# *Prospects for new anapole moment measurements*

- Proof of principle for the ZOMBIES nuclear anapole moment “factory”
- Near-future prospects for anapole measurements
- Questions for theorists: what measurements maximize physics impact?

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*Past Funding*
NSF

DeMille
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# *ZOMBIES @ Yale*

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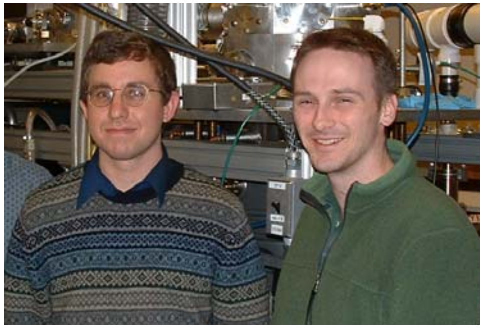

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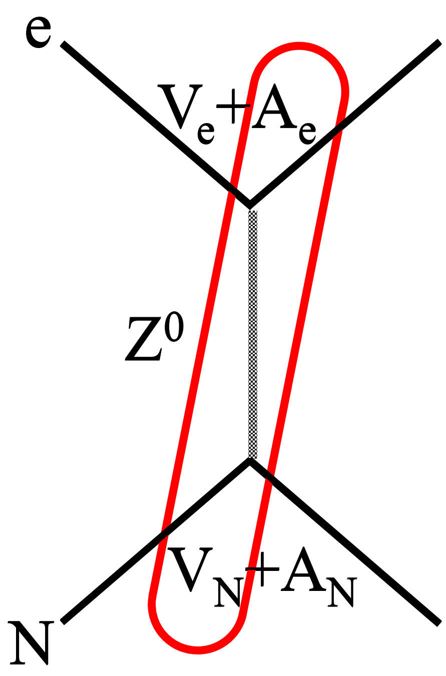
# *Mechanisms for atomic/molecular parity violation*

## *Axial electronic-vector nucleonic interaction*



$A_eV_N$ term leads to term in atomic Hamiltonian

$$H \propto Q_W G_F \left(\vec{\sigma}\cdot\vec{p}\right)\delta^3(\vec{r})$$

axial vector
associated with electron

short-range
Yukawa potential

Coherent coupling to all nuclei = "weak charge"

$Q_W = -N + (1-4\sin^2\theta_W)Z$

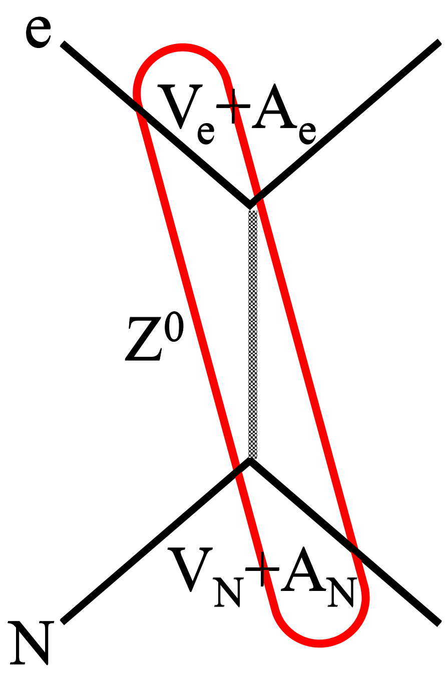
Weak charge measured to 0.4%
[C. Wieman group, 1997]

& interpreted at 0.3% level
[A. Derevianko 2010, V. Flambaum 2012]

$\Rightarrow$ Running of $\sin^2\theta_w$ &
Limits on $Z'$ bosons

# *Mechanisms for atomic/molecular parity violation*

*Vector electronic-axial nucleonic interaction*



Coupling ONLY
to unpaired nucleon
coupling constant $C_2$

$V_eA_N$ term gives Hamiltonian:

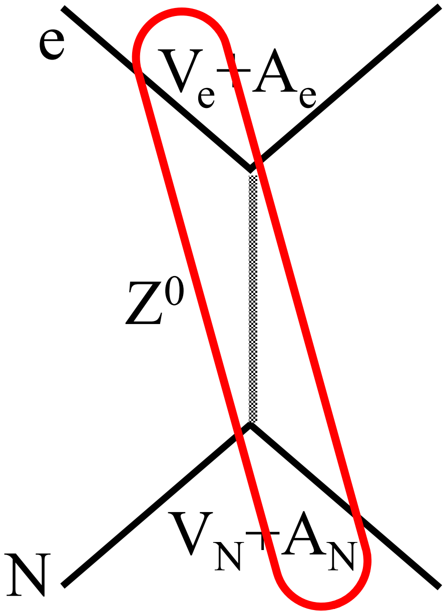
$$H \propto C_2 G_F \left(\vec{\sigma}\cdot\vec{I}\right)\left(\vec{\sigma}\cdot\vec{p}\right)\delta^3(\vec{r})$$

Nuclear spin $I$
= axial vector
associated with nucleon

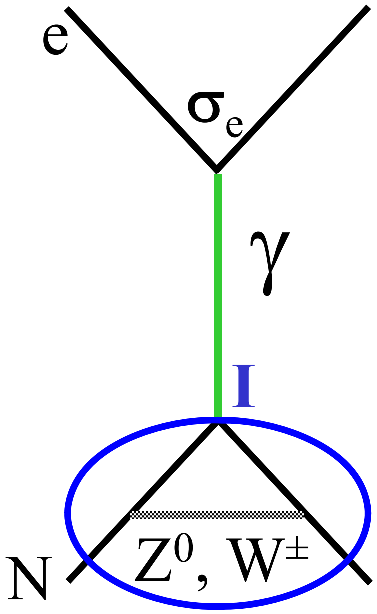
$C_2$ numerically small:
$V_e/A_e = (1\text{-}4\sin^2\theta_W) \sim .08$

*Bottom line*:
$V_eA_N / A_eV_N \sim 10^{-3}$
(for heavy atoms)

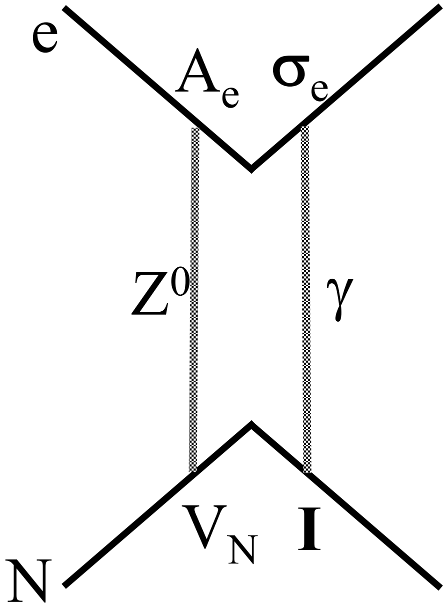
# Suppression of tree-level NSD-PV makes radiative corrections non-negligible



Tree-level NSD-PV from suppressed $V_eA_N$ term: $C_2$ subject to QCD renormalization similar to $g_A$



HPV interactions inside nucleus induce nuclear "anapole moment": couples to electron magnetically

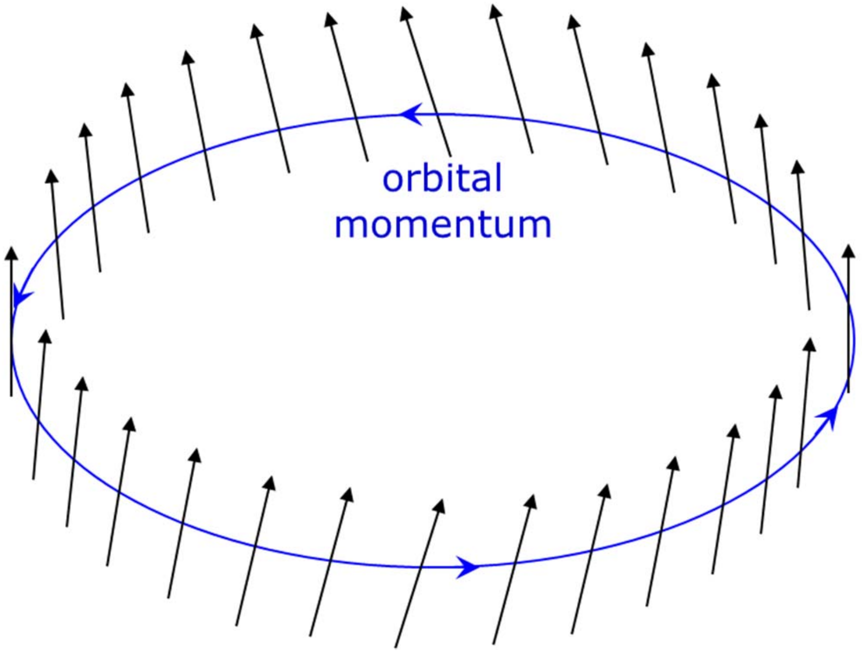


Coherent sum of weak charge $Q_W$ and electromagnetic hyperfine interaction

$$H_{NSD-PV} \propto \left(\kappa'_2 + \kappa'_a + \kappa'_Q\right) G_F \left(\vec{\sigma}\cdot\vec{I}\right)\left(\vec{\sigma}\cdot\vec{p}\right)\delta^3(\vec{r})$$

# *HPV in nucleus induces nuclear spin helix = magnetic dipole + anapole*

$$H_{HPV} \propto \vec{\sigma}_N \cdot \vec{p}_N \Rightarrow$$ spin tilted along momentum



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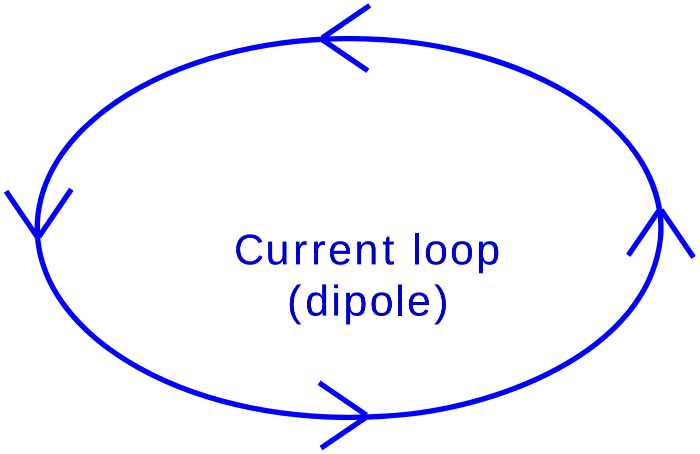

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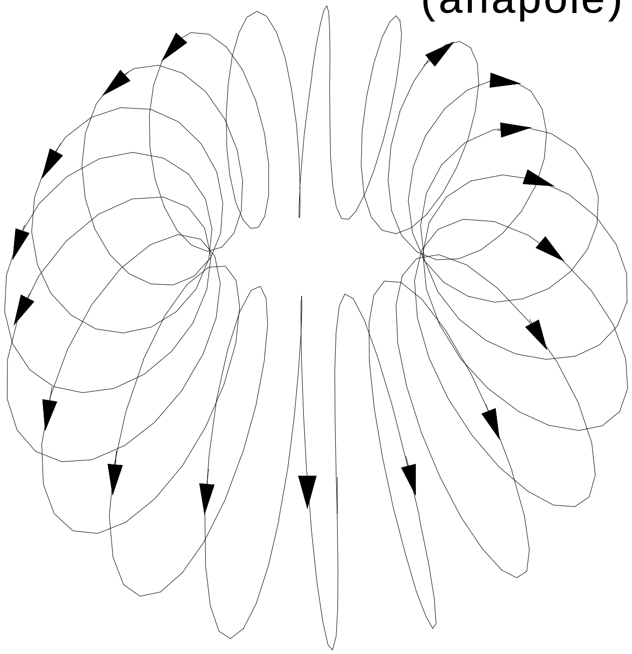


