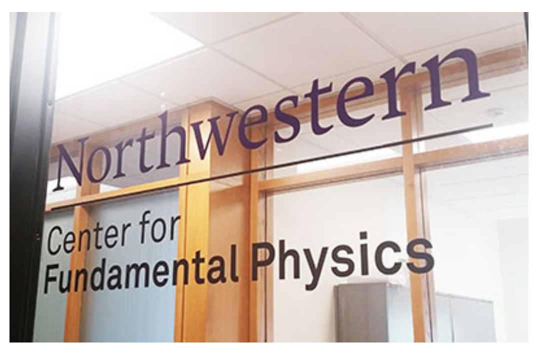
ZOMBIES: an experiment to measure nuclear anapole moments
(and more)

- Nuclear anapole moment and hadronic parity violation
- Nuclear spin-dependent parity violation (NSD-PV) in atoms & molecules: nuclear anapole moment + semi-leptonic
- ZOMBIES approach using amplified NSD-PV effect in molecules
- Proof of principle with ^{19}F in BaF molecules
- Outlook

Dave DeMille
University of Chicago & Argonne National Laboratory

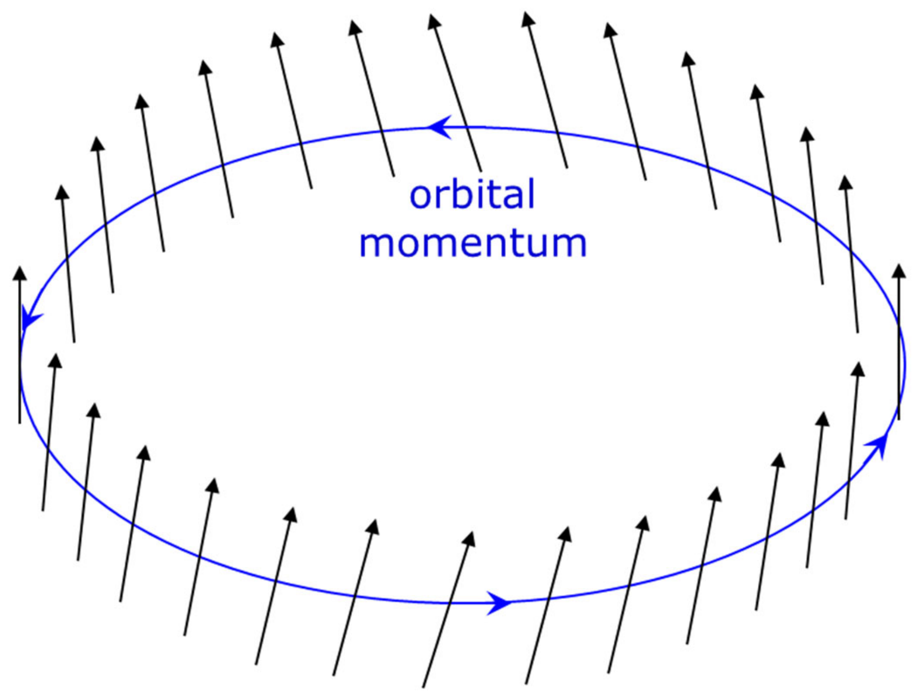
Funding:
Argonne NATIONAL LABORATORY



THE UNIVERSITY OF CHICAGO 1890

Purely hadronic PV in nucleus induces nuclear spin helix = anapole moment

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



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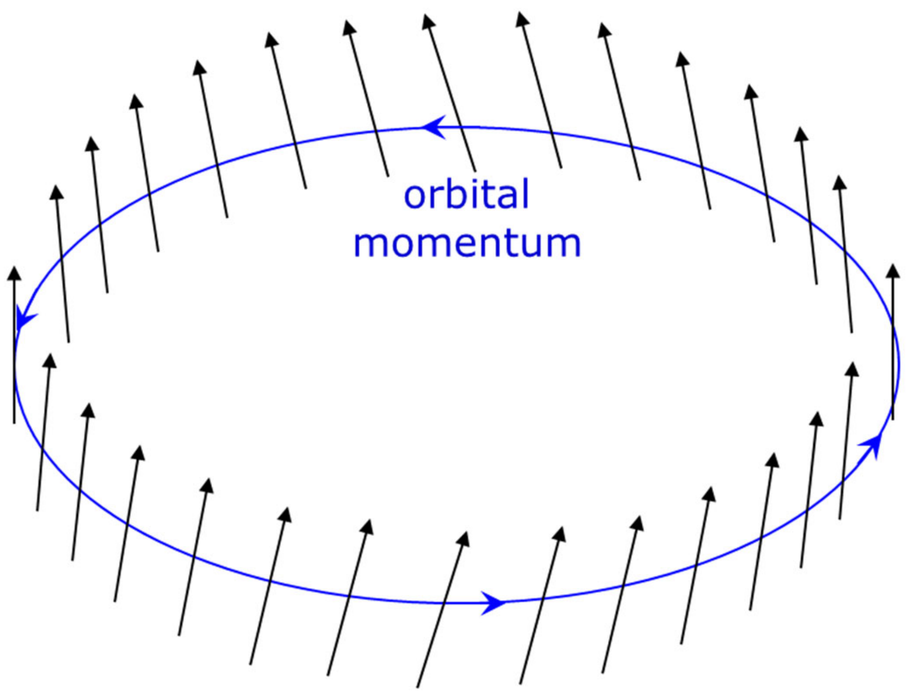

