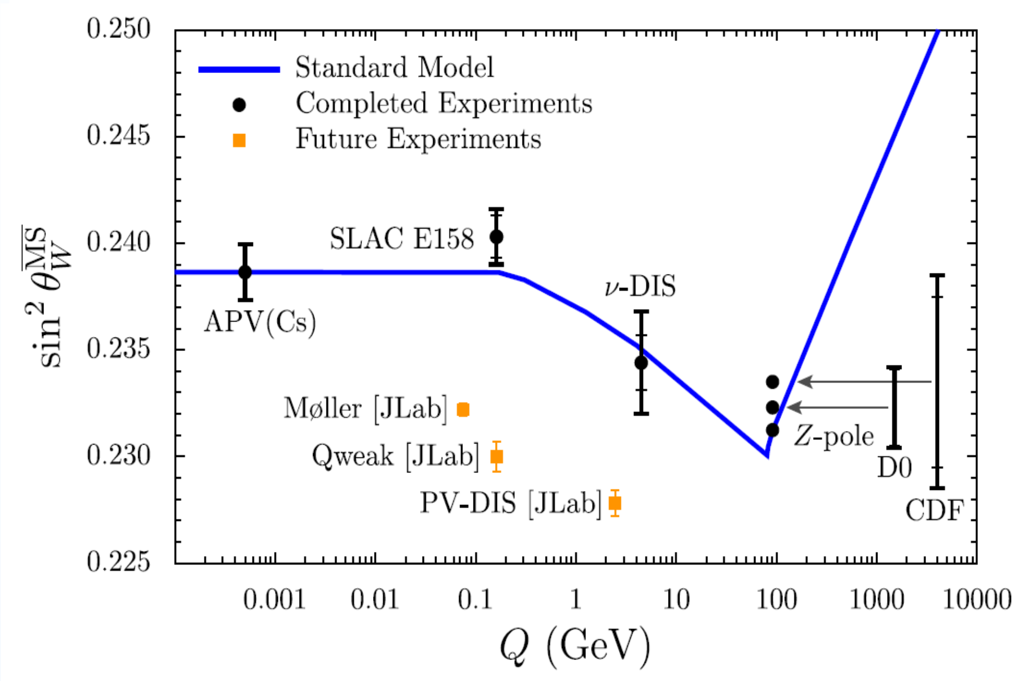
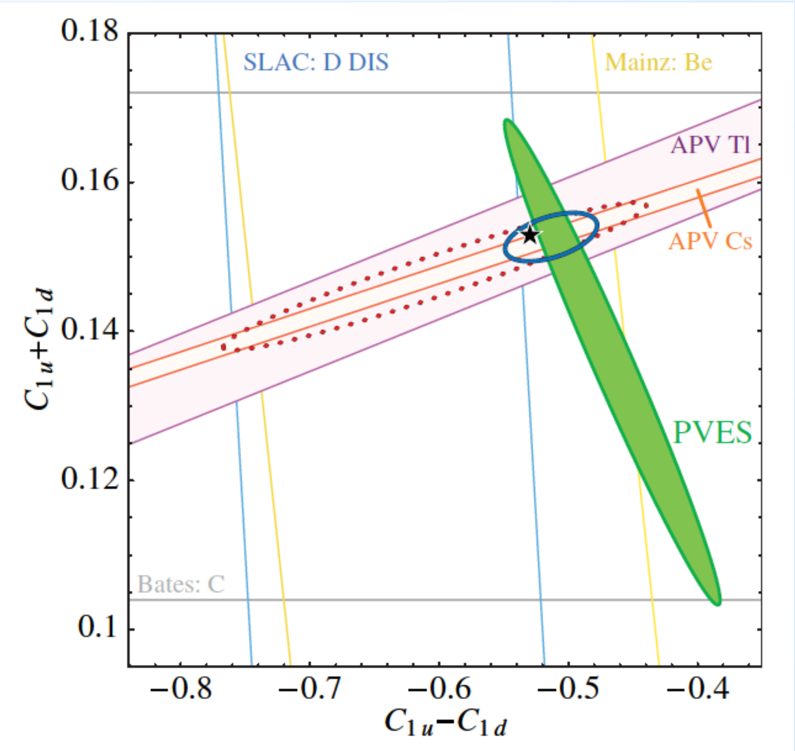
Weak mixing angle



[figure from Bentz *et al.* *Phys. Lett. B* **693**, 462 (2010)]

Effective e^--quark couplings C_{1u} & C_{1d}



[figure from Young *et al.*, *Phys. Rev. Lett.* **99**, 122003 (2007)]

Atomic PNC

$$H_{PNC,\,nsi} = \frac{G}{\sqrt{2}}\frac{Q_{weak}}{2}\gamma_5\,\rho(\vec{r}) \;= \boxed{\text{Parity Odd}}$$

$\Rightarrow$ Electron wavefunction does not have a definite parity !!!

$$\Rightarrow \begin{cases} |S\rangle \to |S\rangle + \varepsilon_{PNC}|P\rangle \\ |P\rangle \to |P\rangle + \varepsilon_{PNC}|S\rangle \end{cases}$$

Parity forbidden transitions become possible (slightly) !!!

$$\varepsilon_{PNC,nsi} \propto Z^3 R \sim 10^{-11} \quad (\mathrm{Cs})$$

relativistic enhancement factor

Francium advantage:

$$\frac{\varepsilon_{PNC,nsi}(Fr)}{\varepsilon_{PNC,nsi}(Cs)} \approx 18$$

Searching for New Physics

Francium can reduce experimental systematics !

… what about theoretical systematics ?

- **Atomic theory** uncertainties are continually improving !!! (~1%) (Safronova, Derevianko, Flambaum, etc …)

- **Nuclear theory** uncertainty is dominated neutron skin radius.
  - → Determine neutron skin in ^{208}Pb (PREX experiment, RCNP).
  - → 1% $R_{neutron}$ error gives a 0.3-0.6% uncertainty on Fr PNC. (Brown PRL 2009)
  - → R_{skin} varies by a factor of 2 for $^{209-221}$Fr.
  - → Hyperfine anomaly measurements inform $R_{neutron}$ (Grossman PRL 1999).

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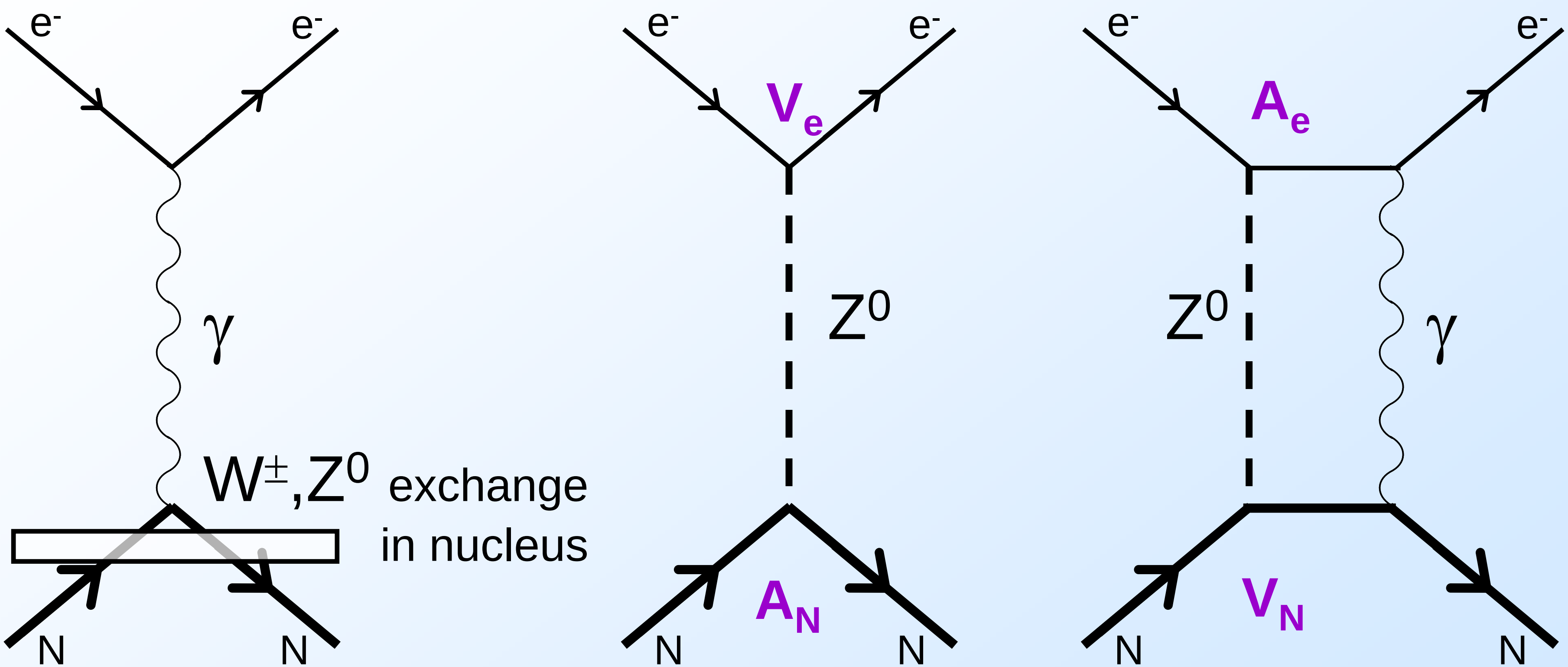
- Use **isotope ratios** to cancel out theoretical uncertainties.
  - → R_{skin} for different isotopes are correlated.
  (Brown, Derevianko, and Flambaum, PRL 2009; Dieperink and Van Isacker EPJA 2009)
  - → Improved sensitivity to new physics (primarily proton couplings).

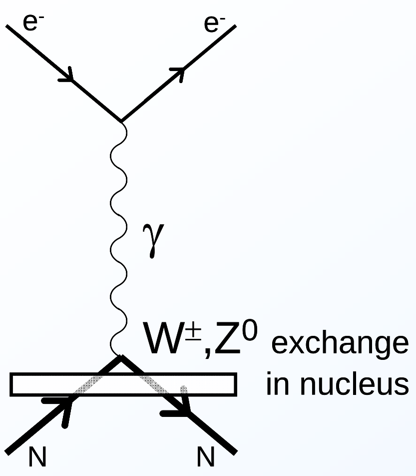
- **Alternative:** use atomic PNC to measure $R_{neutron}$.

Motivation 2: Nuclear Spin-Dependent PNC



Intra-nuclear PNC Anapole moment	Z^0 exchange Electron-Nucleon PNC (vector) (axial)	Hyperfine Interaction + NSI - Z^0 exchange *(nuclear spin-dependent)*

What's an Anapole Moment ?