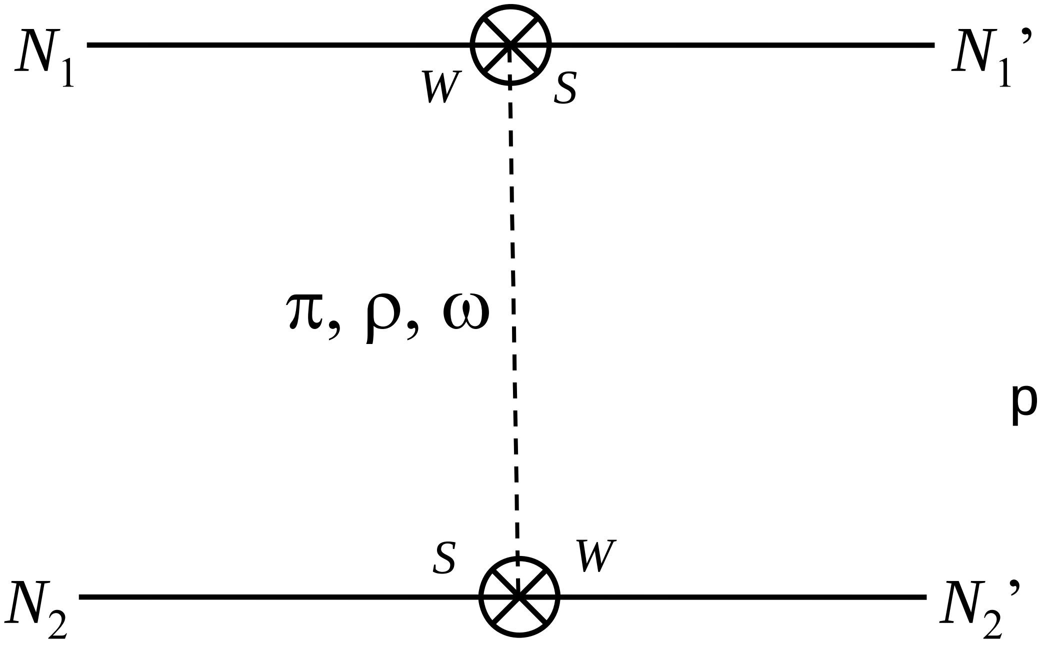
**Simple model for nuclear anapole**

(valence nucleon + constant-density core):

$$\vec{a} \propto g_{eff} A^{2/3} \boxed{\hat{I}}$$

# *Microscopic physics of the nuclear anapole moment*

Nucleon-nucleon HPV interactions perturb nuclear structure:



DDH
description of HPV:
effective meson
exchange
parameterizes range &
isospin structure

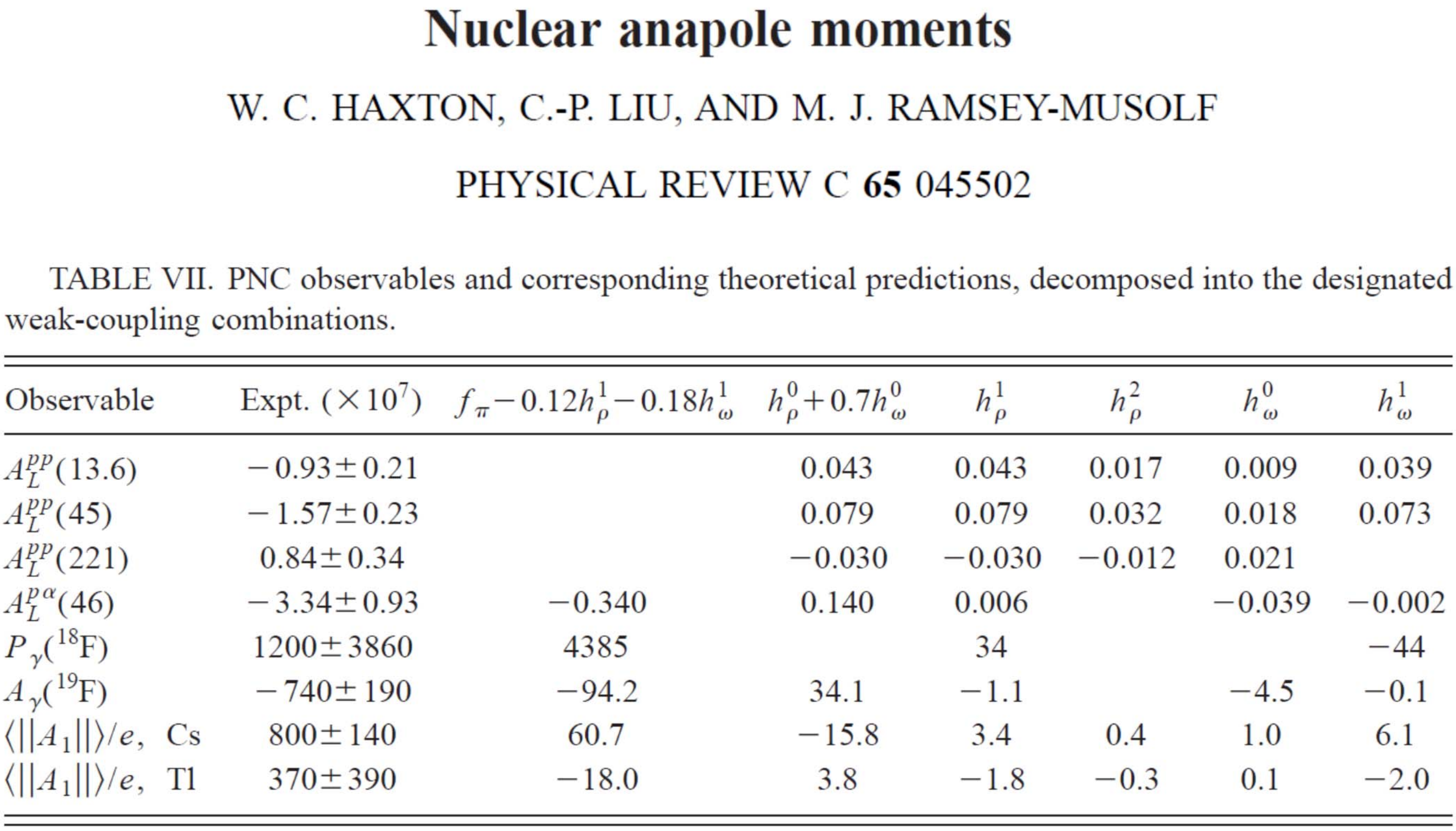
Hamiltonian for unpaired nucleon interacting with paired core gives spin-momentum correlation

$$H_{HPV} \sim G_F \left(\vec{\sigma}_N \cdot \vec{p}_N\right) \sum_i g_{\text{eff},i} F_i(\vec{r},\vec{\tau})$$

6 terms in principle;

*2 linear combinations estimated important for anapole (DDH)*

# *Anapole moments in DDH parameterization*



## Nuclear anapole moments

W. C. HAXTON, C.-P. LIU, AND M. J. RAMSEY-MUSOLF

PHYSICAL REVIEW C **65** 045502

TABLE VII. PNC observables and corresponding theoretical predictions, decomposed into the designated weak-coupling combinations.

| Observable | Expt. ($\times 10^7$) | $f_\pi - 0.12h_\rho^1 - 0.18h_\omega^1$ | $h_\rho^0 + 0.7h_\omega^0$ | $h_\rho^1$ | $h_\rho^2$ | $h_\omega^0$ | $h_\omega^1$ |
|---|---|---|---|---|---|---|---|
| $A_L^{pp}(13.6)$ | $-0.93 \pm 0.21$ | | 0.043 | 0.043 | 0.017 | 0.009 | 0.039 |
| $A_L^{pp}(45)$ | $-1.57 \pm 0.23$ | | 0.079 | 0.079 | 0.032 | 0.018 | 0.073 |
| $A_L^{pp}(221)$ | $0.84 \pm 0.34$ | | −0.030 | −0.030 | −0.012 | 0.021 | |
| $A_L^{p\alpha}(46)$ | $-3.34 \pm 0.93$ | −0.340 | 0.140 | 0.006 | | −0.039 | −0.002 |
| $P_\gamma(^{18}\mathrm{F})$ | $1200 \pm 3860$ | 4385 | | 34 | | | −44 |
| $A_\gamma(^{19}\mathrm{F})$ | $-740 \pm 190$ | −94.2 | 34.1 | −1.1 | | −4.5 | −0.1 |
| $\langle \lVert A_1 \rVert \rangle / e$, Cs | $800 \pm 140$ | 60.7 | −15.8 | 3.4 | 0.4 | 1.0 | 6.1 |
| $\langle \lVert A_1 \rVert \rangle / e$, Tl | $370 \pm 390$ | −18.0 | 3.8 | −1.8 | −0.3 | 0.1 | −2.0 |

# 3 contributions to NSD-PV: scaling with Z & A

$$H_{NSD-PV} \propto \left(\kappa_2' + \kappa_a' + \kappa_Q'\right) G_F \left(\vec{\sigma}\cdot\vec{I}\right)\left(\vec{\sigma}\cdot\vec{p}\right)\delta^3(\vec{r})$$

Overall $Z^2$

$\kappa'_{2P} = -\kappa'_{2N}$

$\cong -g_A(1-4\sin^2\theta_W)/2 \cong -.05$

- ~independent of $A$
- $\mathcal{O}$(20%) corrections from $SU(3)_f$
- $\mathcal{O}$(100%) expt. uncertainty
- Quenching in larger nuclei like $g_A$?

$\kappa'_Q \propto A^{2/3}$ small ($<\kappa'_a/4$)
& well understood
--*ignore*

Simple shell model:
valence nucleon over closed core

$$\kappa'_a \approx \frac{9}{10}\frac{\alpha\mu}{mr_0}A^{2/3}g_{eff} \approx .05\,g_{eff}\left(\frac{A}{50}\right)^{2/3}$$

$$g_{eff,p} \approx 4-6;\; g_{eff,n} \approx 0.1-1;$$

# 3 contributions to NSD-PV: scaling with Z & A

$$H_{NSD-PV} \propto \left(\kappa_2 + \kappa_a + \kappa_Q\right) G_F \left(\vec{\sigma}\cdot\vec{I}\right) \underbrace{(\vec{\sigma}\cdot\vec{p})\,\delta^3(\vec{r})}_{\text{Overall } Z^2}$$

$$\kappa'_{2P} = -\kappa'_{2N} \approx -.05$$

$$\kappa'_a \approx .05\, g_{eff} \left(\frac{A}{50}\right)^{2/3}$$

$$(g_{eff,P} \cong 4,\ g_{eff,N} \lesssim 1)$$

In heavy atoms, anapole term dominates: $|\kappa'_a| > |\kappa'_2|$

(Collective enhancement causes radiative correction > tree level...!)