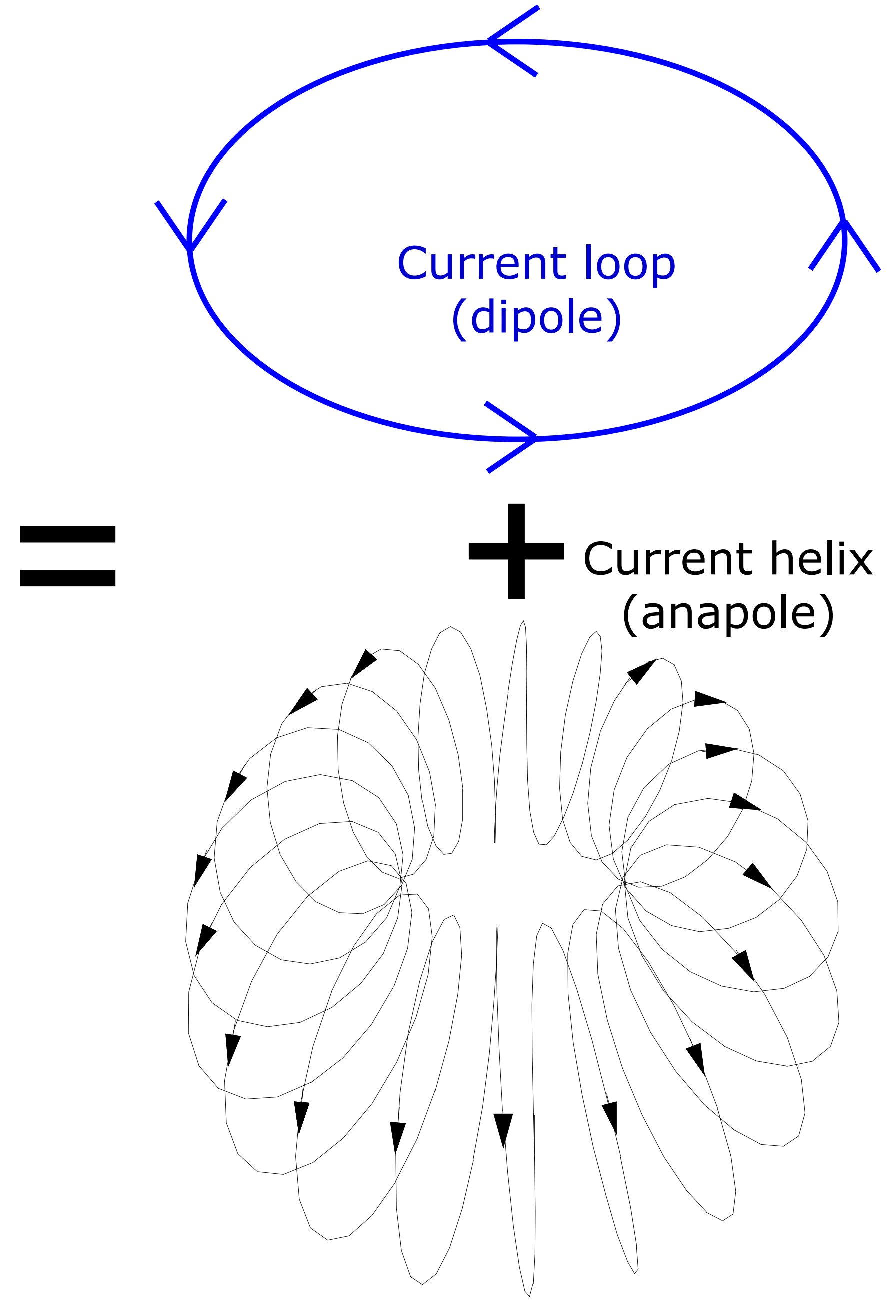

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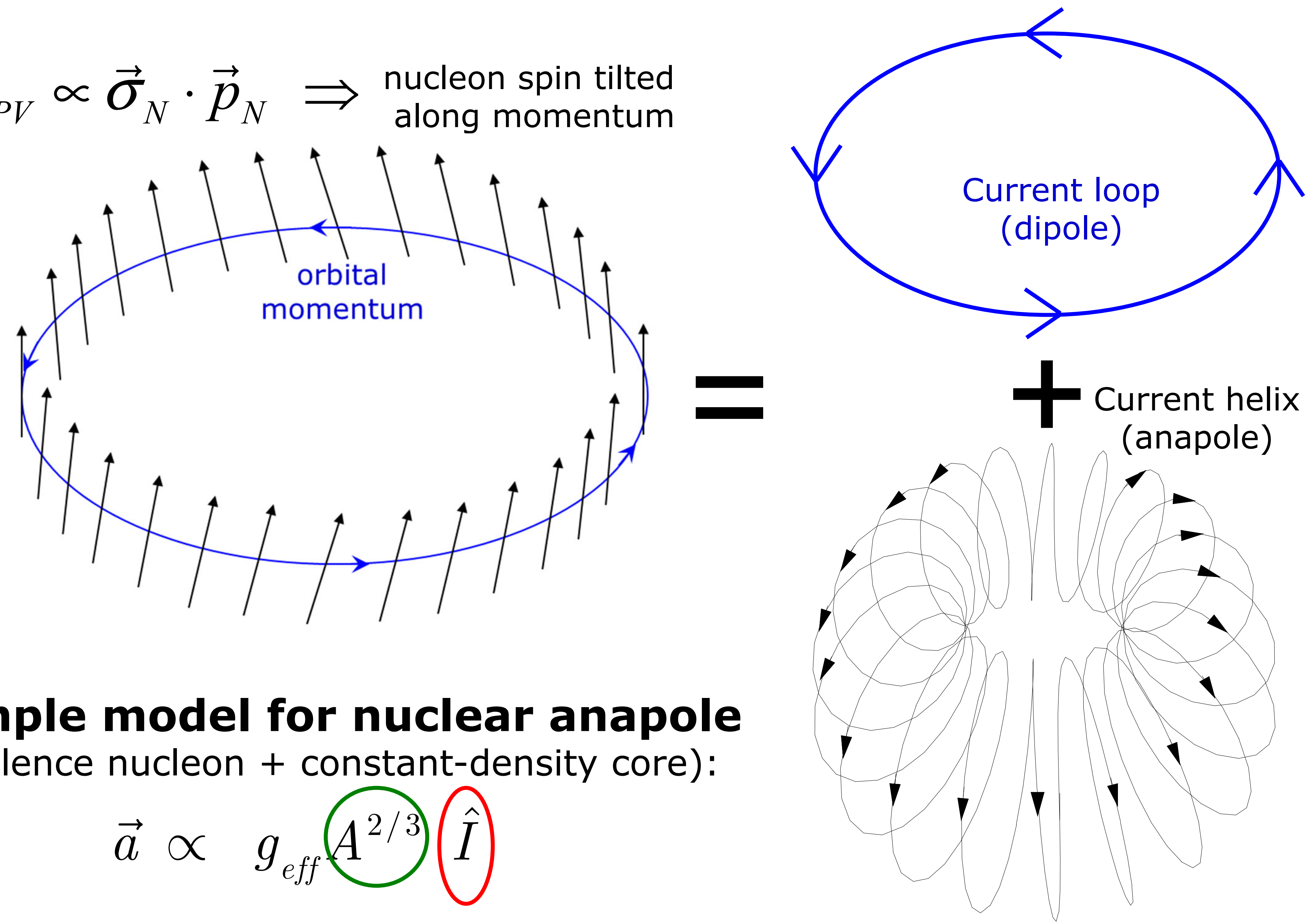