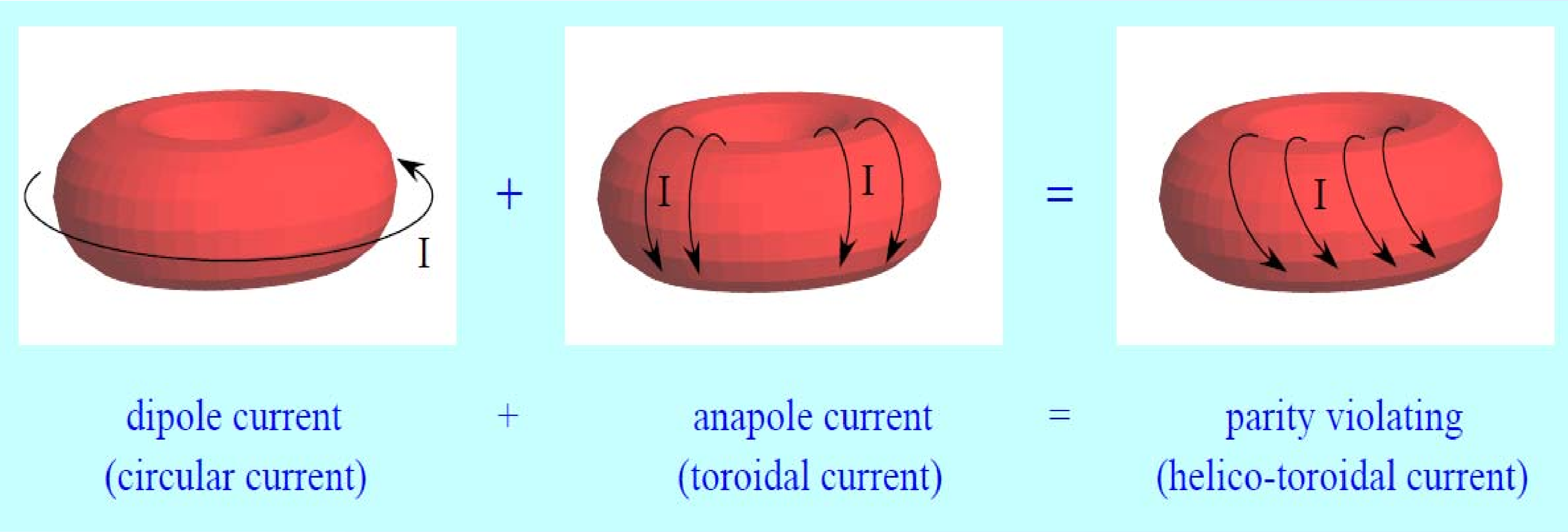
Answer:

Electromagnetic moment produced by a toroidal current.

→ Time-reversal conserving.

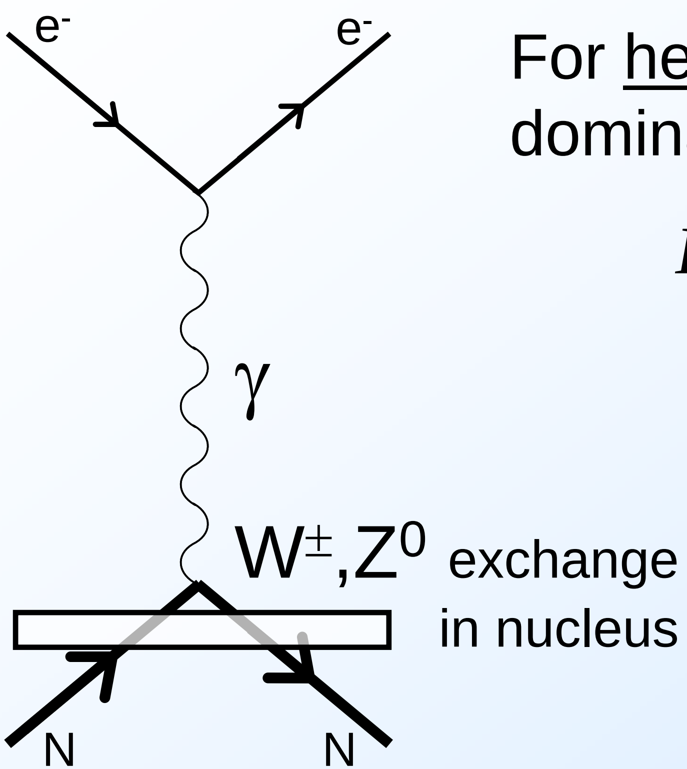
→ PNC toroidal current.

→ Localized moment, contact interaction.



[A. Weis, U. Fribourg (2003)]

Motivation 2: Nuclear Anapole Moment

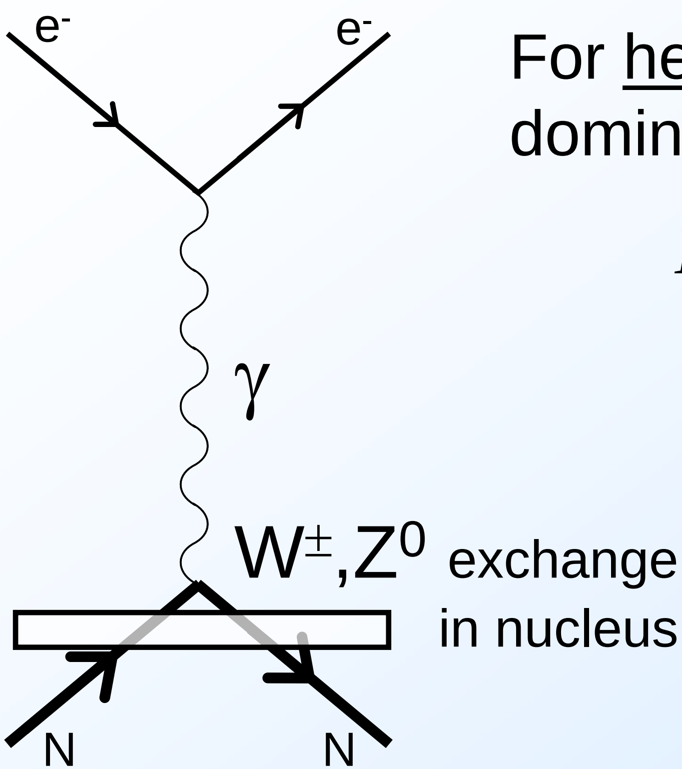


Anapole moment

For heavy atoms, the anapole moment term dominates.

$$H_{PNC,nsd} = \frac{G}{\sqrt{2}} \frac{K}{I\left(I+1\right)} \kappa_{anapole(p,n)} \vec{I} \cdot \vec{\alpha}\, \rho(\vec{r})$$

Motivation 2:
Nuclear Anapole Moment



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$$\kappa_{anapole(p,n)} = \frac{9}{10} g_{p,n} \frac{\alpha \mu_{p,n}}{m_p \tilde{r}_0} (Z+N)^{2/3}$$

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

$I = nuclear\ spin$

$l = valence\ nucleon\ orbital$
$\quad angular\ momentum$

$\alpha = 1/137$

$\mu = nucleon\ magnetic\ moment$

$\tilde{r}_0 = 1.2\ \mathrm{fm} = nucleon\ radius$

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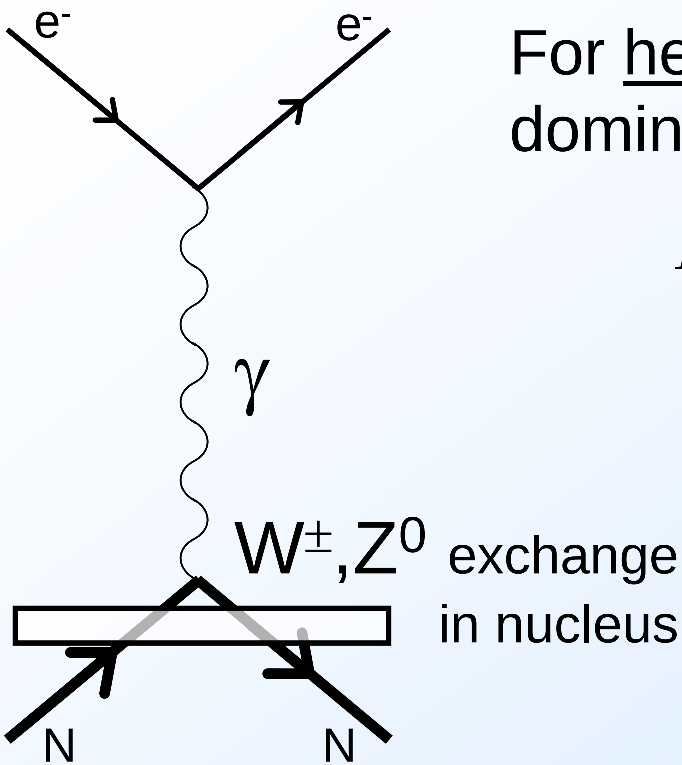

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$g_p \sim 4$ and $0.2 < g_n < 1$ characterize the nucleon-nucleus weak potential.

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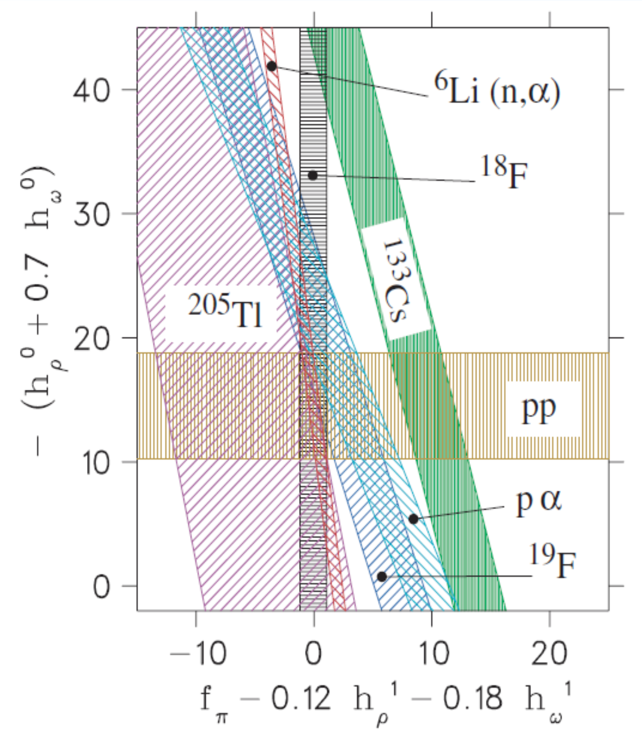
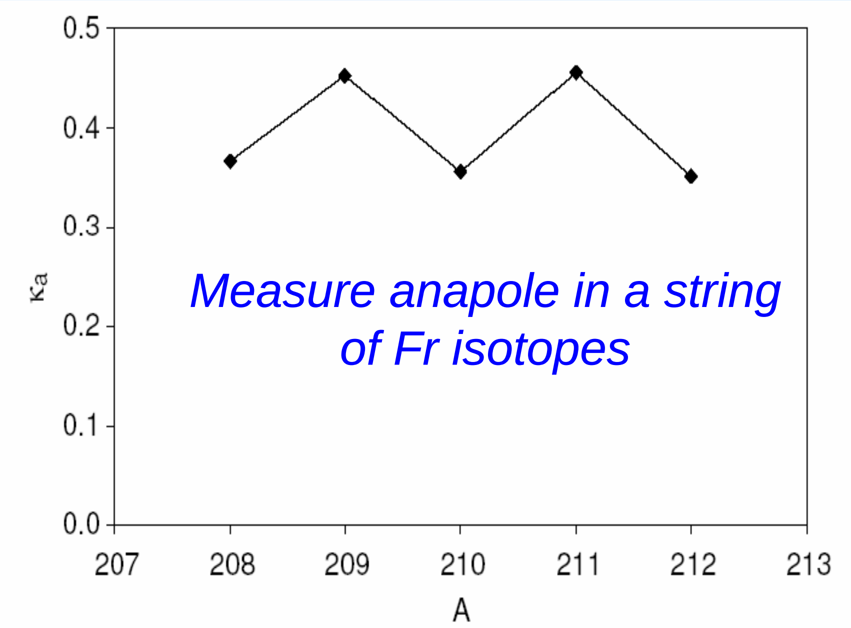
Motivation 2:
Isovector & Isoscalar Nucleon Couplings

Cs anapole (Boulder) and low-energy nuclear PNC measurements produce conflicting constraints on weak meson-nucleon couplings.
(Desplanques, Donoghue, and Holstein model)

Need to understand nuclear structure better.