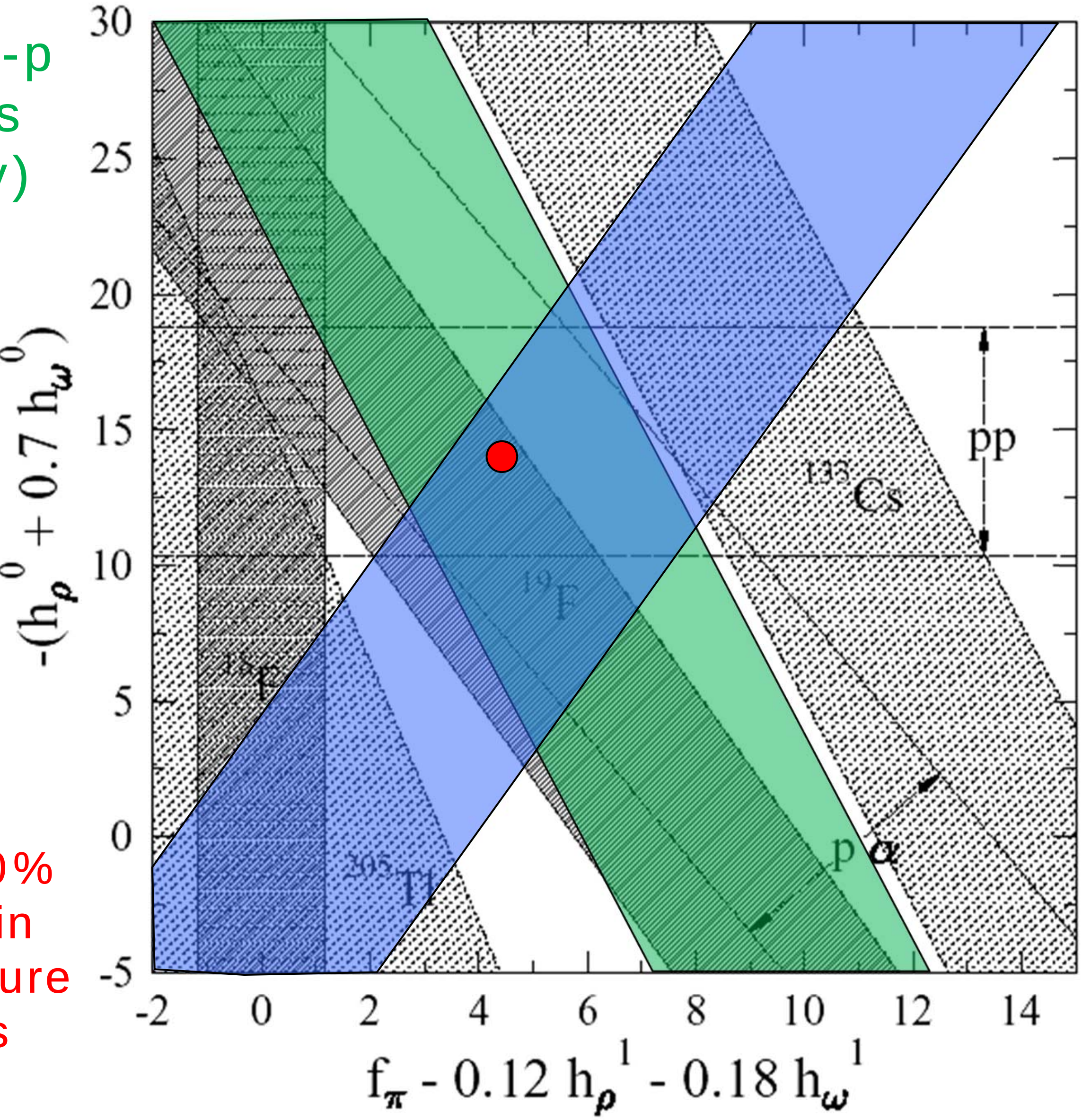
$|\kappa_a| \approx |\kappa_2|$ for $A \approx 10$ (odd proton)

$A \approx 100$ (odd neutron)

# *"Old style" plot of HPNC measurements including anapole measurements (past & future)*

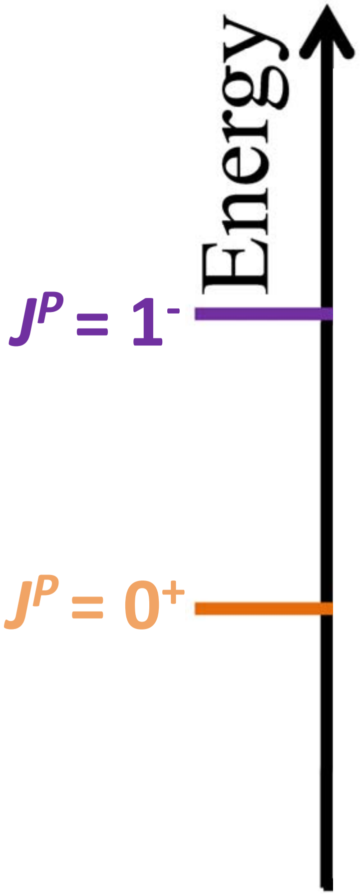
New odd-p isotopes (× many)

New odd-n isotopes (×many)



Assumes ~30% uncertainty in nuclear structure calculations

# *Enhanced NSD-PV mixing in simple molecules*

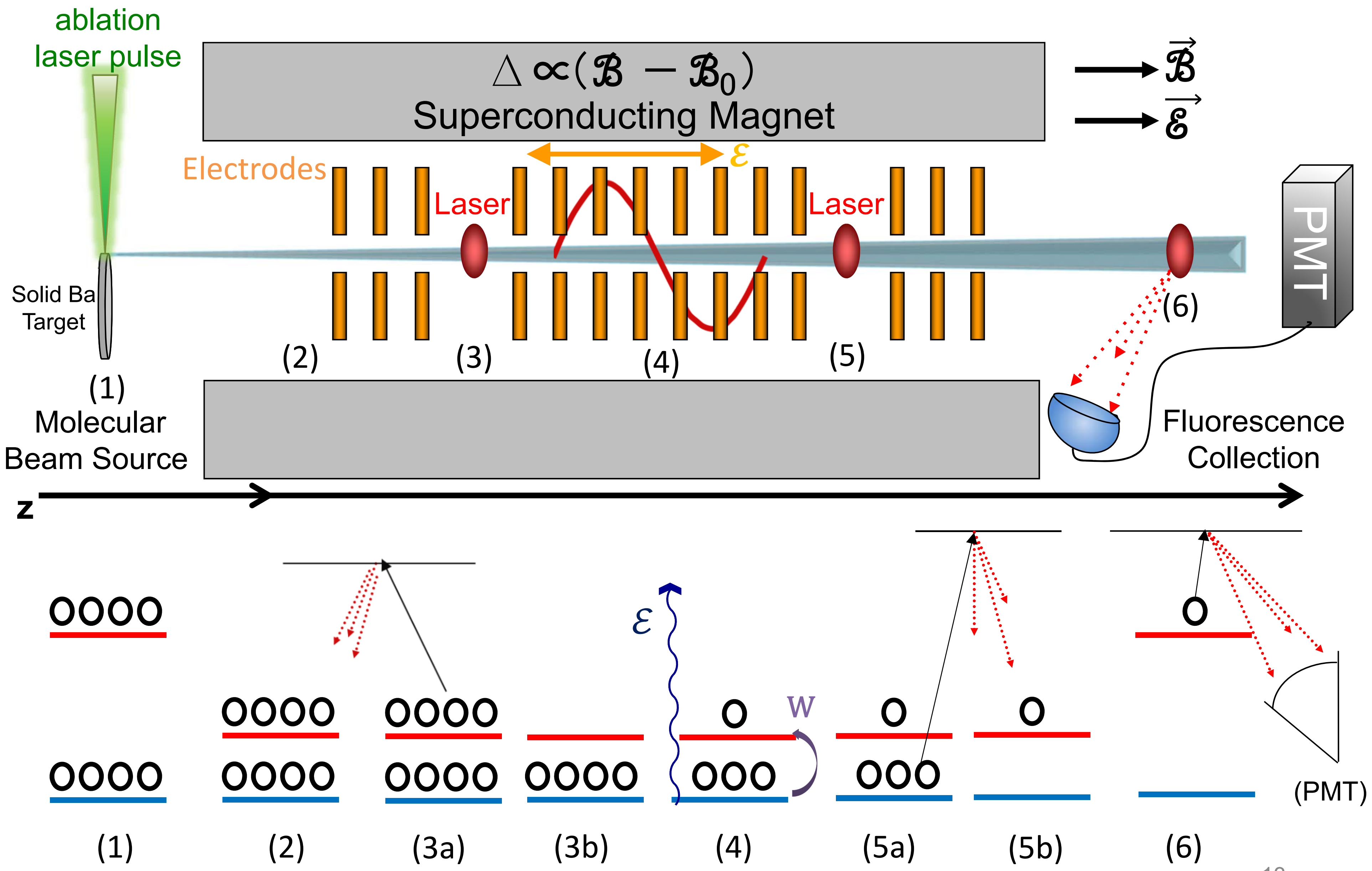


$+/-$ mixing

$$\eta = \frac{\langle + | H_{PV} | - \rangle}{E_+ - E_-}$$

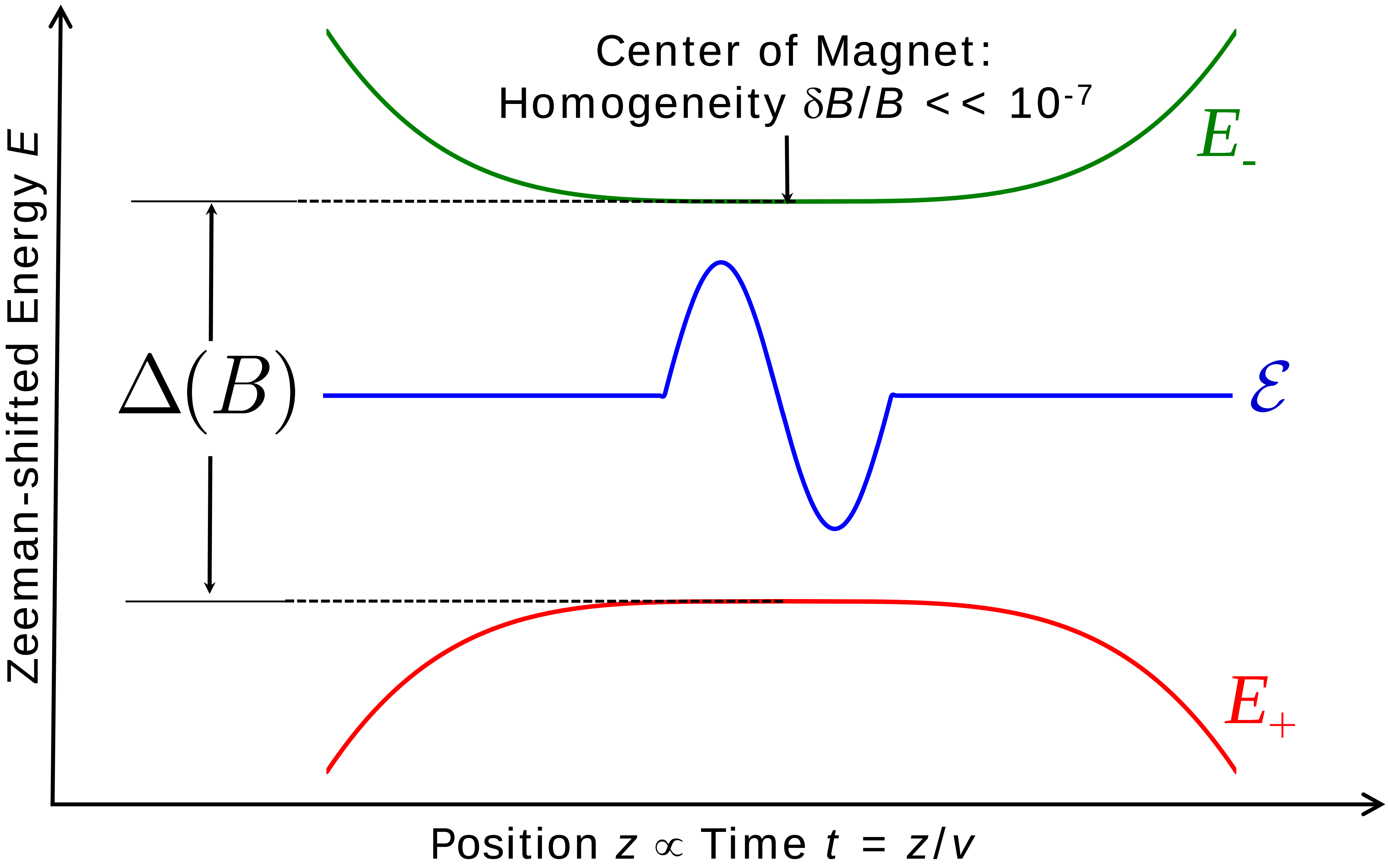
Naturally small rotational splitting ($\sim 10^{-4}$ eV vs. $\sim$1 eV in atoms)
can be bridged w/Zeeman shift:
**$\gtrsim 10^{11}$ enhanced PV mixing vs. classic experiments with atoms**