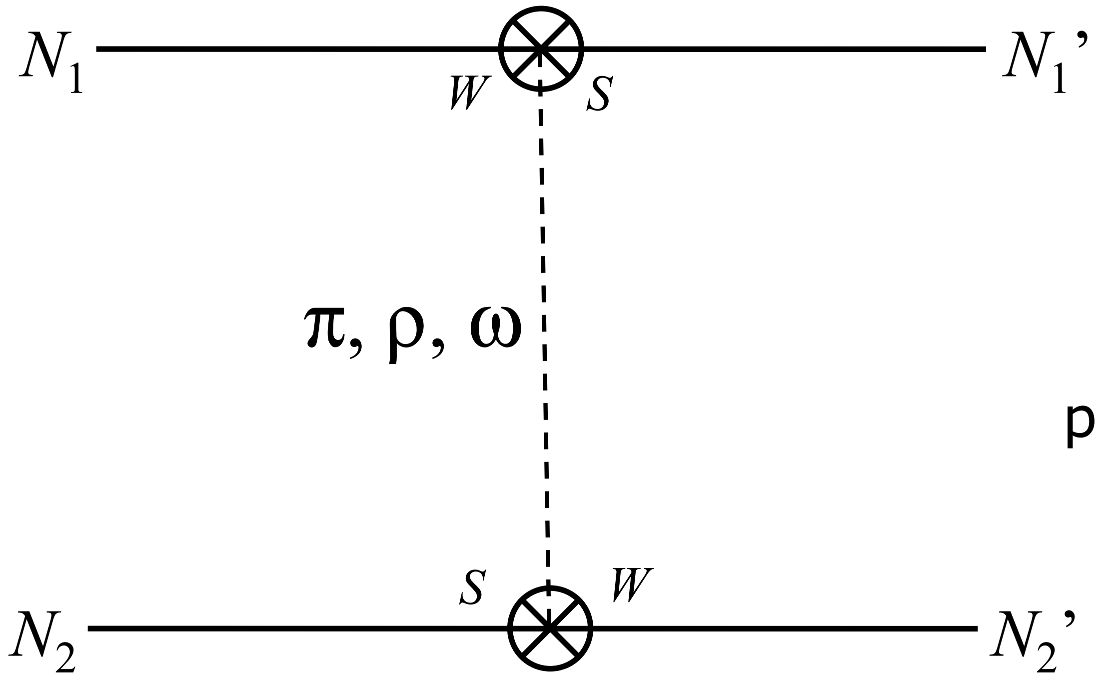
Simple model for nuclear anapole

(valence nucleon + constant-density core):

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

Microscopic physics of nuclear anapole moment

Nucleon-nucleon hadronic parity-violating (HPV) interactions perturb nuclear structure:



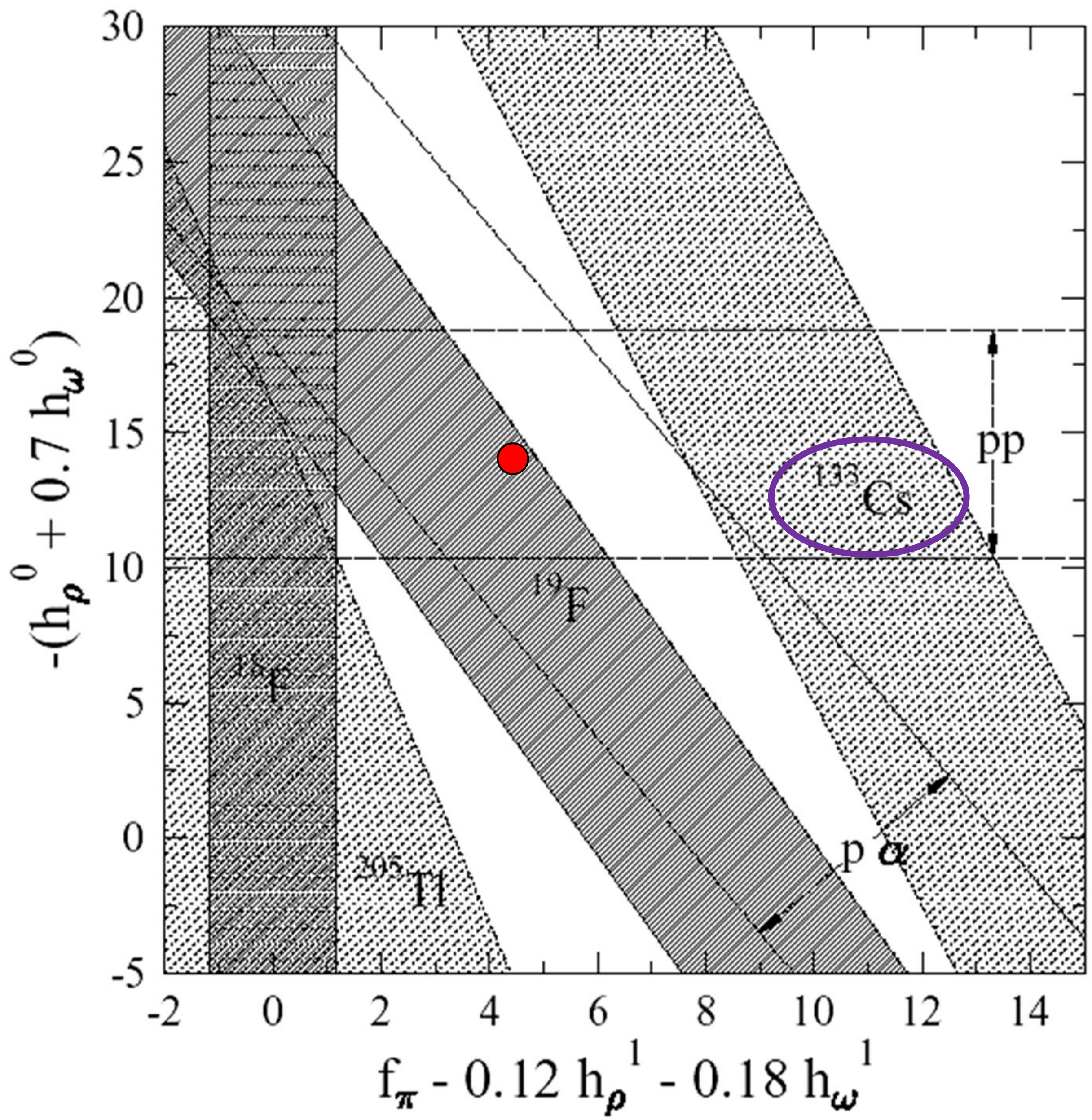
DDH description of HPV: effective meson exchange parameterizes range & isospin structure

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

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

Describe low-energy HPV with 6 dimensionless coupling constants, each associated with different spin/isospin structure & range

HPNC measurements including anapole moments (prior to ~2018) in 2-D slice of DDH parameters