[Haxton *et al.*, Phys. Rev. C **65**, 045502 (2002) and 6Li(n,α) from Vesna Phys. Rev. C **77**, 035501 (2008)]



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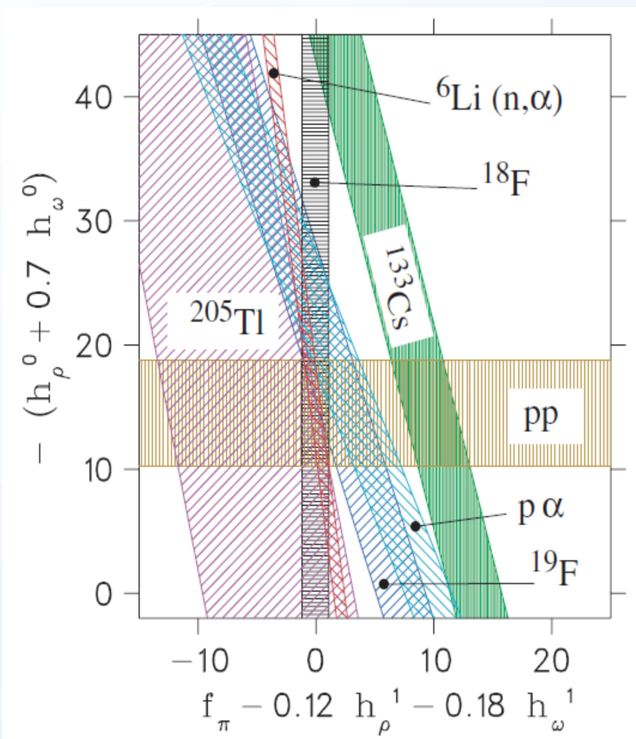
→ Francium isotopes provide orthogonal constraints !!!



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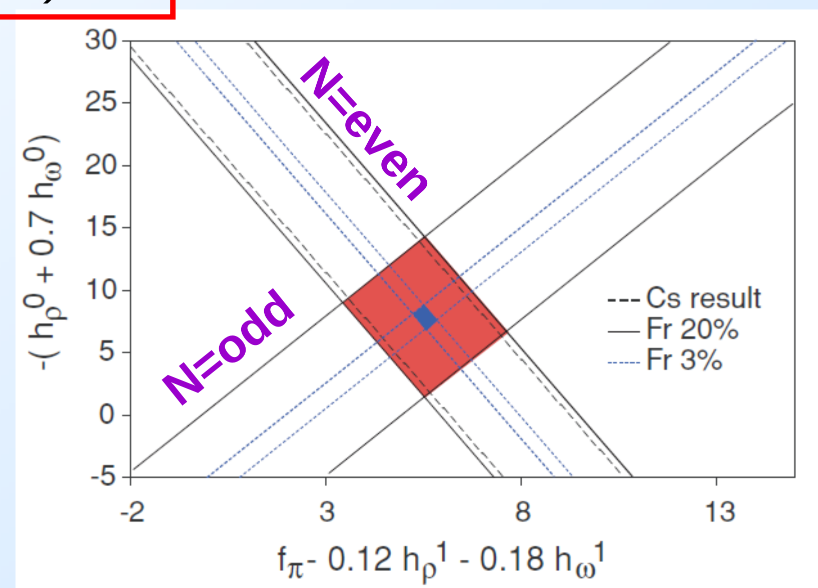


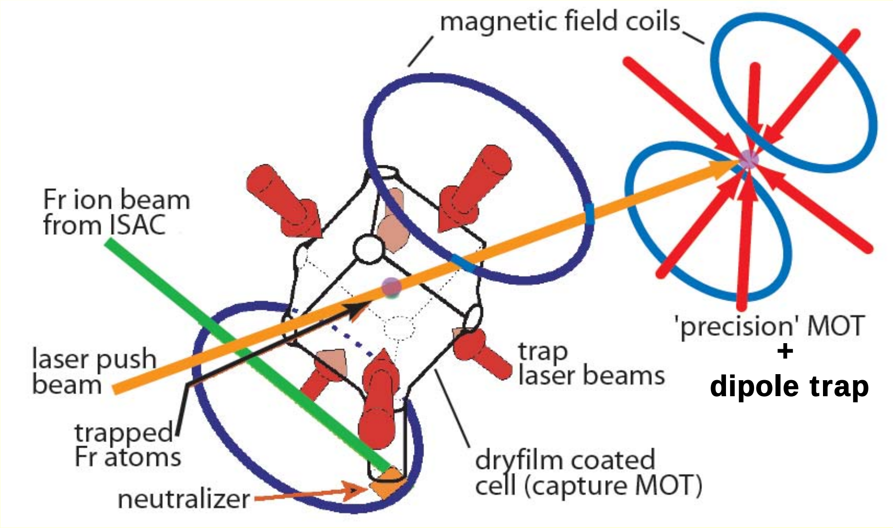
[Behr and Gwinner, *J. Phys. G* **36**, 033101 (2009)]

Francium advantage:

$$\frac{\varepsilon_{PNC,anapole}(Fr)}{\varepsilon_{PNC,anapole}(Cs)} \approx 11$$

FrPNC program:
Atomic PNC Experiments in Francium

- Fr is the heaviest of the simple (alkali atoms).
  - → Electronic structure is well understood.
  - → Particle/nuclear physics can be reliably extracted.
- Fr has large (relatively) PNC mixing.
  - → $\varepsilon_{PNC} \sim 10^{-10}$ is still really really small … we're going to need a lot of Fr.
- Fr does not exist sufficiently in nature.



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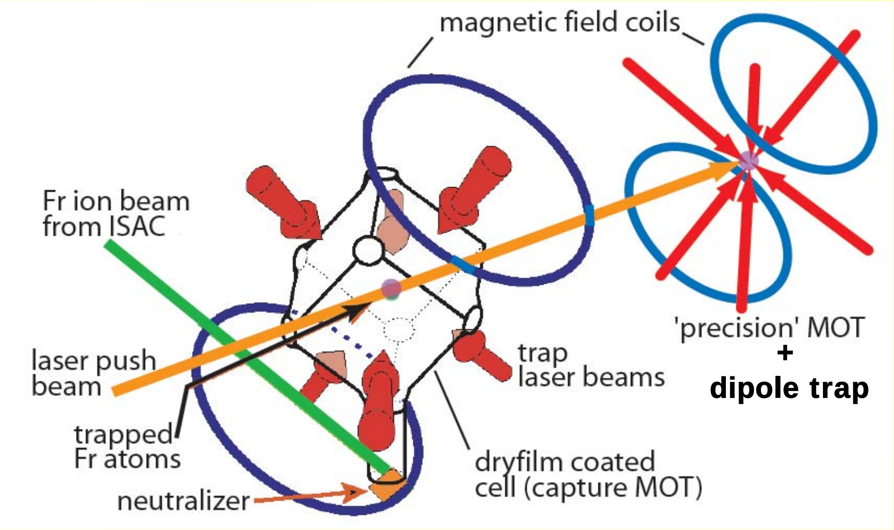
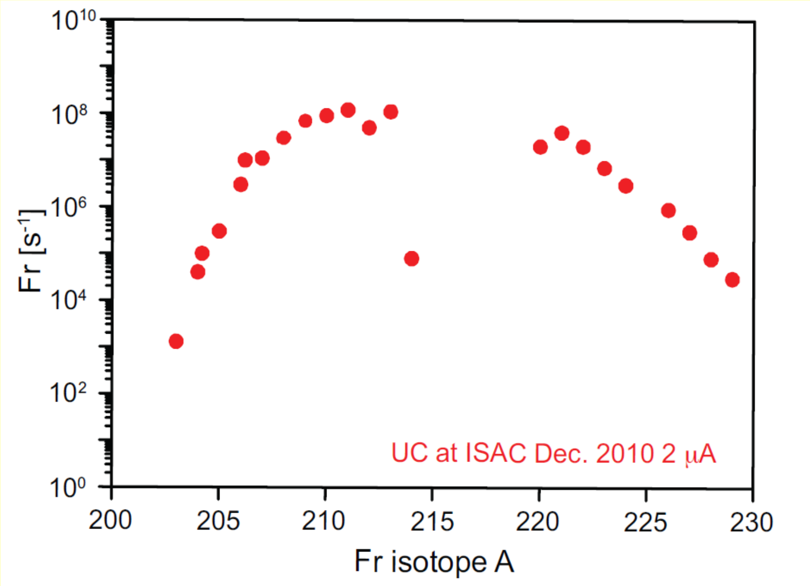
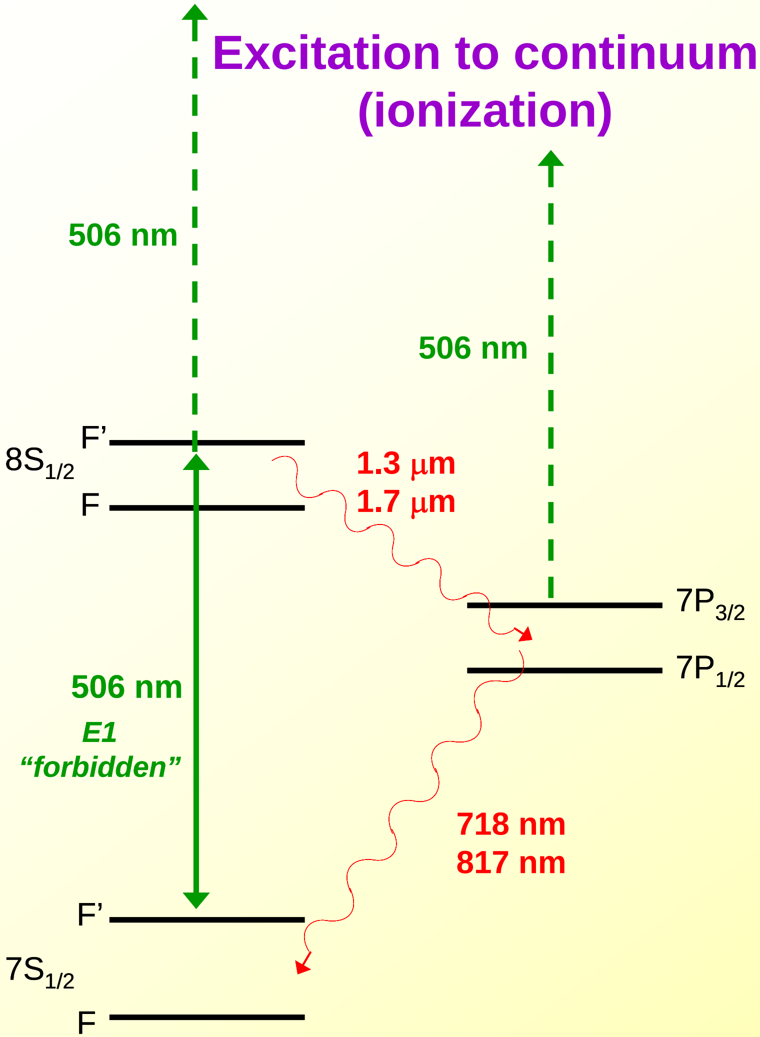
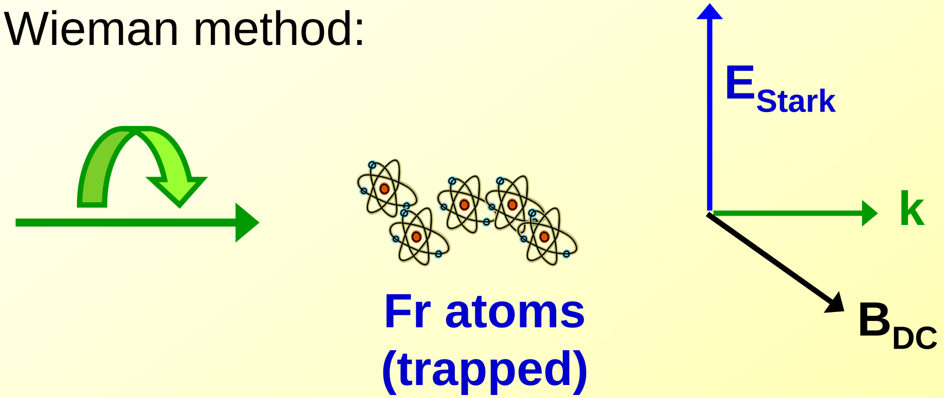




Atomic PNC in Fr (NSI)



Wieman method:



$$\varepsilon_{PNC} \propto \vec{B}_{DC} \cdot \left(\vec{k} \times \vec{E}_{Stark}\right)$$

M1 is strongly suppressed.