# *ZOMBIES experimental schematic*

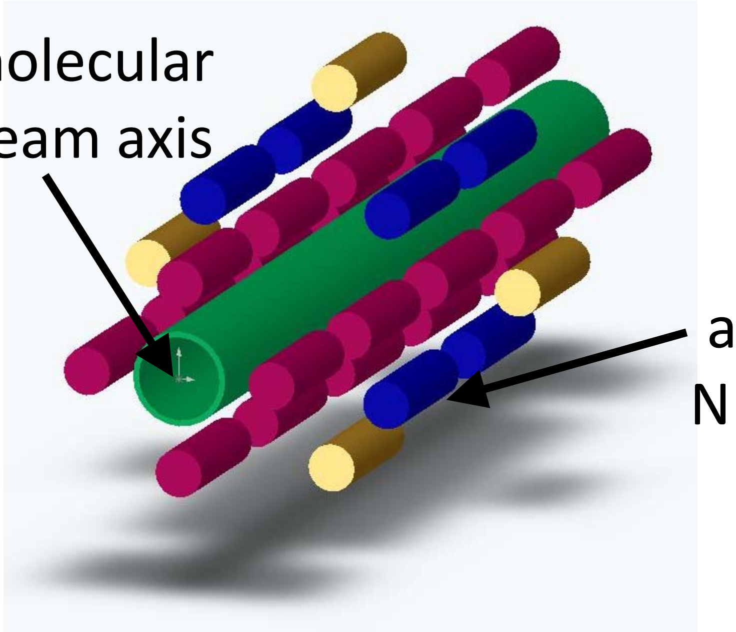


# Stark interference method:

## apply oscillating $\mathcal{E}$-field to mix nearly-degenerate levels



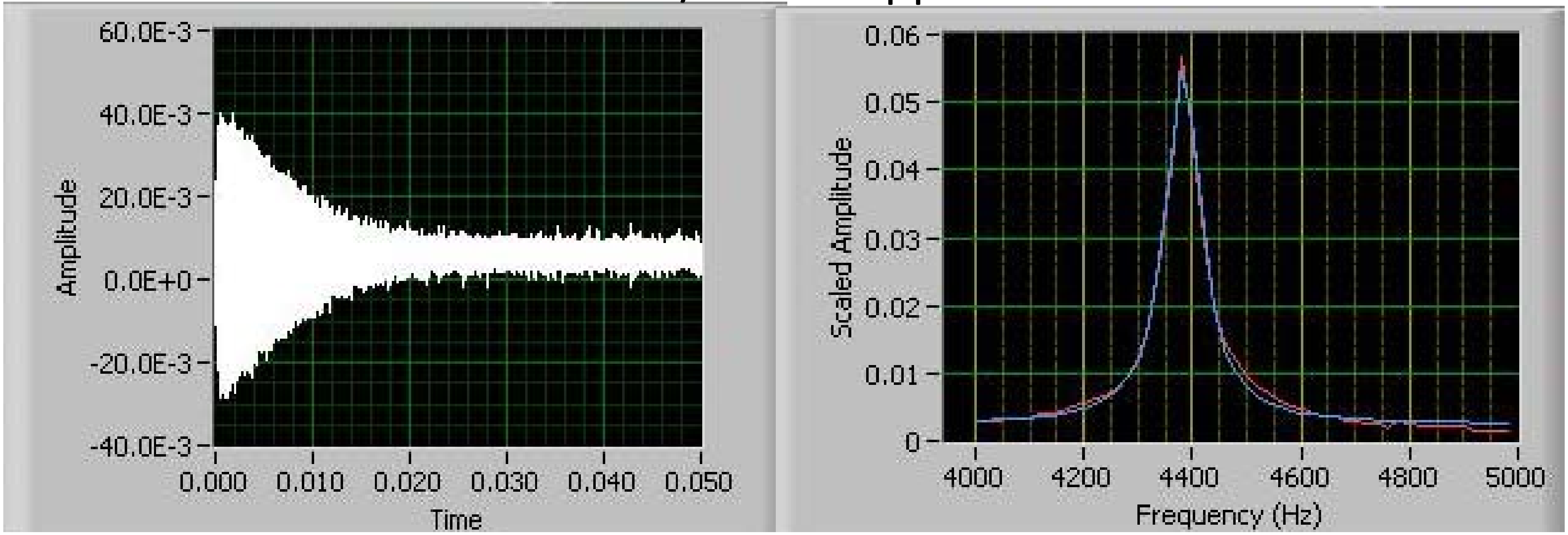
# *Magnetic field measurement: initial/crude*



molecular beam axis

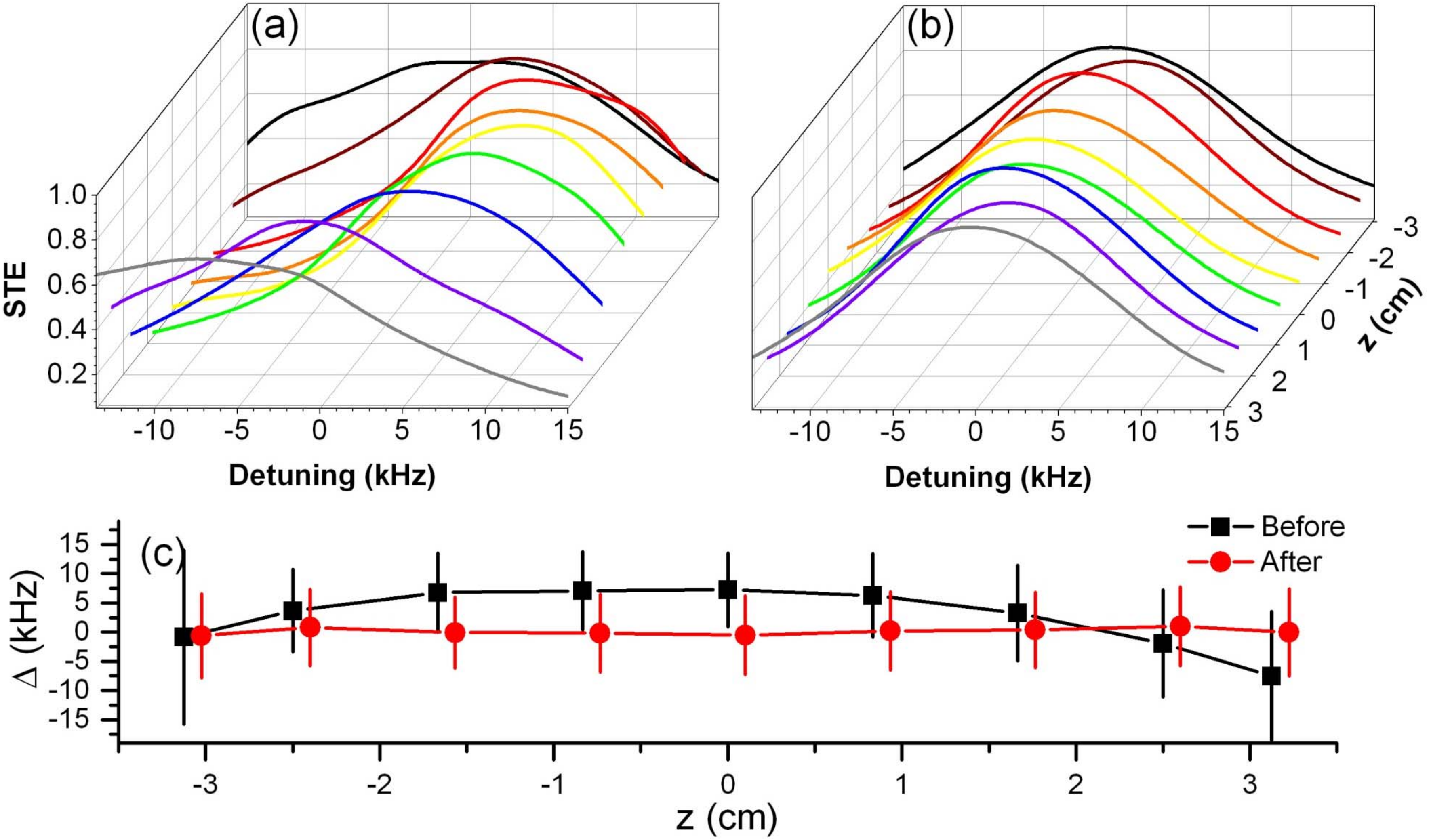
array of 32 NMR B-field probes

broadband probe on flex circuit



FID trace + FFT fit: $\delta B/B$ = 0.01 ppm in one 60 ms shot

# *Magnetic field control: results with 52 shim coils*

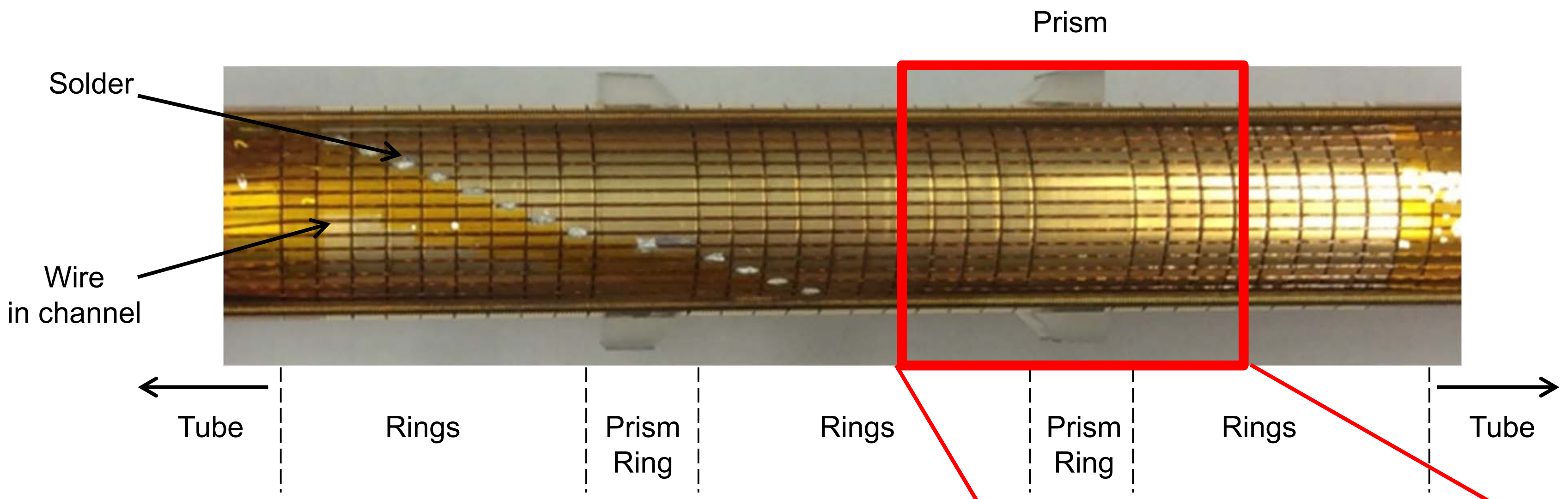


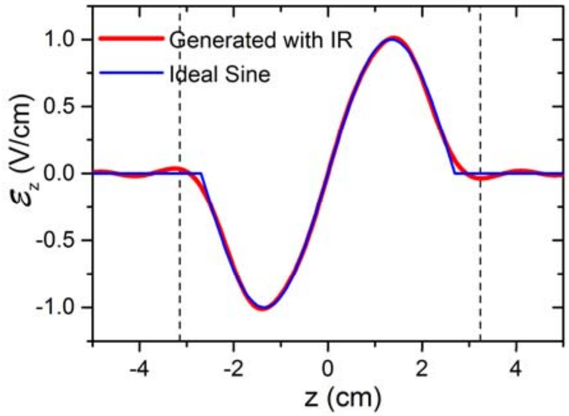
Using molecules for final measurement & shimming:

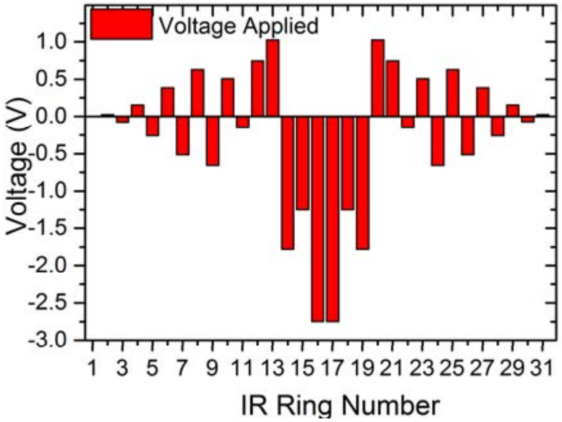
r.m.s. variation $\delta B/B < 20$ ppb [6 cm L. x 1 cm D. cylinder]

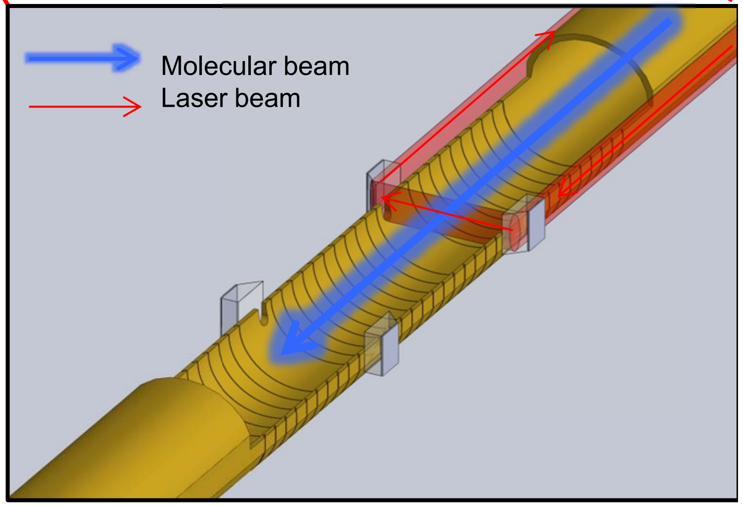
# $\mathcal{E}$-field control

## Ring electrodes create sine wave $\mathcal{E}$-field along **z**-axis:

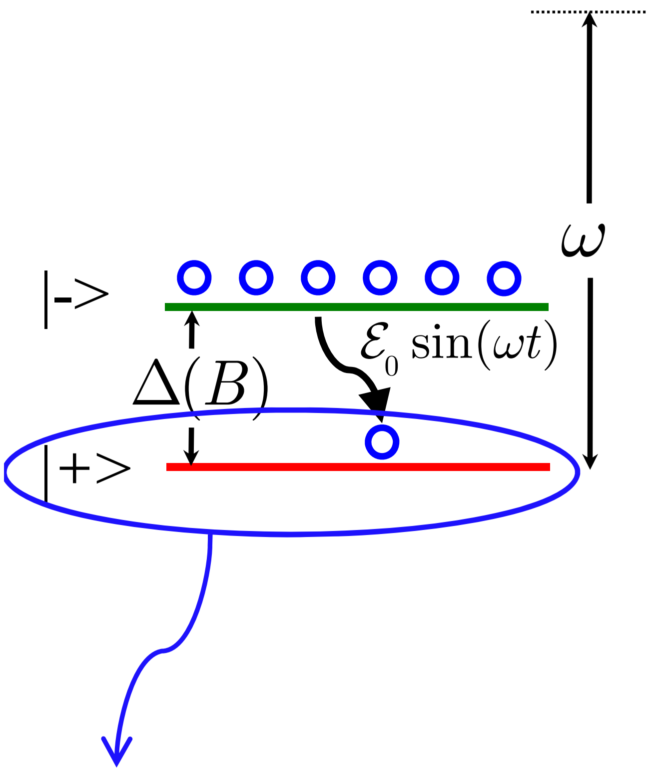








# *Detecting PV in near-degenerate levels: AC Stark shift*



PV mixing $iW$ encodes physics of interest

$$H = \begin{pmatrix} 0 & iW + d\mathcal{E}(t) \\ -iW + d\mathcal{E}(t) & \Delta \end{pmatrix}$$

Apply oscillating $\mathcal{E}$-field, 1 cycle:

$$\mathcal{E}(t) = \mathcal{E}_0 \sin(\omega t) \qquad \begin{bmatrix} \omega \gg \Delta,\ d\mathcal{E}_0; \\ T = 2\pi / \omega \end{bmatrix}$$

$$S = \left|\langle + | \psi(T) \rangle\right|^2 = 4\sin^2\left(\frac{\Delta T}{2}\right)\left[\left(\frac{d\mathcal{E}_0}{\omega}\right)^2 + 2\frac{W}{\Delta}\frac{d\mathcal{E}_0}{\omega}\right]$$

*"Large"*
*Stark Term*
*Even in $\mathcal{E}_0$*

*Small*
*PV Term*
*Odd in $\mathcal{E}_0$*

**D.D., S.B. Cahn, *et al.***
PRL **100,** 023003 (2008)

# *Signal, Asymmetry, Sensitivity*

- - Measure signal $S\left(\mathcal{E}_0\right) \approx 4N_0 \sin^2\left(\frac{\Delta T}{2}\right)\left[\left(\frac{d\mathcal{E}_0}{\omega}\right)^2 + 2\frac{W}{\Delta}\frac{d\mathcal{E}_0}{\omega}\right]$

with opposite-sign $\mathcal{E}$-fields $+\mathcal{E}_0, -\mathcal{E}_0$

- - Form asymmetry to extract $W$ in terms of known quantities :

$$\mathcal{A} = \frac{S(+\mathcal{E}_0) - S(-\mathcal{E}_0)}{S(+\mathcal{E}_0) + S(-\mathcal{E}_0)} \approx 2\frac{W}{\Delta}\frac{\omega}{d\mathcal{E}_0}$$

Dispersion-like function of detuning $\Delta$

Statistical Uncertainty

$$\delta W = \frac{1}{2\sqrt{2}}\frac{1}{\sqrt{N_0}}\frac{1}{T} \leftarrow$$

best sensitivity from large interaction time $T$

# *Properties of NSD-PV asymmetry: example $^{137}$BaF*

Typical numbers for $^{137}$BaF:

$$\Delta_0 \sim 1/T \sim 2\pi \times 1\ \text{kHz}$$

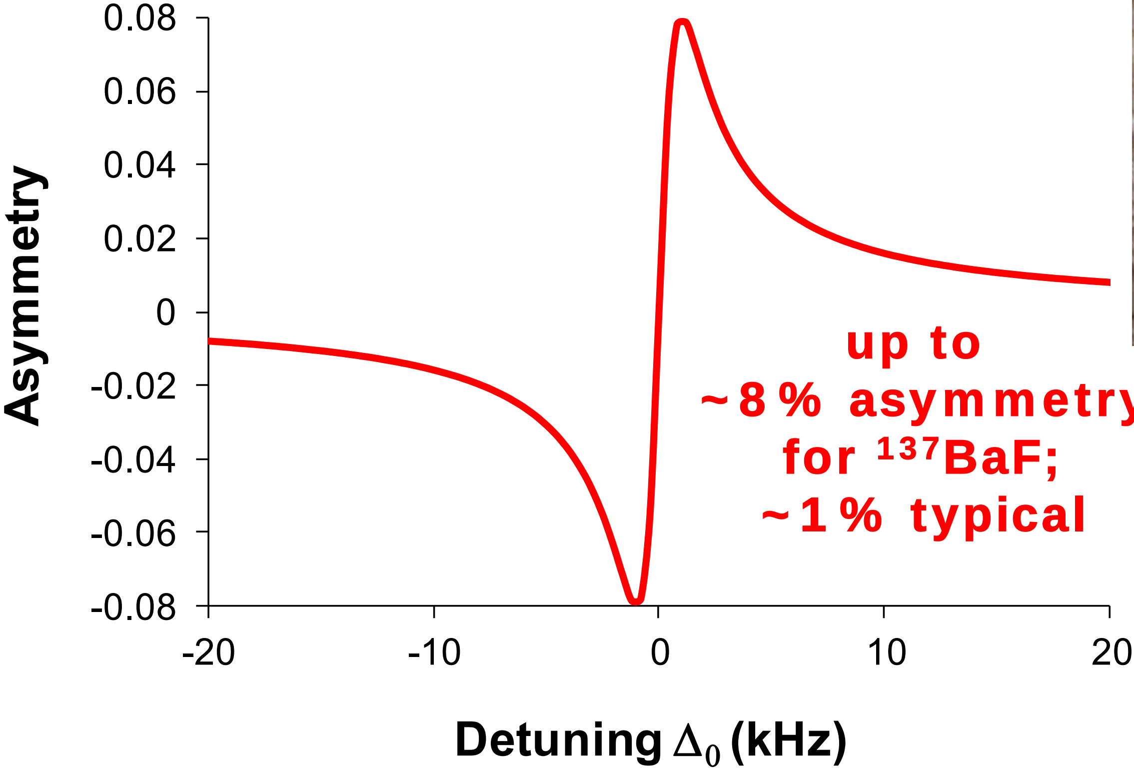
$$\omega = 2\pi \times 100\ \text{kHz}$$

$$dE_0/\omega = 0.1$$

$$W = 2\pi \times 5\ \text{Hz}$$

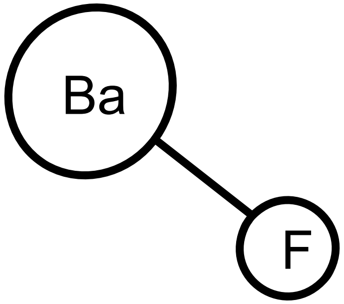
PV Invariant

$$\left(d\vec{\mathcal{E}}\,/\,dt\right)\cdot\left(\vec{\mathcal{B}}-\vec{\mathcal{B}}_c\right)$$



**up to ~8% asymmetry for $^{137}$BaF; ~1% typical**

# *NSD-PV with BaF*



Initial physics goal: NSD-PV with $^{137}$BaF

- Odd neutron ($^{133}$Cs had odd proton)
- Heavy → large effect, anapole moment dominates
- Large enough natural abundance – don’t need enriched source
- Required lasers = simple, cheap diodes