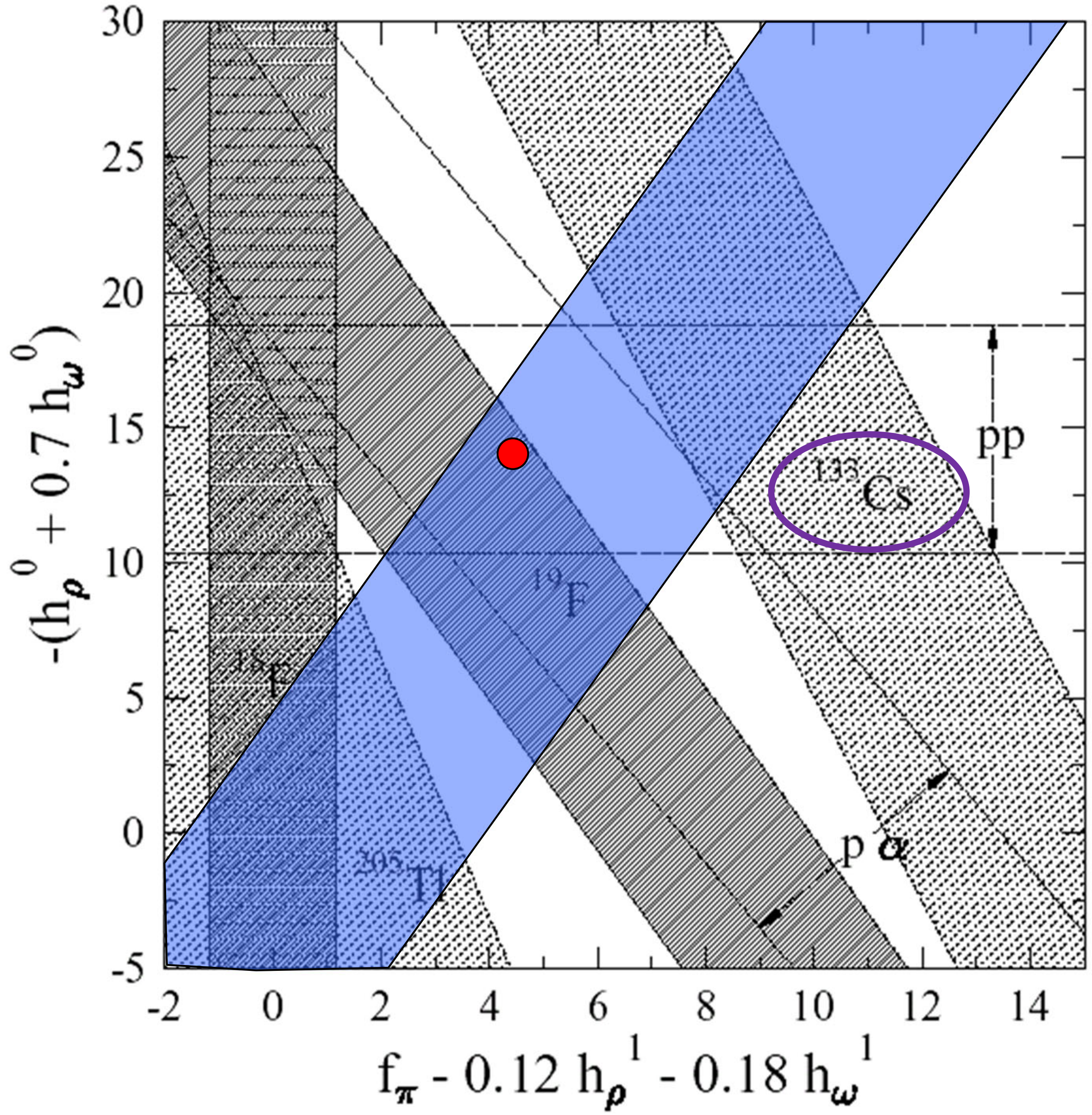


Single prior anapole measurement from atomic PV in ^{133}Cs
[C. Wieman group, JILA, 1997]

Poor agreement with all other data (nuclear theory problem…?)

Assumes ~30% uncertainty in nuclear structure calculations

HPNC measurements including anapole moments (prior to ~2018) in 2-D slice of DDH parameters



Odd-n isotopes

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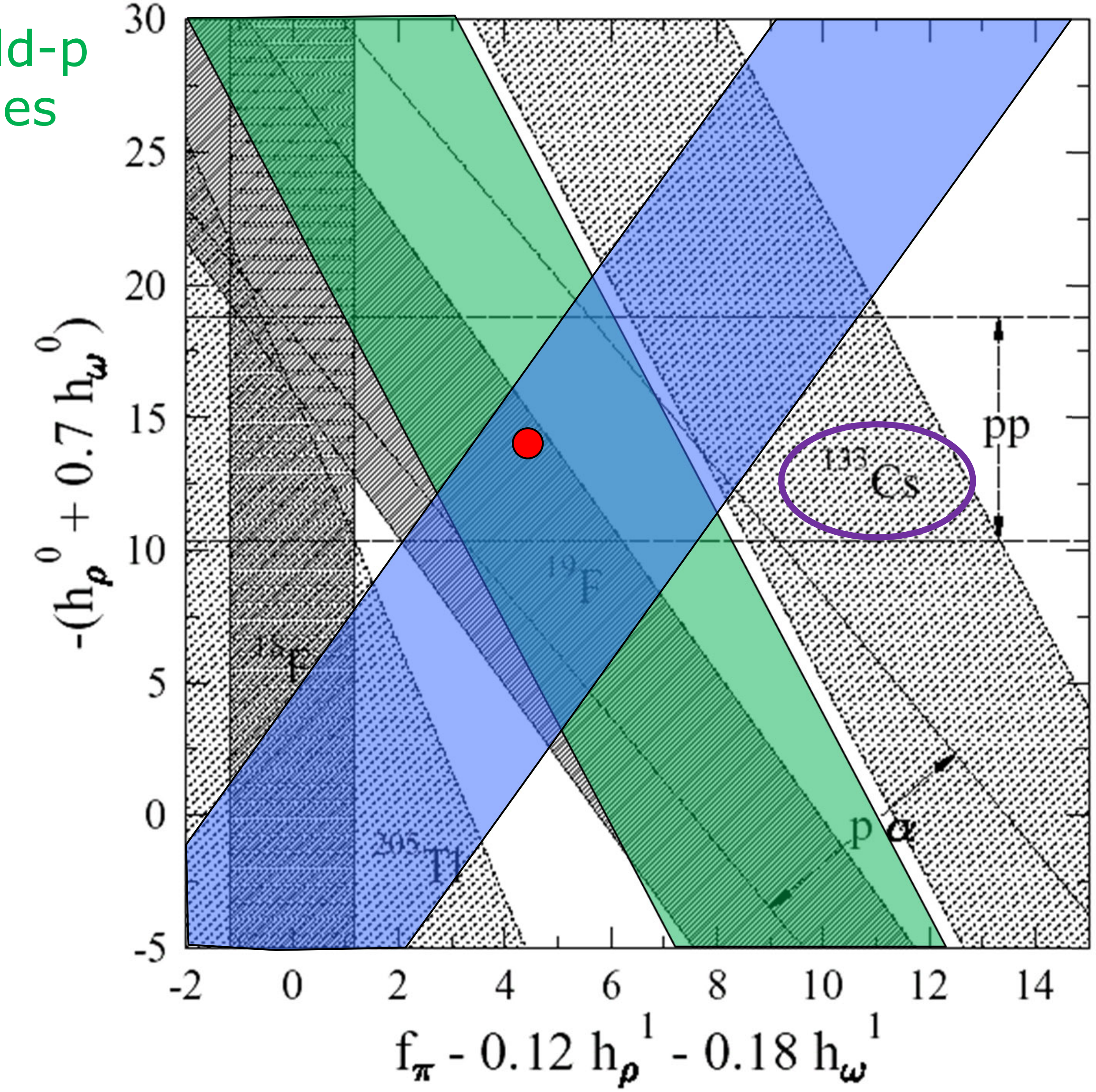
HPNC measurements including anapole moments (prior to ~2018) in 2-D slice of DDH parameters