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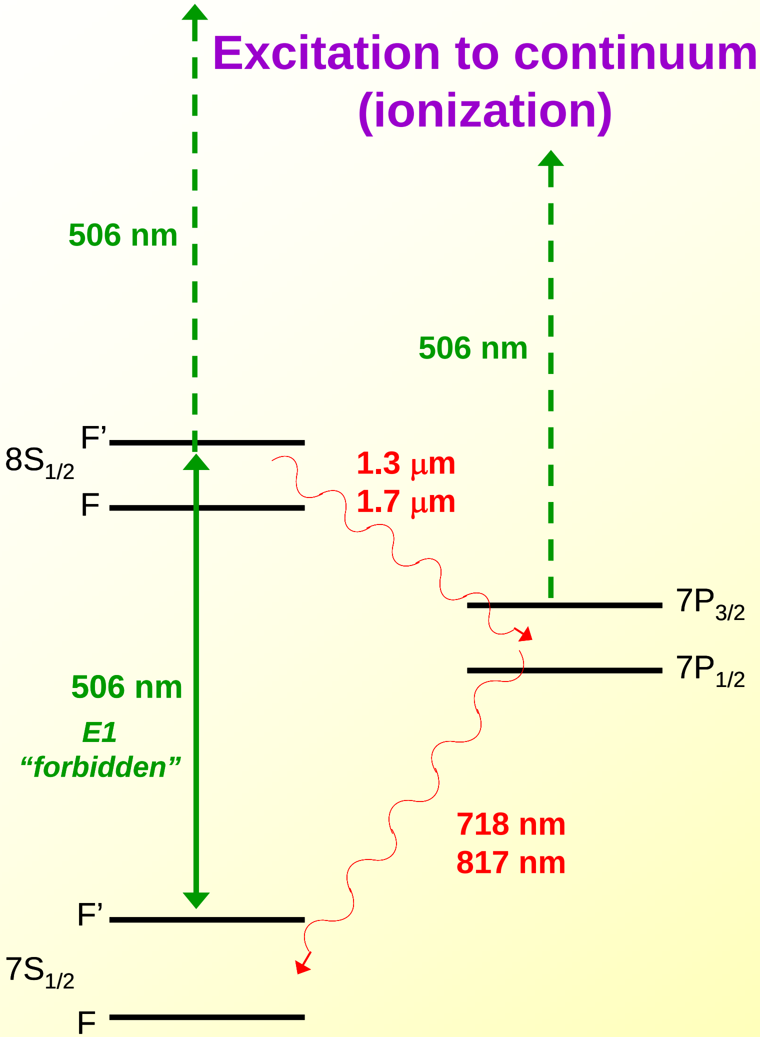

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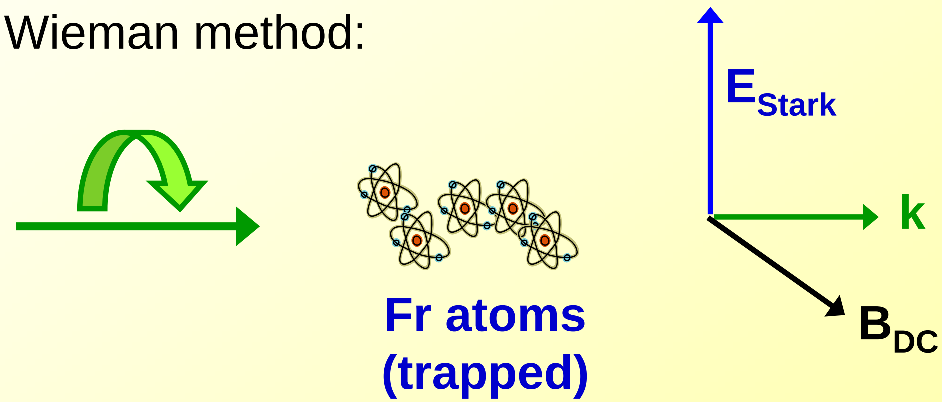

$$\varepsilon_{PNC} \propto \vec{B}_{DC} \cdot \left(\vec{k} \times \vec{E}_{Stark}\right)$$

Amplification by Stark Interference

$$Transition\ Rate = \left|A_{Stark} \pm A_{PNC}\right|^2$$
$$= \left|A_{Stark}\right|^2 \pm 2\,\mathrm{Re}\left(A_{Stark} A_{PNC}{}^*\right) + \left|A_{PNC}\right|^2$$

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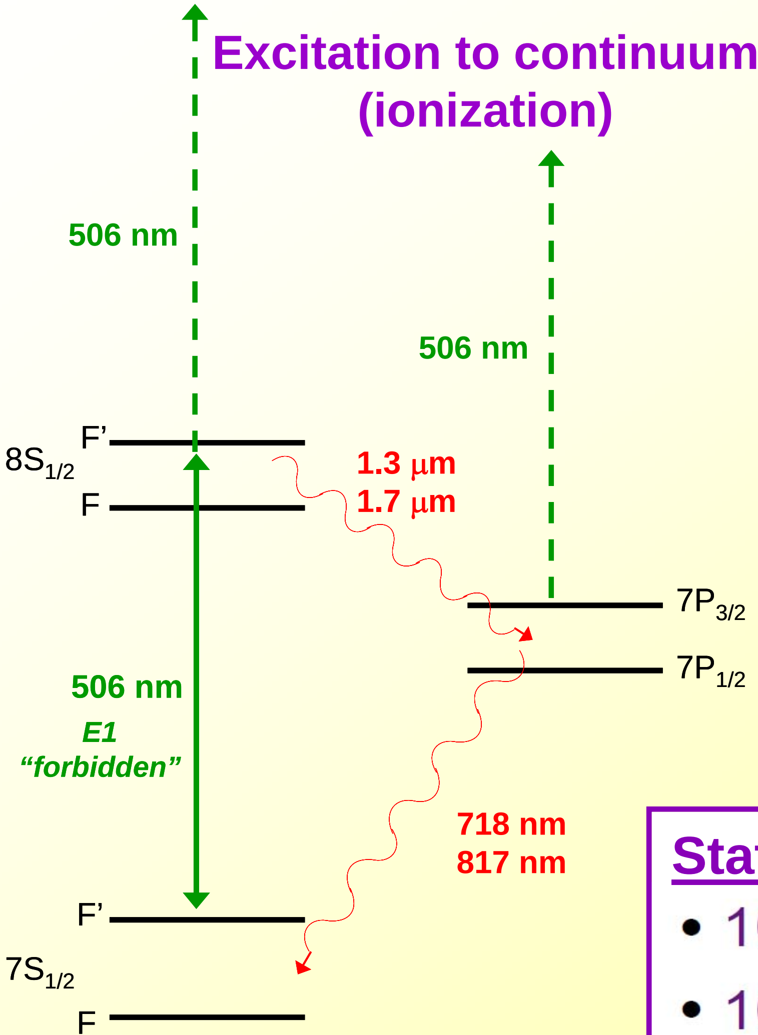

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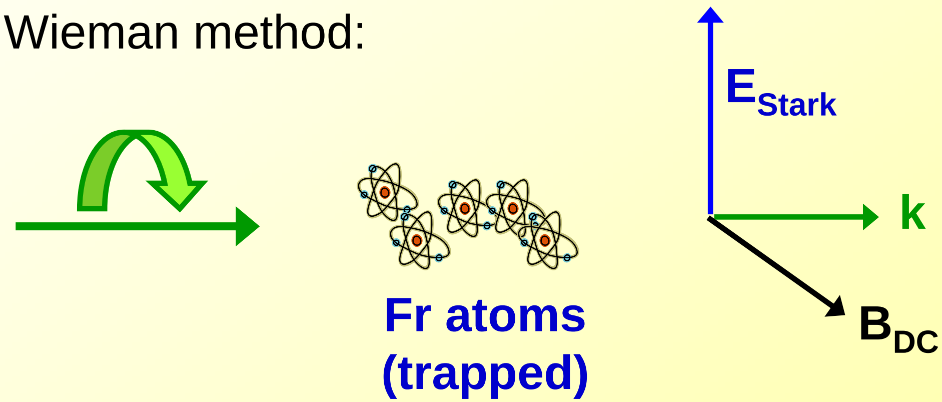

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Statistical Sensitivity:

- 10^6 trapped atoms, 1.0% APNC: 2.3 hours
- 10^7 trapped atoms, 0.1% APNC: 23 hours

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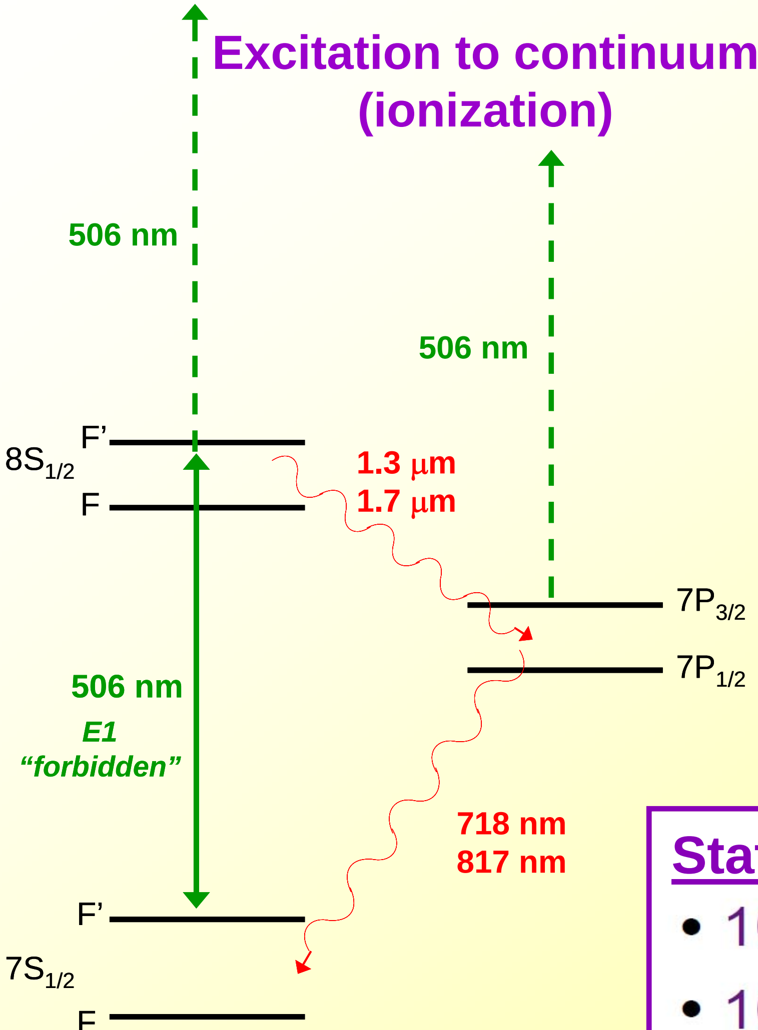