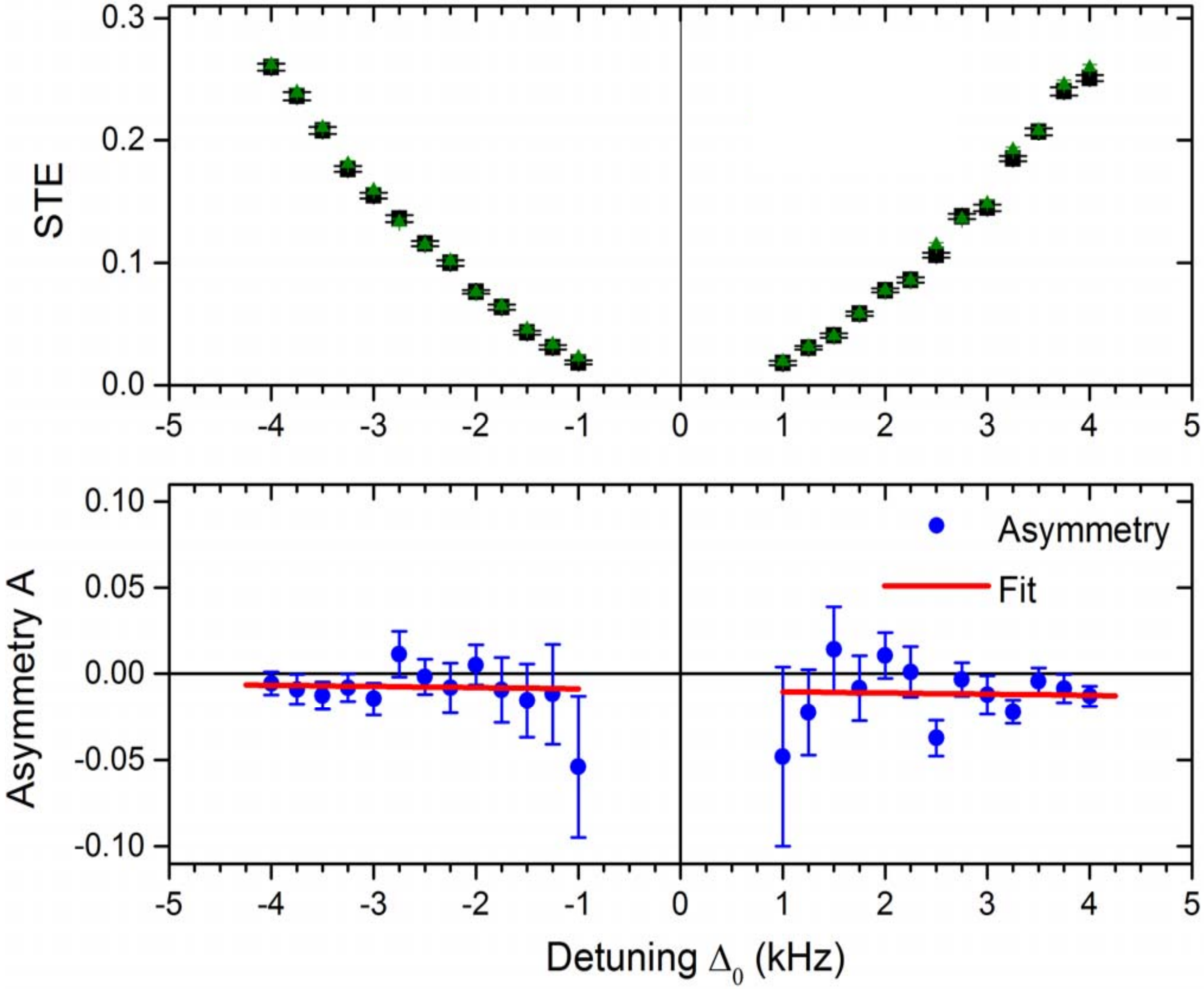
Proof of principle using $^{138}$Ba$^{19}$F: recently completed

- Larger natural abundance (~75% vs ~11% for $^{137}$Ba)
- Uses same beam source, lasers, magnet, etc. as $^{137}$BaF
- $W(^{138}\text{Ba}) = 0$ Hz (no unpaired nucleons = no NSD-PV)
  $W(^{19}\text{F}) \approx 0.002$ Hz $\approx 0$ (light, small electron spin density in BaF)
- **Test for systematics with known answer**

# *NSD-PV data with $^{138}$Ba$^{19}$F*

- Measure, cancel, & remeasure $\mathcal{B}$-field gradients and non-reversing $\mathcal{E}$-fields to suppress possible systematics

- Measure NSD-PV signal & asymmetry



$$S \propto \sin^2\left(\Delta \frac{T}{2}\right)\left(\frac{d\mathcal{E}_0}{\omega}\right)^2$$

$$\mathcal{A} = \frac{S(+\mathcal{E}_0) - S(-\mathcal{E}_0)}{S(+\mathcal{E}_0) + S(-\mathcal{E}_0)}$$

Fit to function

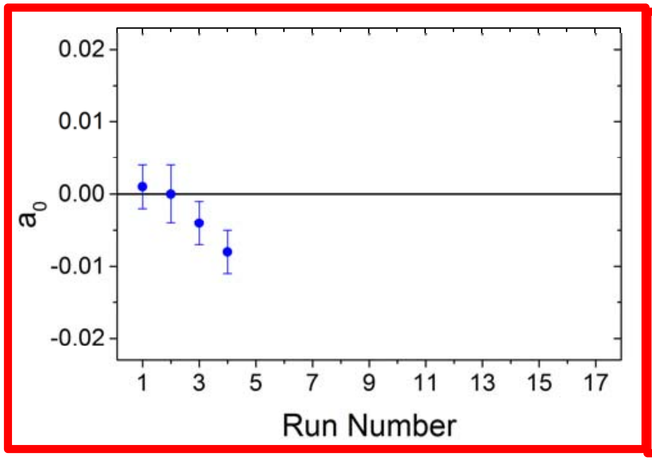
$$\mathcal{A}_{\text{fit}}\left(\Delta\right) =$$

$$2\frac{W_{\text{fit}}}{\Delta}\frac{\omega}{d\mathcal{E}_0} + a_0 + a_1\Delta$$

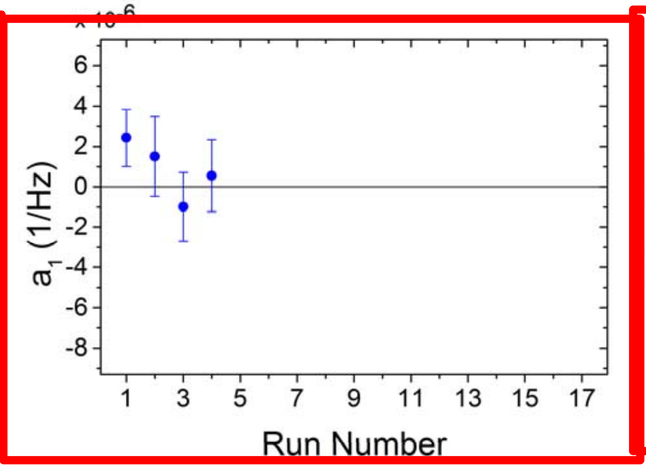
# *NSD-PV data with $^{138}$Ba$^{19}$F*

Fit to $$\mathcal{A}_{\text{fit}}(\Delta) = 2\frac{W_{\text{fit}}}{\Delta}\frac{\omega}{d\mathcal{E}_0} + a_0 + a_1\Delta$$