New odd-p isotopes



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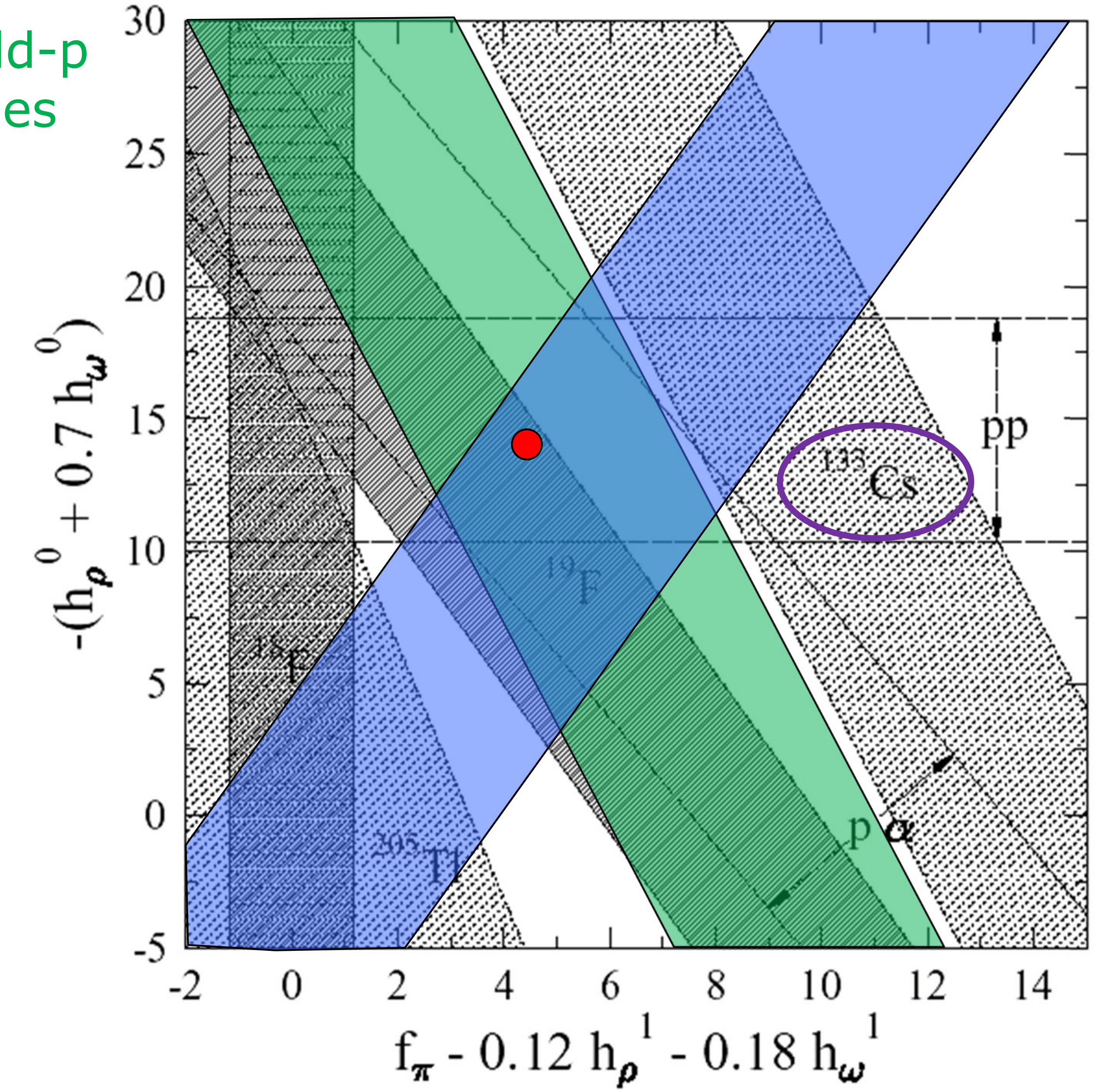

NOTE:
anapole moments not yet evaluated in new EFT parameterization & large N_c analysis of HPV

See M. Sarsour talk this session

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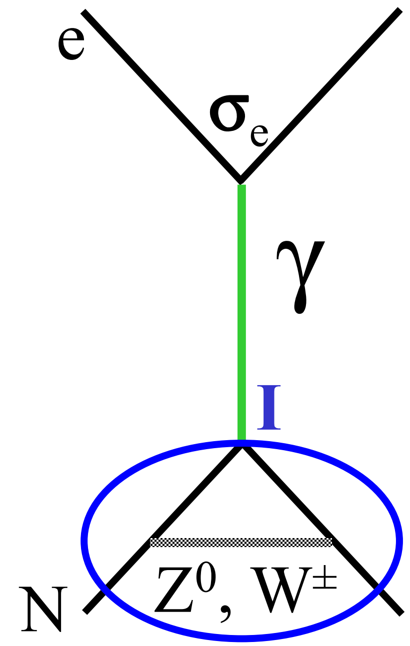
[C. Wieman group, JILA, 1997]

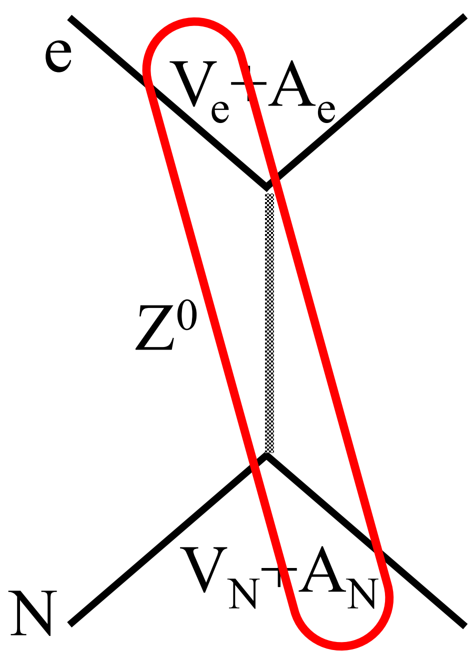
Assumes ~30% uncertainty in nuclear structure calculations