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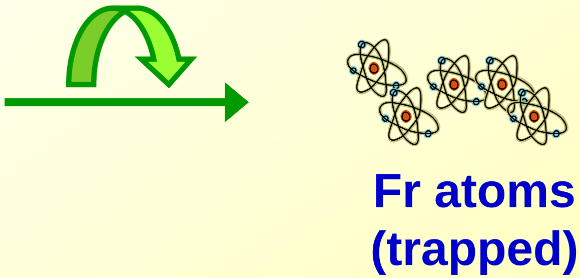

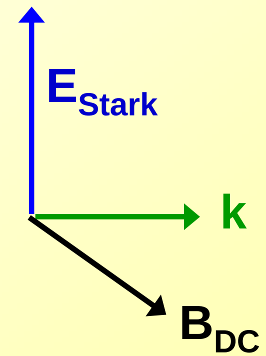

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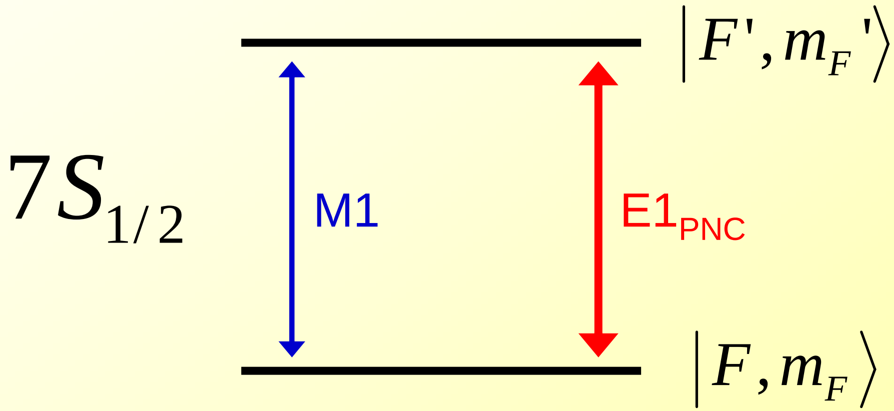
Alternative method: PNC energy shift, M.-A. Bouchiat, PRL 100, 123003 (2008).

Anapole Moment in Fr

<u>New Method:</u> Anapole can be measured by driving a parity forbidden E1 transition between two hyperfine states with $\Delta F=\pm 1$, $\Delta m_F=\pm 1$.

π/2 pulse preparation: the atoms are prepared in a 50/50 superposition of the initial and final states (equivalent to interference amplification) before application of the microwave driving E-field.



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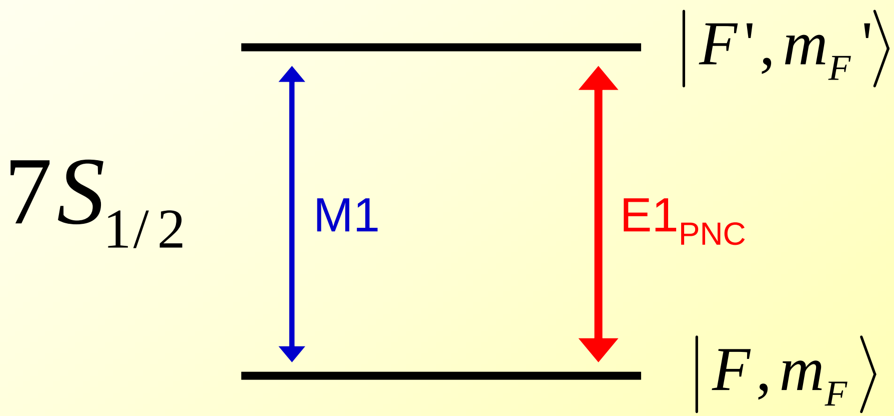

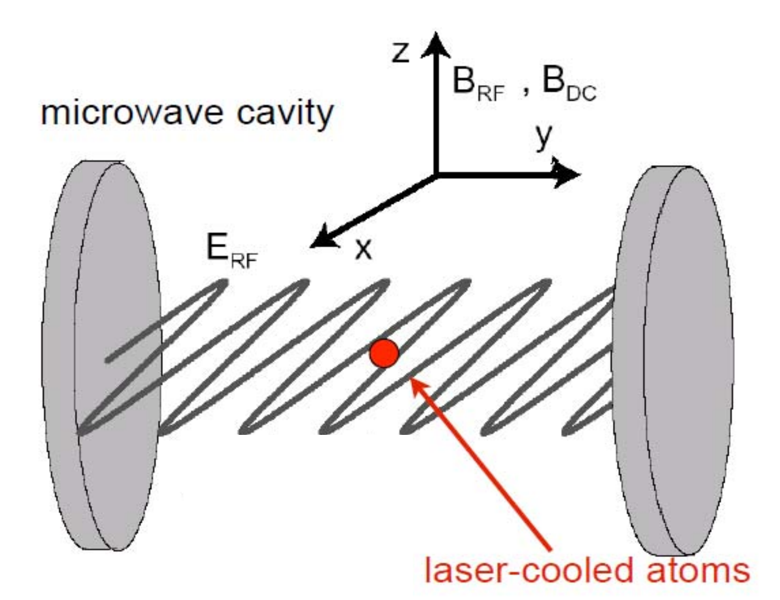

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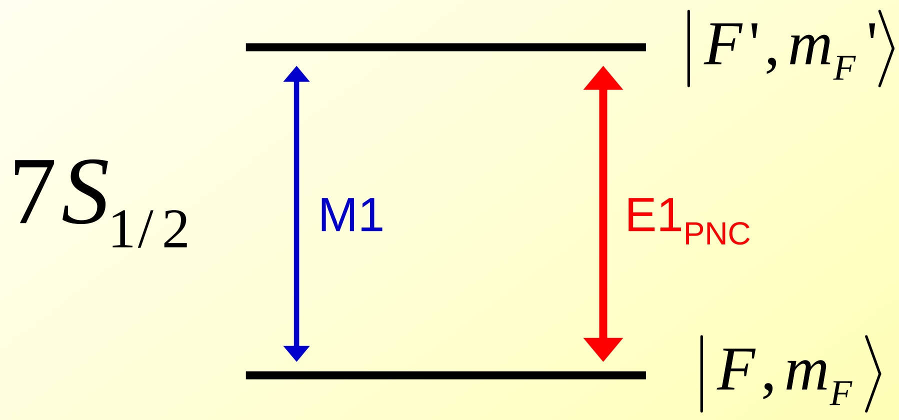
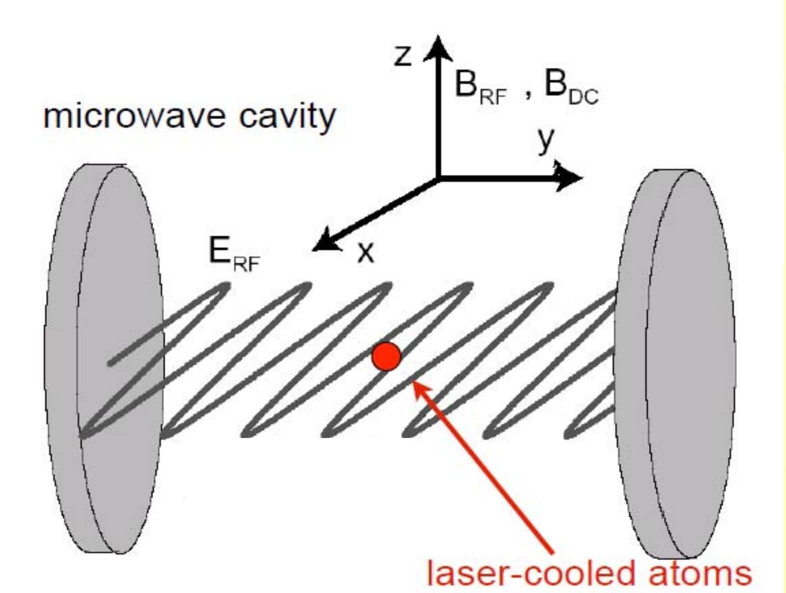




$$\varepsilon_{anapole} \propto \vec{B}_{DC} \cdot \left(\vec{M}1_{\pi/2} \times \vec{E}_{microwave}\right)$$

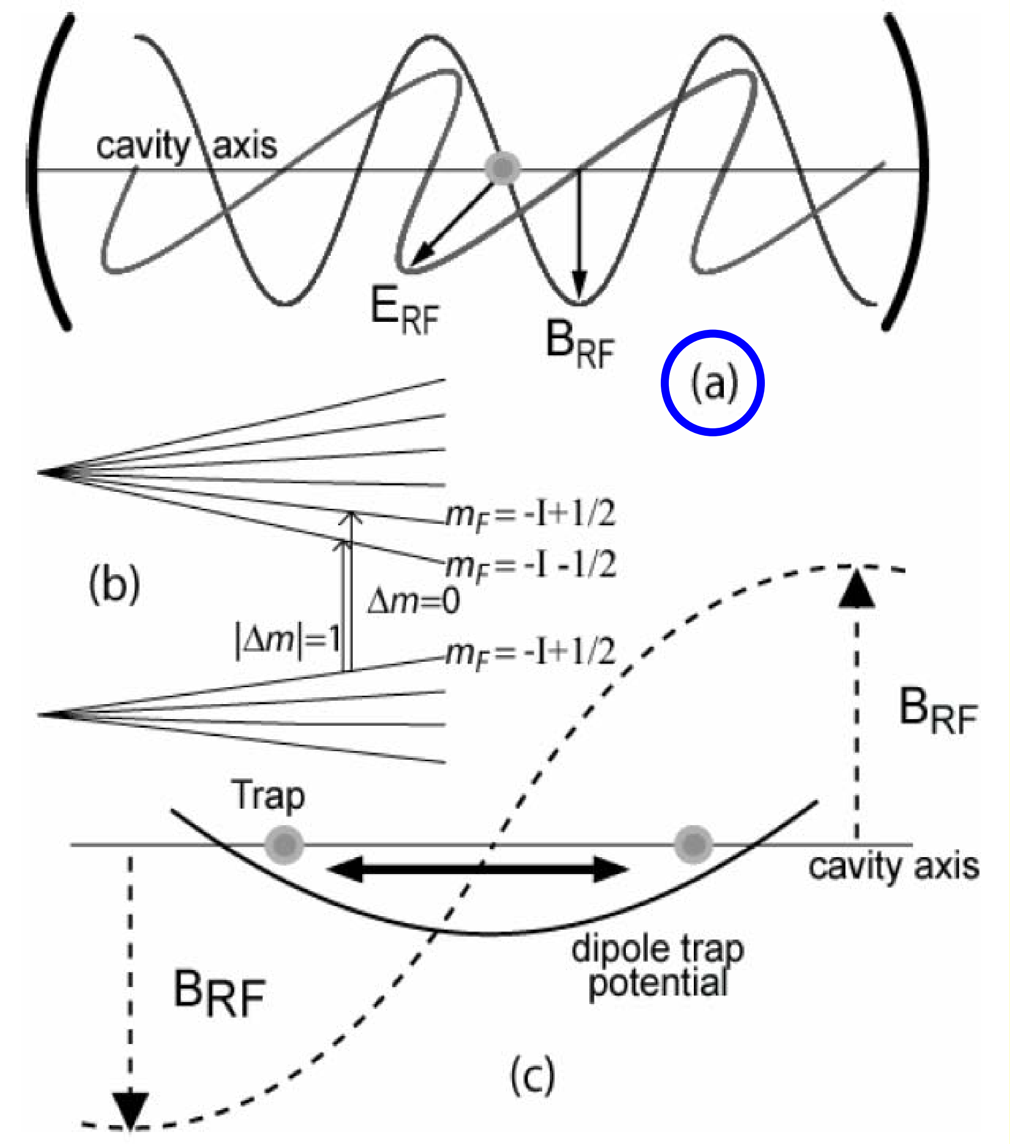
$$Signal - to - noise \sim 20\sqrt{Hz^{-1}}$$

for $E_{microwave}$~0.5 kV/cm and 10^6 atoms.