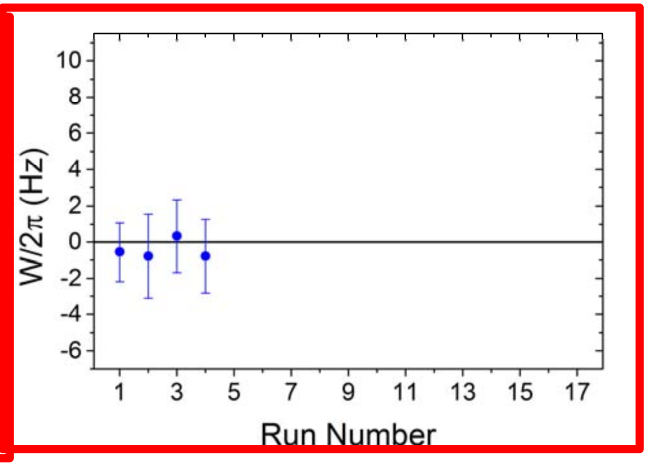
from stray $\mathcal{E}$-fields alone

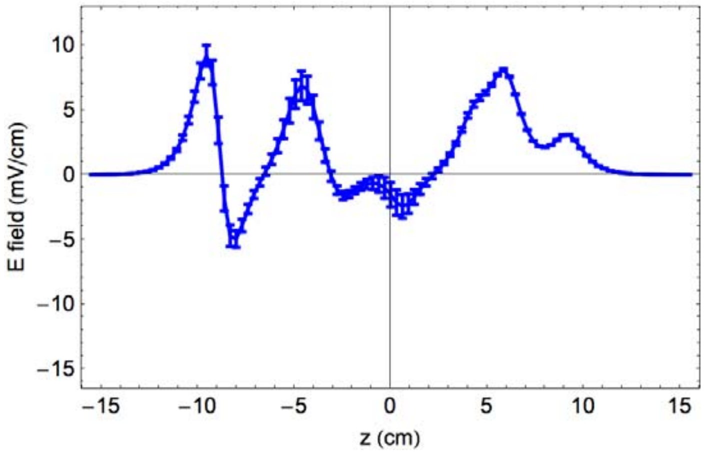


From combined stray $\mathcal{E}$-fields & $\mathcal{B}$-field gradients



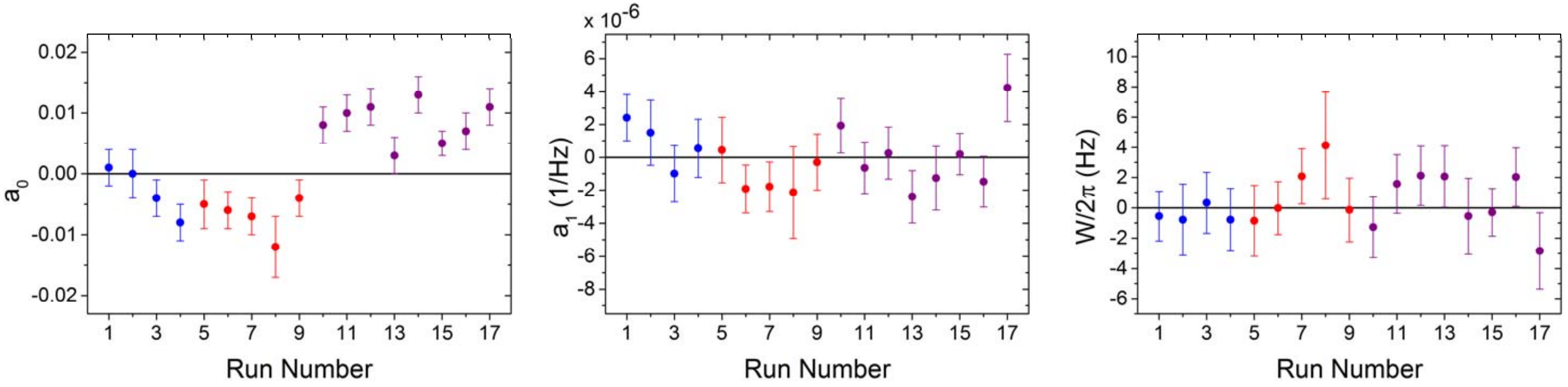
NSD-PV

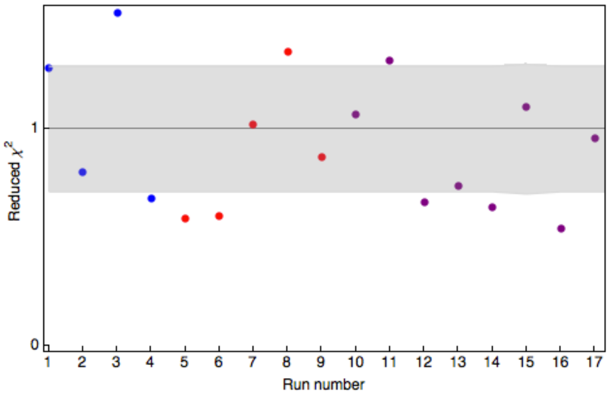




- stray $\mathcal{E}$-fields always below 15mV/cm

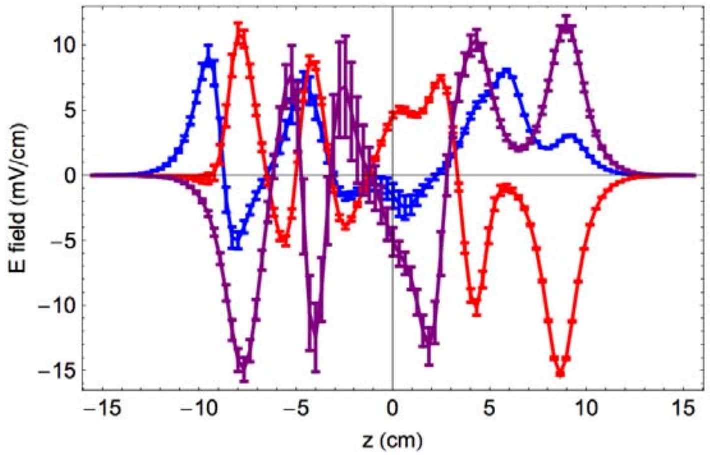
# *NSD-PV data with $^{138}$Ba$^{19}$F*





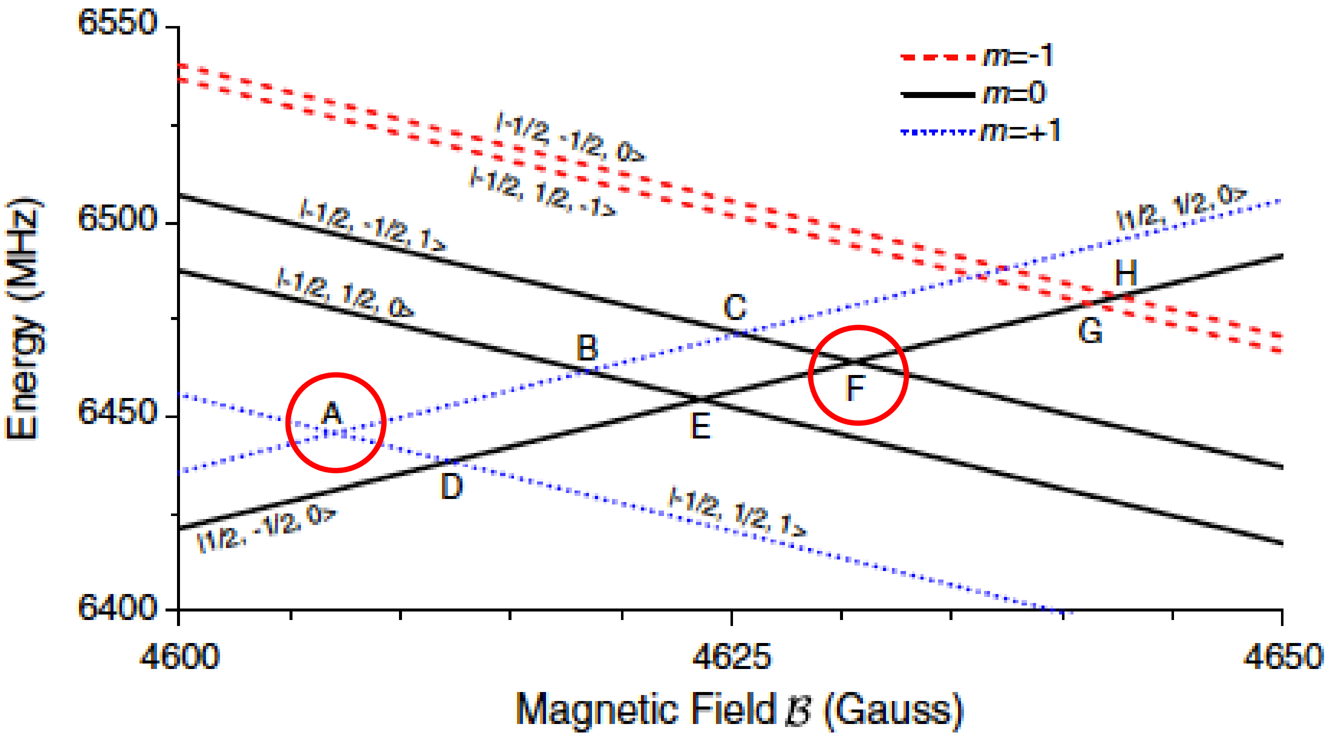
Weighted average $\rightarrow \frac{W}{2\pi}=0.32\pm0.49_{\text{stat}}$ Hz

$$a_1=\left(-1.27\pm4.02_{\text{stat}}\right)*10^{-7}\ 1/\text{Hz}$$



- $^{138}$BaF expected $W$ = 0
- Measured with 3 different stray $\mathcal{E}$-fields (all below 15 mV/cm)
- $a_1$ terms consistent with zero: no systematics

# Different level crossings to suppress systematics



$|m_S, m_I, m_N>$

$S$: electron spin

$I$: nuclear spin

$N$: rotation

n: molecular axis

$$\boxed{W} = W_P\left(\kappa_2' + \kappa_a'\right)\left\langle\left(\hat{n}\times\vec{S}\right)\cdot\vec{I}\right\rangle$$

Measured quantity, different for each crossing

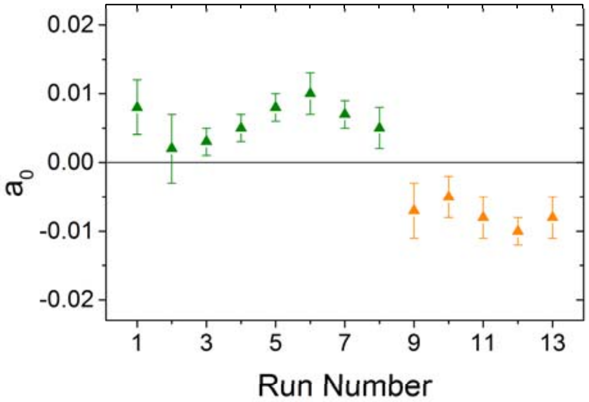
Molecular wavefunctions: same at all crossings, accurately computed

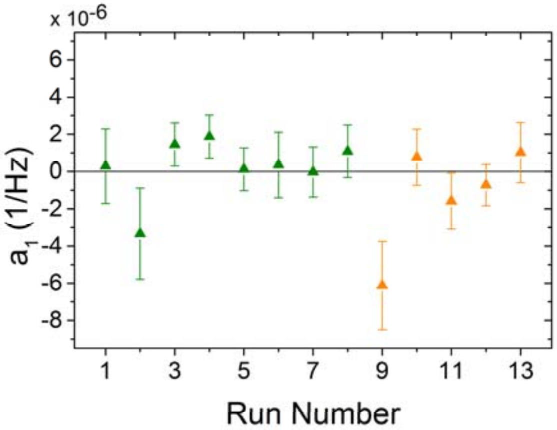
NSD-PV parameters: same at all crossings

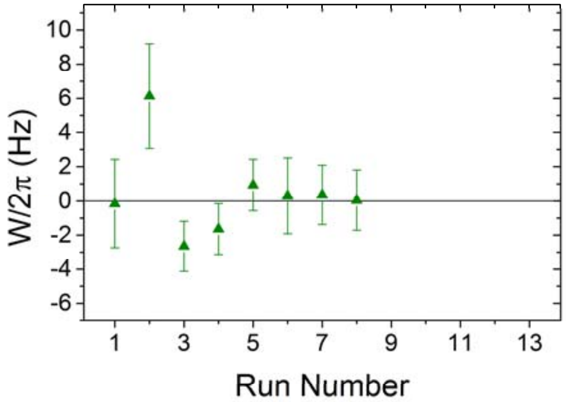
Angular factor:

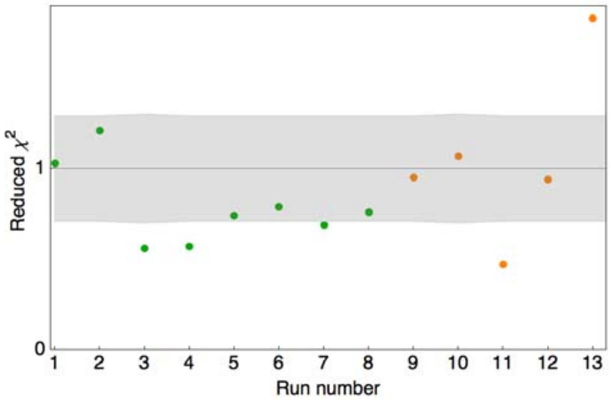
- Different for each crossing (sign & magnitude)
- Analytically calculable

# NSD-PV data with $^{138}$Ba$^{19}$F: 2nd crossing W → -W



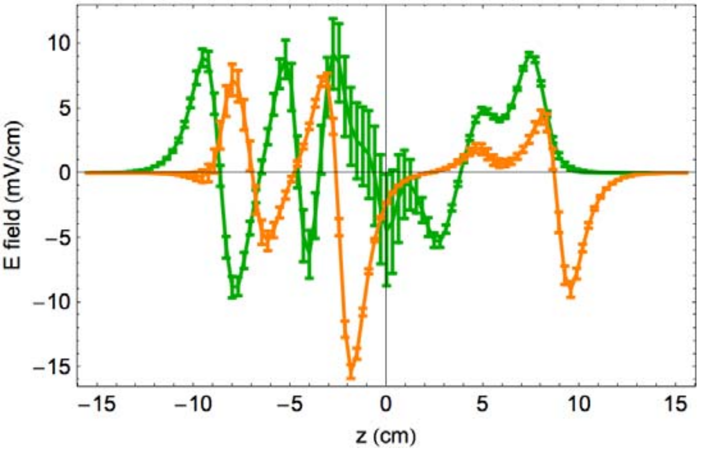






$$\text{Weighted average} \rightarrow \frac{W}{2\pi} = 0.05 \pm 0.51_{\text{stat}} \ \text{Hz}$$

$$a_1 = \left(-1.69 \pm 3.98_{\text{stat}}\right) * 10^{-7} \ 1/\text{Hz}$$



- $^{138}$BaF expected $W = 0$
- Measured with 2 different stray E-fields (all belo 15mV/cm)
- No systematics → $a_1$ terms consistent with zero

# *Systematic & total uncertainty evaluation*

## Strategy

- Deliberately exaggerate imperfection by known, large factor
- Measure effect on the NSD-PV matrix element *W*
  from coupling to ambient imperfections in the experiment

| Parameter | Shift | Systematic Uncertainty $\delta W_{\mathrm{sys}}$ (Hz) |
|---|---|---|
| Bipolar $\mathcal{E}_{nr}$ Pulses | | 0.12 |
| Unipolar $\mathcal{E}_{nr}$ Pulses | | 0.16 |
| $\mathcal{B}$-Field Inhomogeneities | | 0.24 |
| $\delta\nu_{L2}$ and $\mathcal{E}_{nr}$ at and near Gap 22 | -0.04 | 0.21 |
| Total Systematic | -0.04 | 0.38 |

## Final Error Budget with $^{138}$Ba$^{19}$F

| Crossing | $W/(2\pi)$ (Hz) | $C$ | $d$ (Hz/(V/cm)) | $W_{\mathrm{mol}} = \kappa' W_P/(2\pi)$ (Hz) |
|---|---|---|---|---|
| A | $0.28 \pm 0.49_{\mathrm{stat}} \pm 0.38_{\mathrm{sys}}$ | -0.41 | 3360 | $-0.68 \pm 1.20_{\mathrm{stat}} \pm 0.93_{\mathrm{sys}}$ |
| F | $0.01 \pm 0.51_{\mathrm{stat}} \pm 0.38_{\mathrm{sys}}$ | +0.39 | 3530 | $0.03 \pm 1.30_{\mathrm{stat}} \pm 0.97_{\mathrm{sys}}$ |
| Weighted Average | - | - | - | $-0.36 \pm 0.88_{\mathrm{stat}} \pm 0.95_{\mathrm{sys}}$ |

~170 h data
~6x10$^7$ molecules total

$$W_{mol} = 2\pi \times (-0.36 \pm 1.29)\ \mathrm{Hz}$$

# What does this $^{138}$Ba$^{19}$F result mean?

$$W_{mol} \equiv \left(\kappa_2' + \kappa_a'\right) W_P = 2\pi \times \left(-0.36 \pm 1.29\right) \text{ Hz}$$

$\Rightarrow$ Limit on $^{19}$F anapole + $C_{2P}$ :

$$W_P\left({}^{19}\text{F in BaF}\right) = 2\pi \times 0.05 \text{ Hz}$$

$$\kappa'\left({}^{19}\text{F}\right) = -7 \pm 25 \qquad \text{vs. } \kappa'\left({}^{19}\text{F}\right)\left[\text{shell model}\right] = 0.08$$

$\Rightarrow$ Proves we have no unknown systematics

$\Rightarrow$ Systematics limited by statistical power (so far)

but not really informative about HPV

….So What?