Mechanisms for nuclear spin-dependent parity violation in atoms and molecules



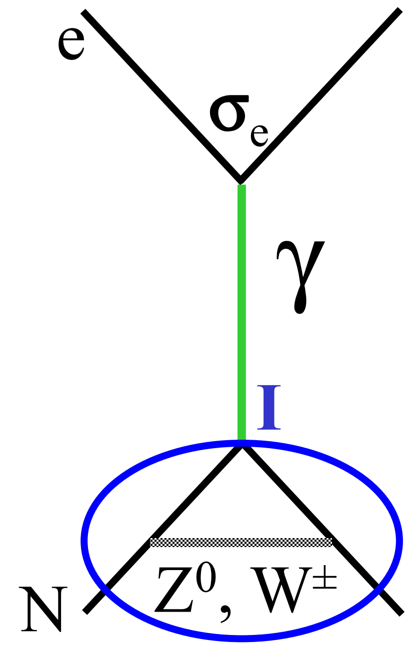
HPV interactions
inside nucleus induce
nuclear
anapole moment:
couples magnetically
to penetrating electron

Mechanisms for NSD-PV in atoms and molecules



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

+



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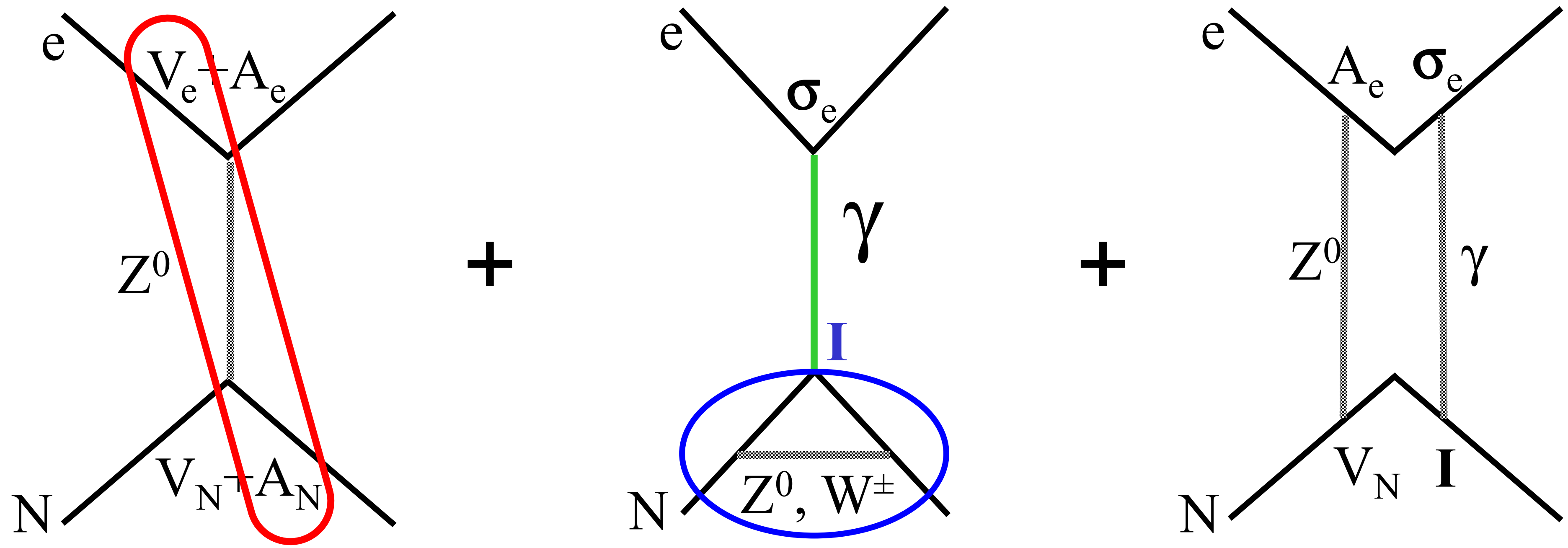

Tree-level NSD-PV from **suppressed** $V_e A_N$ term: C_2 couplings subject to QCD renormalization analogous to g_A

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

Coherent sum: weak charge Q_W and EM hyperfine interaction (small, well-understood)

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

3 contributions to NSD-PV in atoms/molecules: 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

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

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

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

Challenge for atomic/molecular approaches:

Signals by far easiest to detect with high Z & A

BUT

Best chance for reliable interpretation with lowest Z & A

3 contributions to atom/molecule NSD-PV: scaling with Z & A

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

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

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

Heavy atoms/molecules→anapole term dominates: $|\kappa'_a| > |\kappa'_2|$

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

Light atoms/molecules→tree-level Z exchange term dominates: $|\kappa'_a| > |\kappa'_2|$