[E. Gomez *et al.*, *Phys. Rev. A* **75**, 033418 (2007)]

M1 suppression

M1 hyperfine transition mimics $E1_{PNC}$ and must be suppressed by 10^9 !!!



a) Suppress $B_{microwave}$:

Fabry-Perot cavity: Place atoms at B node, E anti-node.

→ Suppression: 5×10^{-3}.

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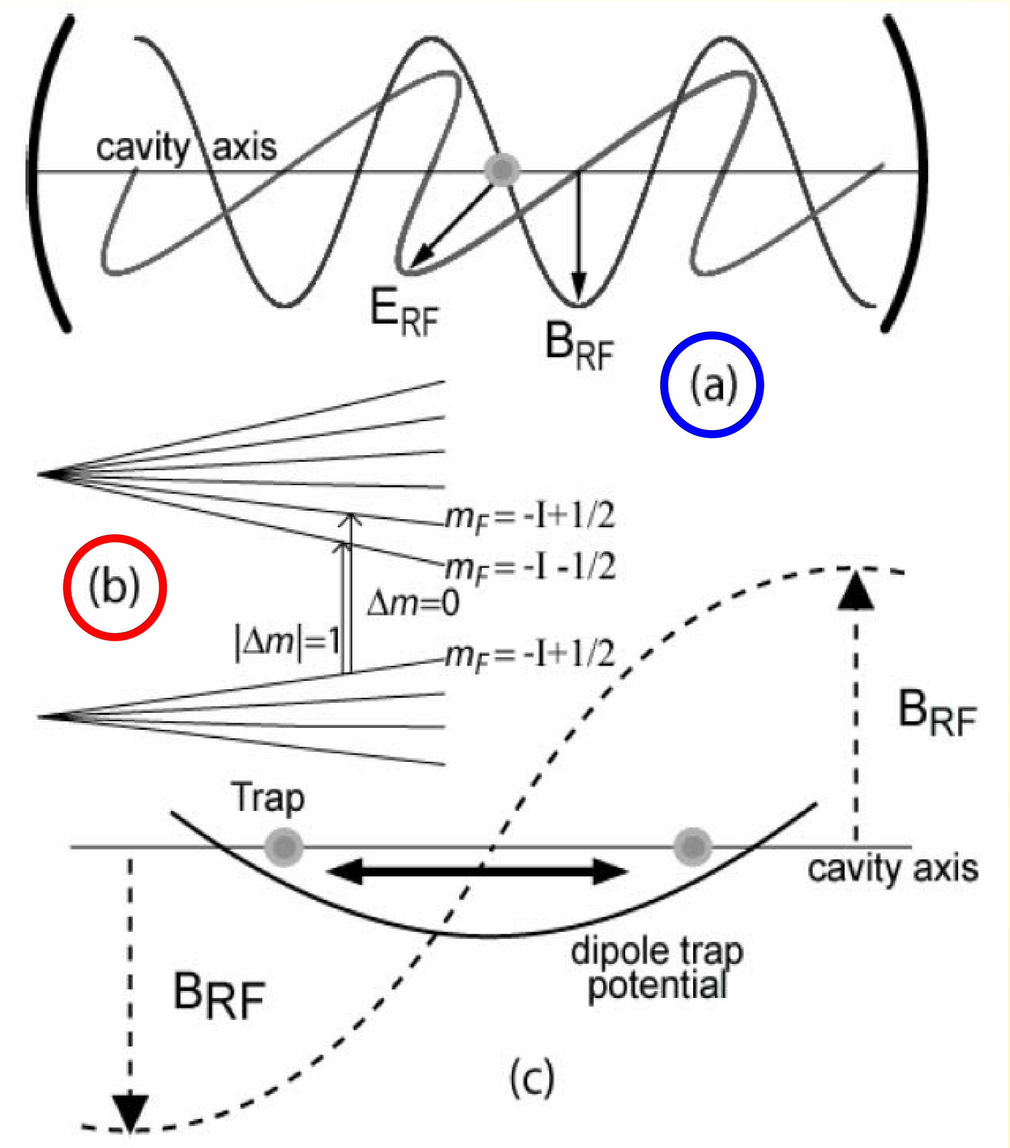

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b) Selection rule:
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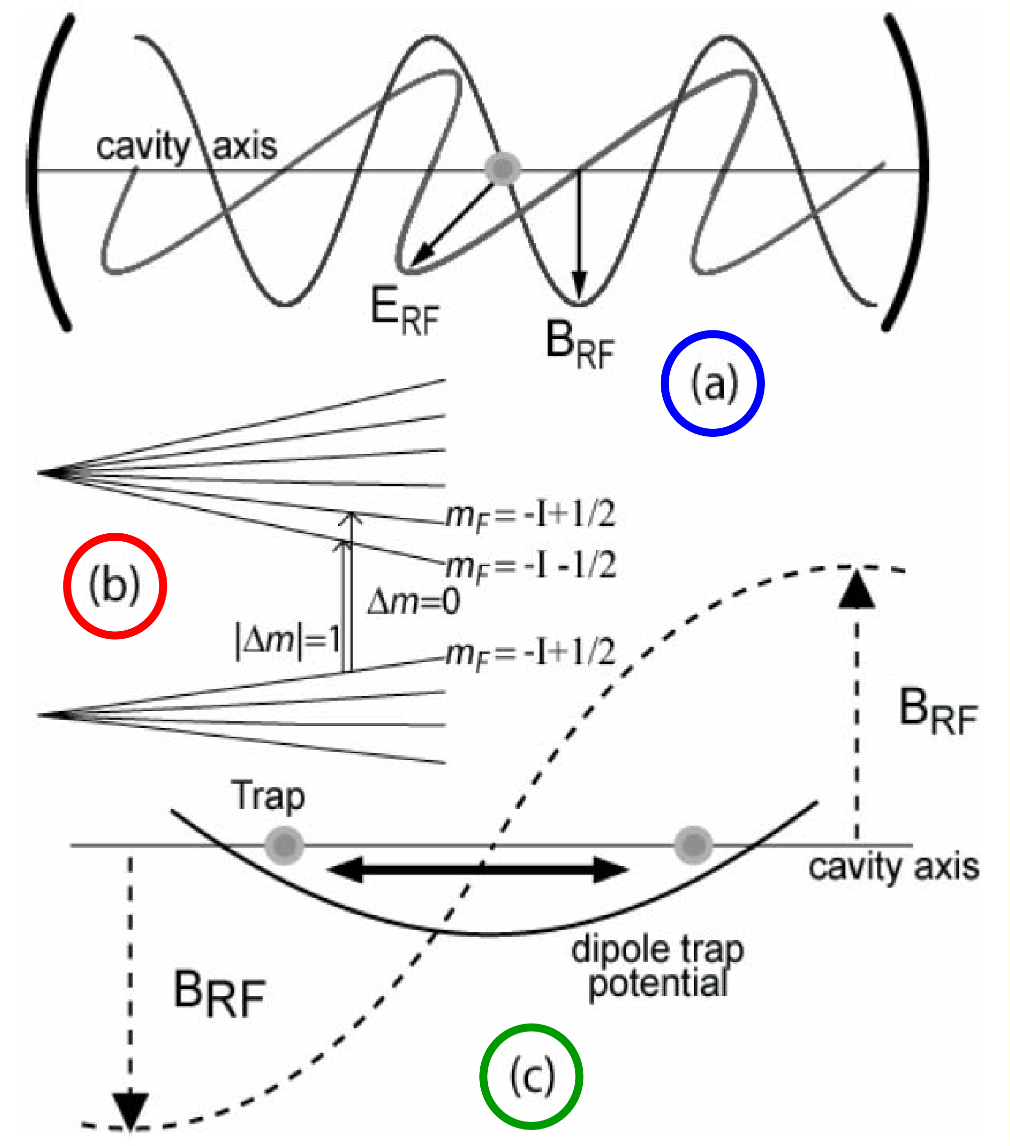

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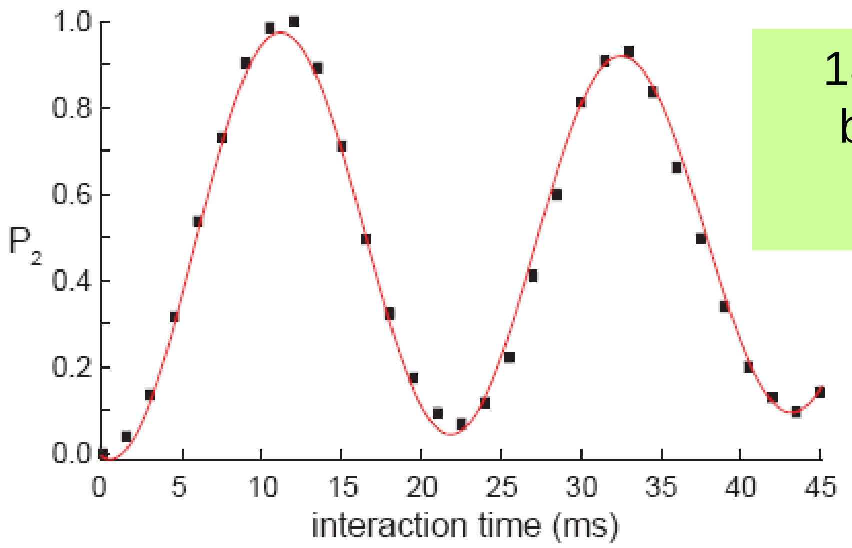
→ Suppression: 10^{-3}.

c) Dynamical averaging:
Atomic motion around the B node, averages away M1.

… E_{RF} dipole force provides some self-centering on anti-node.