# *What does thE $^{138}$Ba$^{19}$F result mean?*

$$W_{mol} \equiv \left(\kappa_2' + \kappa_a'\right) W_P = 2\pi \times \left(-0.36 \pm 1.29\right) \text{ Hz}$$

More useful comparison:

$$W_P\left({}^{137}\text{Ba in BaF}\right) = 2\pi \times 160 \text{ Hz}$$

Same experimental uncertainty in $^{137}$BaF would mean

$$\underbrace{\delta\kappa'\left({}^{137}\text{Ba}\right) = 0.008 \quad \text{vs. } \kappa'\left({}^{137}\text{Ba}\right)\left[\text{shell model}\right] \approx 0.07}_{}$$

**~10% of predicted value**

Compares favorably to JILA $^{133}$Cs result: $\kappa'\left({}^{133}\text{Cs}\right) = 0.39 \pm 0.06$

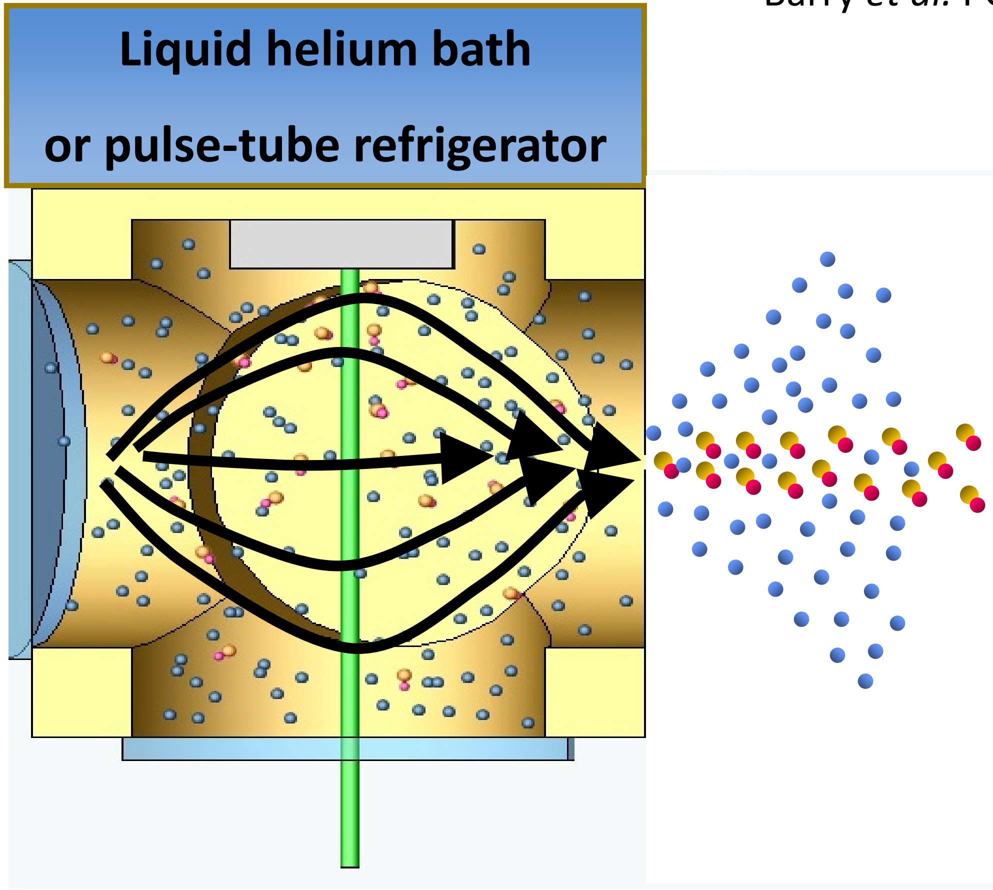
C.S. Wood *et al.*, Science **275**, 1759 (1997)

- Unprecedented sensitivity to NSD-PV
- General technique enables measurements in broad range of nuclei

E. Altuntas, J. Ammon, S. B. Cahn, DD arXiv:1801.05316; arXiv:1711.01988

# *Cryogenic Buffer Gas-cooled Beam*

[Maxwell *et al.* PRL 2005; Patterson & Doyle J Chem Phys 2007; Barry *et al.* PCCP 2011; Hutzler *et al.* PCCP 2011]



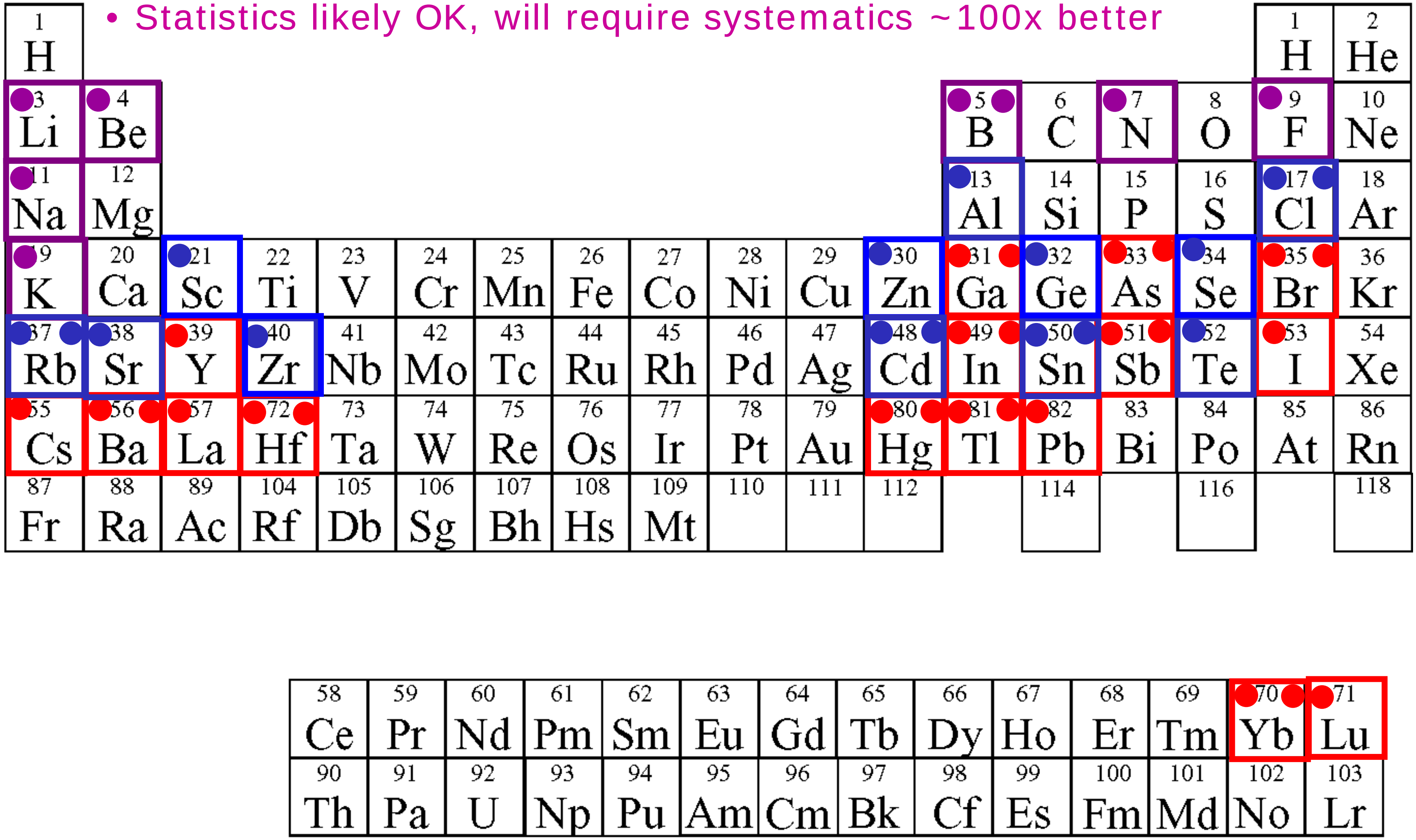
- Inject hot molecules (e.g. via laser ablation)
- Cool w/cryogenic buffer gas @ high density
- Efficient extraction to beam via "wind" in cell: $10^{-4} \to$ 10%-40%
- "Self-collimated" by extraction dynamics
- Rotational cooling in expansion: $T \sim 4$ K
- Moderately slow: $v \sim 200$ m/s

Beam brightness ~ ***$10^3\times$*** larger flux; interaction time ~ ***$3\times$*** larger;
enables magnetic focusing $\Rightarrow$ ~ ***$20\times$*** flux

**Gain in NSD-PV statistical sensitivity: 400×** (@ same total time)

# *Viable nuclei for anapole/NSD-PV measurement*

- 10% measurement possible with demonstrated sensitivity, $\lesssim$1 h data
- Requires systematics ~2-10x better
- Statistics likely OK, will require systematics ~100x better



| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 H | | | | | | | | | | | | | | | | 1 H | 2 He |
| 3 Li | 4 Be | | | | | | | | | | | 5 B | 6 C | 7 N | 8 O | 9 F | 10 Ne |
| 11 Na | 12 Mg | | | | | | | | | | | 13 Al | 14 Si | 15 P | 16 S | 17 Cl | 18 Ar |
| 19 K | 20 Ca | 21 Sc | 22 Ti | 23 V | 24 Cr | 25 Mn | 26 Fe | 27 Co | 28 Ni | 29 Cu | 30 Zn | 31 Ga | 32 Ge | 33 As | 34 Se | 35 Br | 36 Kr |
| 37 Rb | 38 Sr | 39 Y | 40 Zr | 41 Nb | 42 Mo | 43 Tc | 44 Ru | 45 Rh | 46 Pd | 47 Ag | 48 Cd | 49 In | 50 Sn | 51 Sb | 52 Te | 53 I | 54 Xe |
| 55 Cs | 56 Ba | 57 La | 72 Hf | 73 Ta | 74 W | 75 Re | 76 Os | 77 Ir | 78 Pt | 79 Au | 80 Hg | 81 Tl | 82 Pb | 83 Bi | 84 Po | 85 At | 86 Rn |
| 87 Fr | 88 Ra | 89 Ac | 104 Rf | 105 Db | 106 Sg | 107 Bh | 108 Hs | 109 Mt | 110 | 111 | 112 | | 114 | | 116 | | 118 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 58 Ce | 59 Pr | 60 Nd | 61 Pm | 62 Sm | 63 Eu | 64 Gd | 65 Tb | 66 Dy | 67 Ho | 68 Er | 69 Tm | 70 Yb | 71 Lu |
| 90 Th | 91 Pa | 92 U | 93 Np | 94 Pu | 95 Am | 96 Cm | 97 Bk | 98 Cf | 99 Es | 100 Fm | 101 Md | 102 No | 103 Lr |

# *Other ongoing anapole-sensitive experiments*

Mainz: $^{171}$Yb, $^{173}$Yb (similar to JILA Cs experiment)

FrPNC @ TRIUMF: $^{xxx}$Fr (cooled & trapped Fr atoms)

Mainz: new ideas using NMR signals for light nuclei….?

# *ZOMBIES NSD-PV: Outlook & questions*

- New lab under renovation, occupancy this summer with cryogenic beam source
- Realistic goal: ~2 years to $^{137}$Ba measurement

**Question for theorists: what to do next with this method?**

--lightest nuclei (accessible via no-core shell model)…?

--could $C_2$ values be extracted reliably from light nuclei with existing HPV data & understanding?

--is consistency check among many heavier nuclei useful?
--isotope comparisons?
--any special cases of particular interest?

--quantitative uncertainties on shell model calculations!