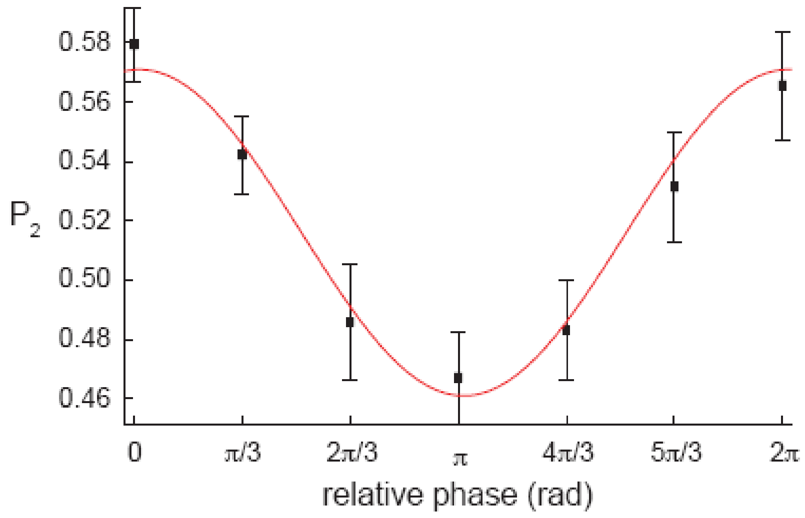
Simulating Fr Anapole with Rb



180 ms coherence time in blue-detuned dipole trap

(π/2 pulse with Rb)

[Data by D. Sheng (Orozco Group, U. of Maryland)]



Simulating the PNC Interference

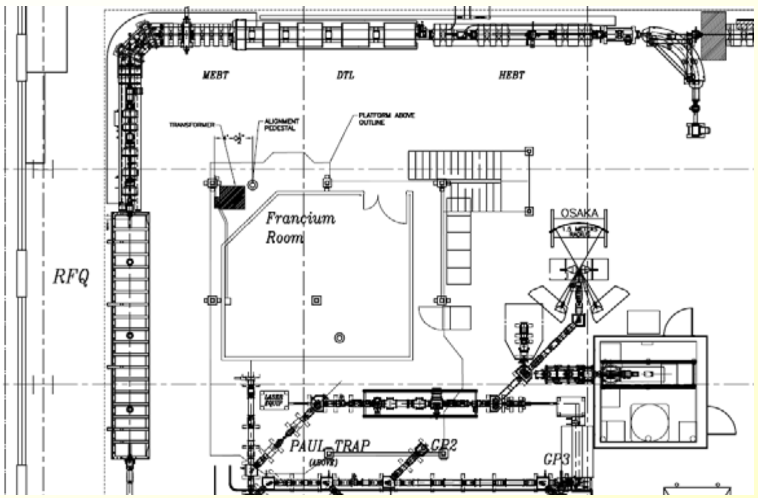
$$Transition\ Rate = \left|1/2 \pm A_{PNC}\right|^2$$

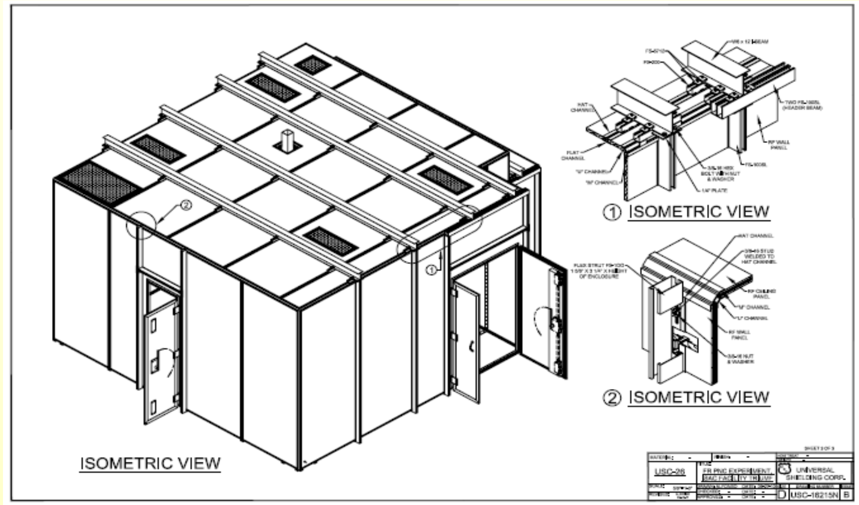
$$\approx 1/4 \pm \left|A_{PNC}\right| \cos\theta_{phase}$$

A_{PNC} simulated with 10^{-4} M1 transition

FrPNC: Current Status

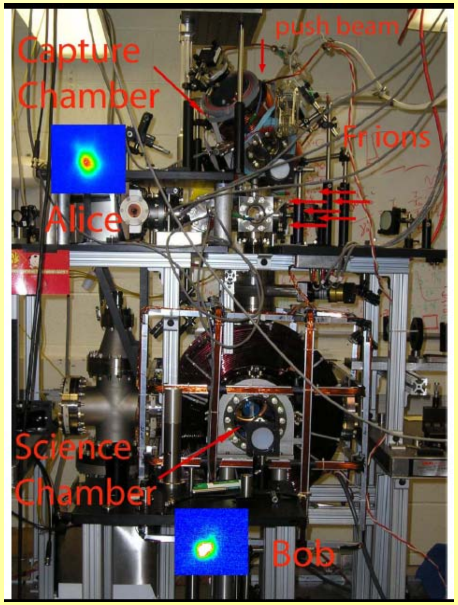
<u>Present:</u> Construction of an on-line, shielded laser laboratory at TRIUMF with 100 db RF suppression.





<u>Fall 2011:</u> *(13 shifts in December)*

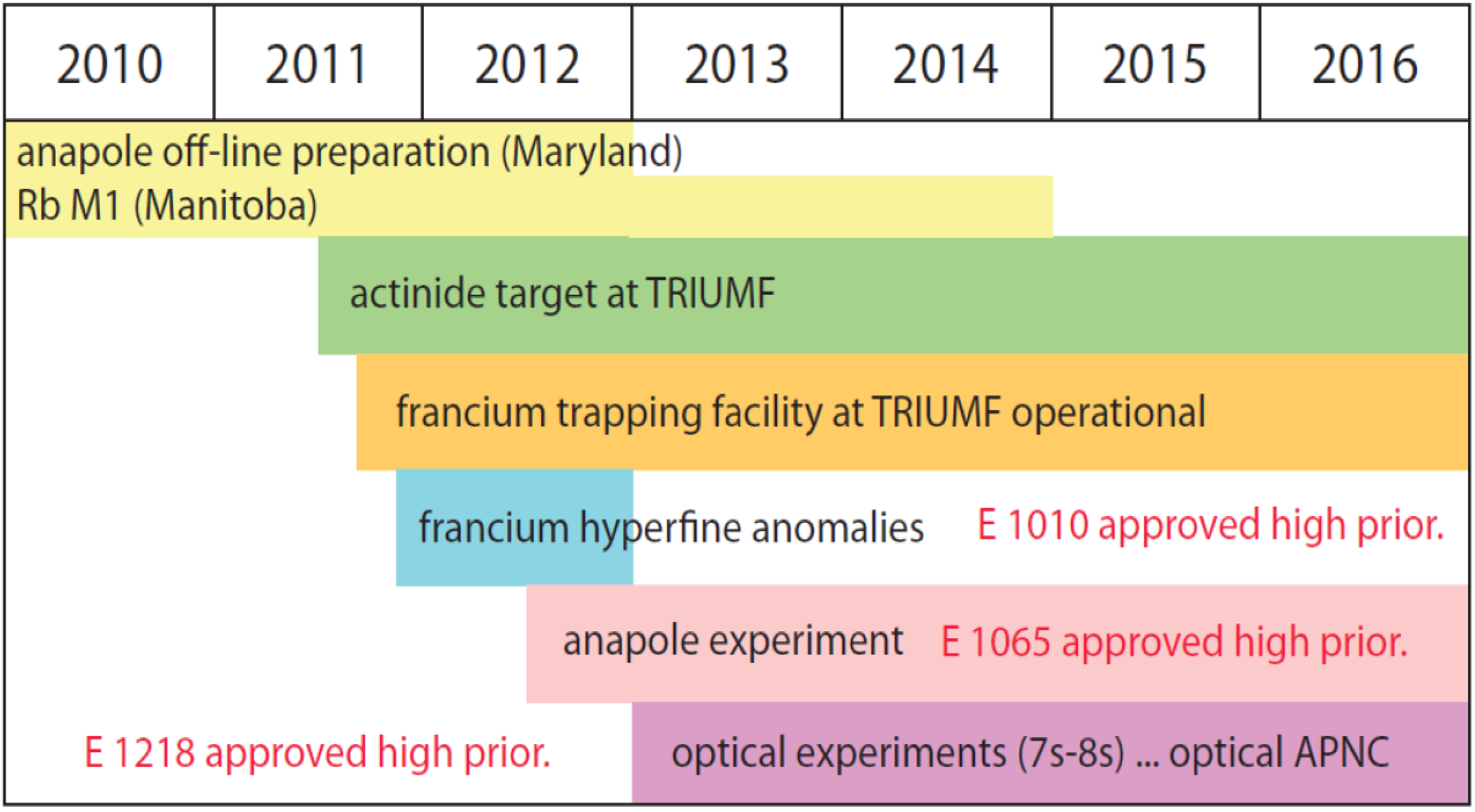
Installation of high efficiency MOT (from U. of Maryland).



<u>2012:</u> Physics starts !!!

Hyperfine anomaly (Pearson), 7S-8S M1 (Gwinner), Anapole (Orozco), optical PNC (Gwinner), …

FrPNC: Schedule



FrPNC collaboration

S. Aubin *(College of William and Mary)*

J. A. Behr, K. P. Jackson, M. R. Pearson *(TRIUMF)*

V. V. Flambaum *(U. of New South Wales, Australia)*

E. Gomez *(U. Autonoma de San Luis Potosi, Mexico)*

G. Gwinner, R. Collister *(U. of Manitoba)*

D. Melconian *(Texas A&M)*

L. A. Orozco, J. Zhang *(U. of Maryland at College Park)*

G. D. Sprouse *(SUNY Stony Brook)*

Y. Zhao *(Shanxi U., China)*

Funding

Outline

Theory

A. Motivation 1: Spin-independent PNC

→ Testing the electroweak standard model.

B. Motivation 2: Spin-dependent PNC

→ Nuclear anapole moment.

→ Weak meson-nucleon couplings problem.

Experiment

1. The FrPNC program

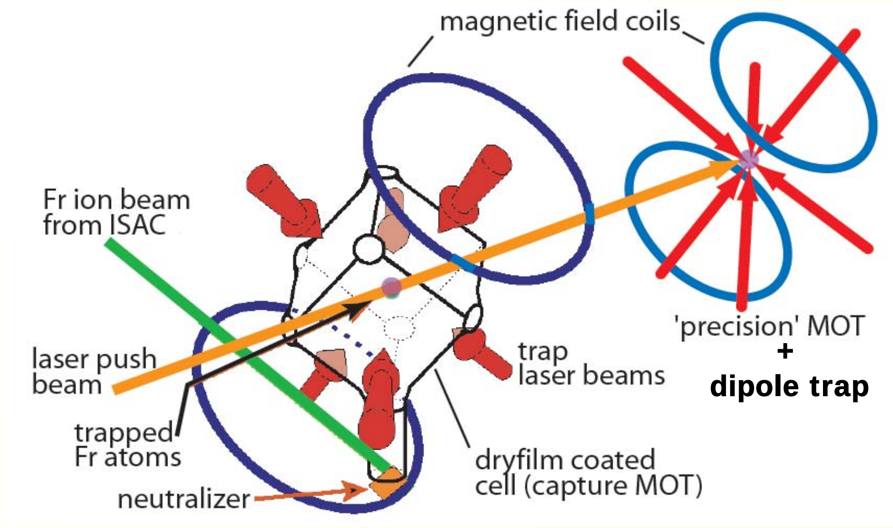
→ Methods.

→ Expected sensitivities.

2. Current Status

FrPNC program:
Atomic PNC Experiments in Francium

- Fr is the heaviest of the simple (alkali atoms).
  - → Electronic structure is well understood.
  - → Particle/nuclear physics can be reliably extracted.
- Fr has large (relatively) PNC mixing.
  - → $\varepsilon_{PNC} \sim 10^{-10}$ is still really really small … we're going to need a lot of Fr.
- Fr does not exist sufficiently in nature.

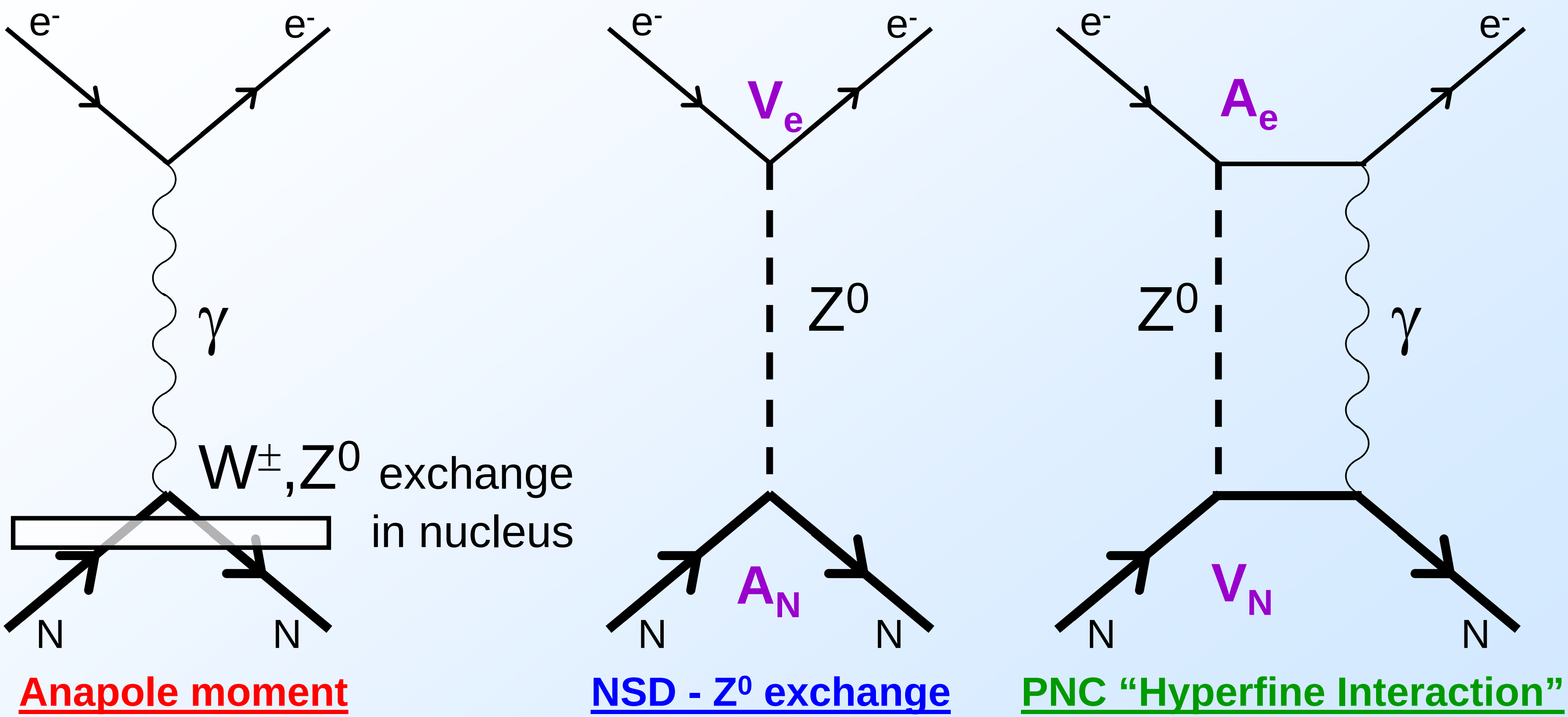


ISAC facility @ TRIUMF

500 MeV protons (2 μA) on UC (30 g/cm^2).

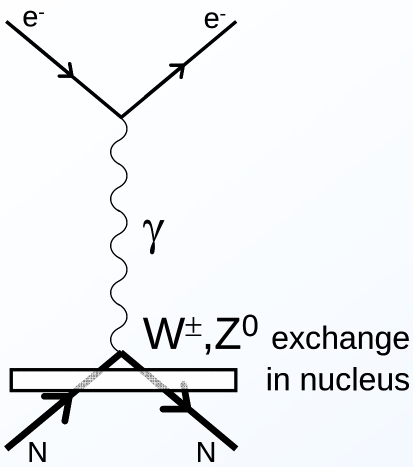
Demonstrated production: 10^7-10^8 Fr/s

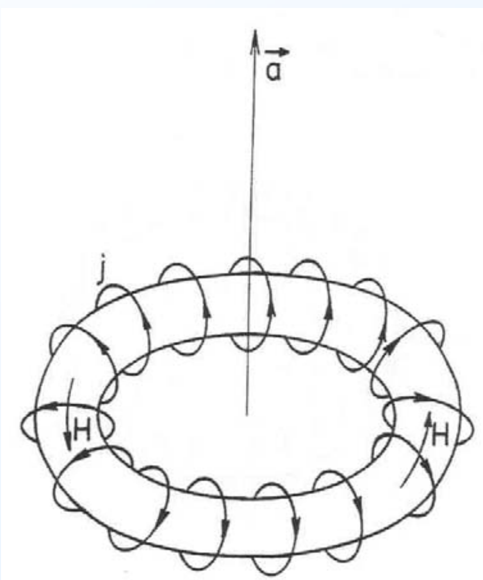
Motivation 2:
Nuclear Spin-Dependent PNC



$$H_{PNC,nsd} = \frac{G}{\sqrt{2}} \frac{K}{I(I+1)} \vec{I} \cdot \vec{\alpha} \left(\kappa_{anapole(p,n)} - \frac{K-1/2}{K} \kappa_{2(p,n)} + \frac{I+1}{K} \kappa_{Q_W} \right) \rho(\vec{r})$$

What's an Anapole Moment ?





[figure from V. V. Flambaum, Atomic Physics 16: ICAP 16., edited by W. E. Baylis and G. W. F. Drake (AIP, 1998)]

<u>Answer:</u>

Electromagnetic moment produced by a toroidal current.

→ Time-reversal conserving.

→ PNC toroidal current.

→ Localized moment, contact interaction.

$$H_{anapole} = e\vec{\alpha}\cdot\vec{a}\,\tilde{\delta}(r)$$

$$\vec{a} = -\pi\int d^3r\, r^2 \vec{J}(\vec{r})$$

$$= \frac{1}{e}\frac{G}{\sqrt{2}}\frac{K}{j(j+1)}\kappa_{anapole(p,n)}\,\vec{j}_{p,n}$$

nucleon angular momentum

Neutron nuclear skin radius

Observable	Constraint	Set value	Stability
$A_{Ry}A_{E1}$	Microwave amplitude	476 V/cm	0.03
$A_{Ry}A_{Ry}$	Raman amplitude	121 rad	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 Gauss	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 birrefringence	0 rad	1×10^{-4} rad
	Trap displacement	0 m	3×10^{-11} m

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

Motivation 1: Sensitivity to Std. Model extensions

Atomic PNC experiments are sensitive to certain high-energy extensions of the Standard Model.

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, ILC: > 5 TeV (?)
Leptoquarks	M_S	>0.7 TeV	> 256 GeV, >1200 GeV indir.
Composite Fermions	L	>14 TeV	>6 TeV

[figure from G. Gwinner and adapted from D. Budker, WEIN 98.]

Outline

Justification 1: Low-energy parity violation → sensitivity to extra neutral bosons.

Justification 2: Anapole moment → resolve nucleon-meson weak couplings discrepancy (Cs133 anapole vs. F18/19 gamma)

Why francium?

Brief of History of francium experiments.

Z0 experiment

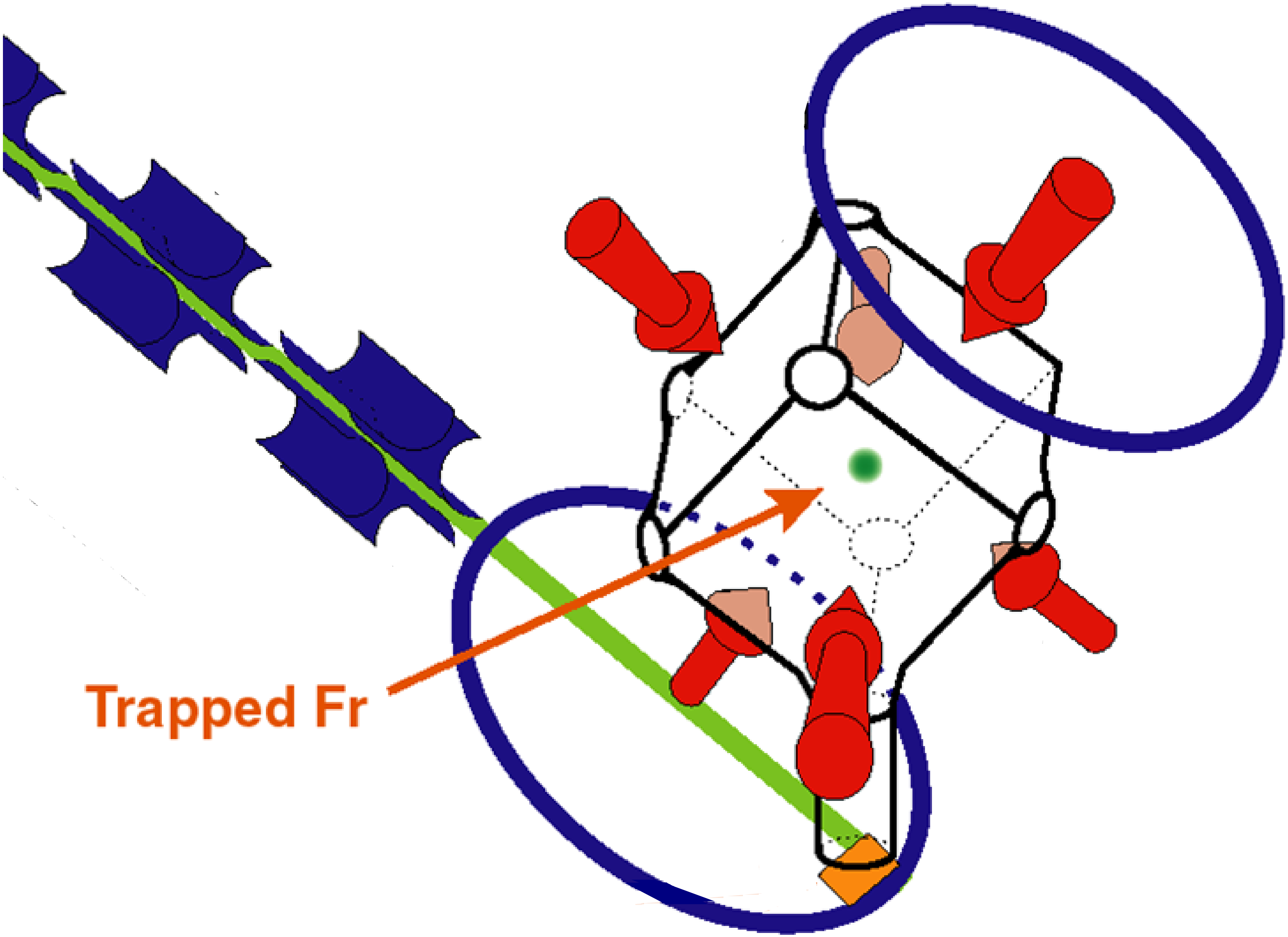
→ expected sensitivity.

Anapole experiment

→ expected sensitivity.

Challenges of an accelerator environment … shielding necessary!!!

Current status: group members, funding, shielded laboratory.


Trapped Fr