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

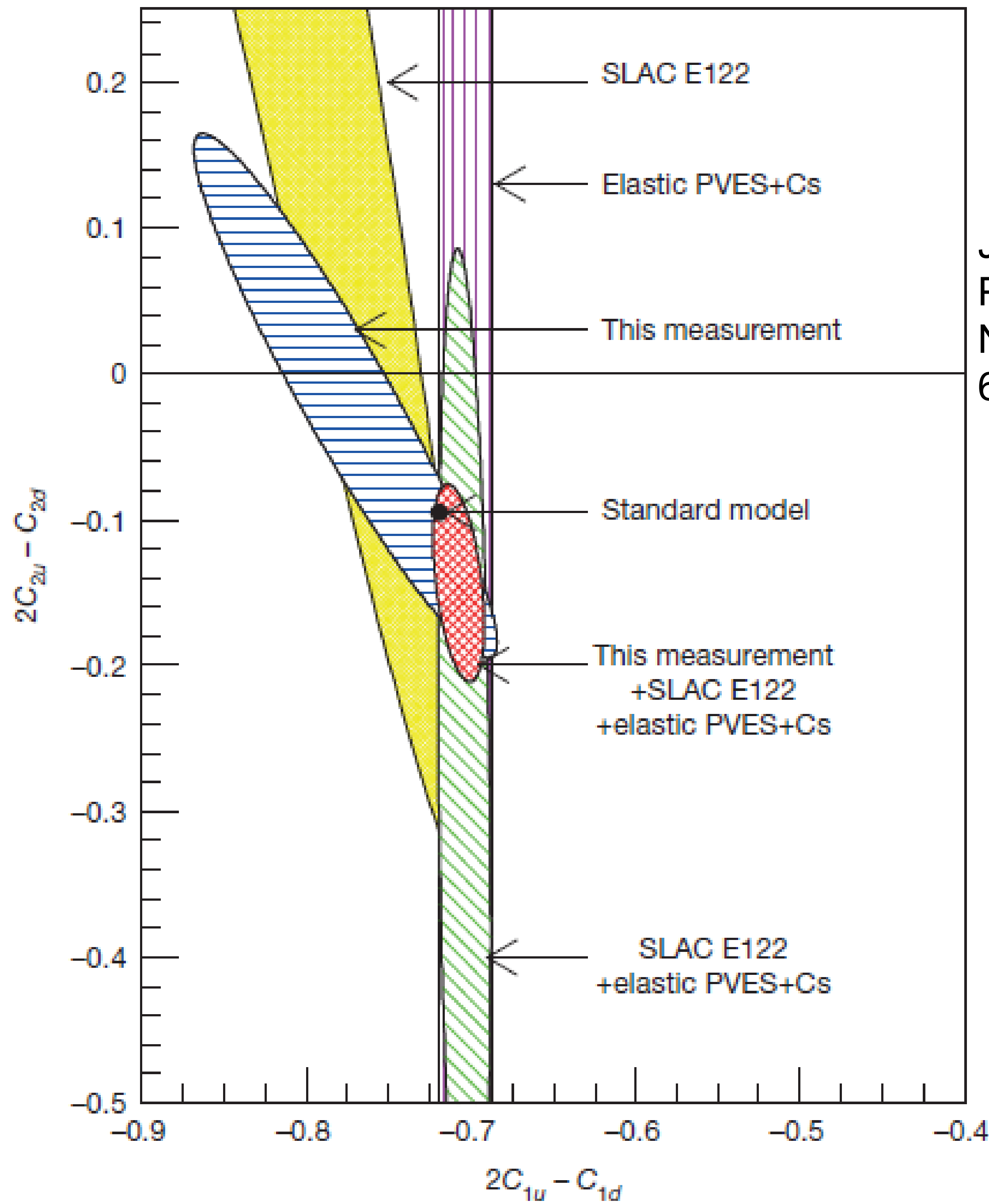
$A \approx 100$ (odd neutron)

More physics motivation for κ measurements: neutral weak currents & QCD

κ_2: Tree-level Z^0 Exchange

- Vector electron – axial nucleon weak coupling constants (C_{2N}, C_{2P})
- Related to fundamental electron-quark couplings (C_{2u}, C_{2d}) via QCD
- Complementary to PVDIS e-p measurements at JLAB (different linear combinations of C_2's & nucleons vs. quarks)

See D. Adhikari talk this session



JLAB PVDIS Collab. Nature **506**, 67 (2014)

ZOMBIES overarching goal:
understand electroweak interactions in strongly-interacting environment at low q^2

- **Pure hadronic (nucleon-nucleon) parity violating interactions: still poorly understood**

--complementary to recent few-nucleon probes (NPDGamma, polarized n on ^{3}He, neutron spin rotation, …)

--sensitive to different linear combinations in multi-parameter space

--connect to recent developments in nuclear structure calculations & HPV theory

--rich data set for consistency checks

-- benchmark for 0υββ matrix element calculations…???

- **Nucleon-level V_eA_h (C_{2P}, C_{2N}) vs. Nucleus-level V_eA_h**

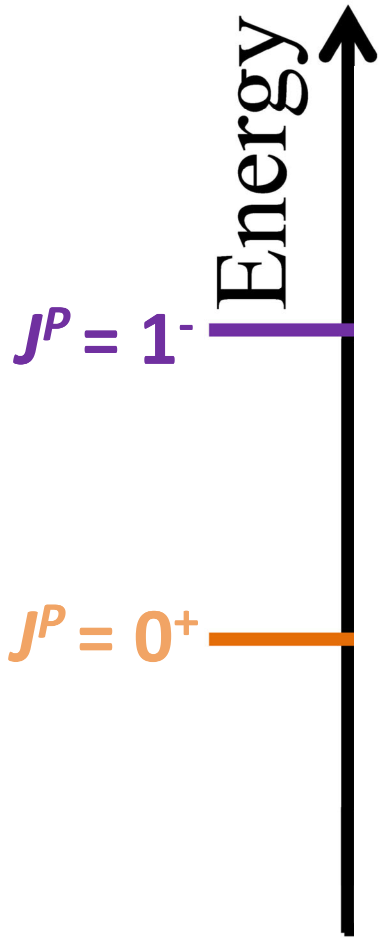
--quenching as for g_A in charged currents…?

- **Quark-level V_eA_h(C_{2u}, C_{2d}) vs. nucleon-level V_eA_h(C_{2P}, C_{2N}) neutral current couplings ?**

--matching as $q^2 \rightarrow 0$…?

--potential for lattice QCD prediction & post-hoc verification?

ZOMBIES principle: amplified NSD-PV mixing in molecules w/unpaired electron

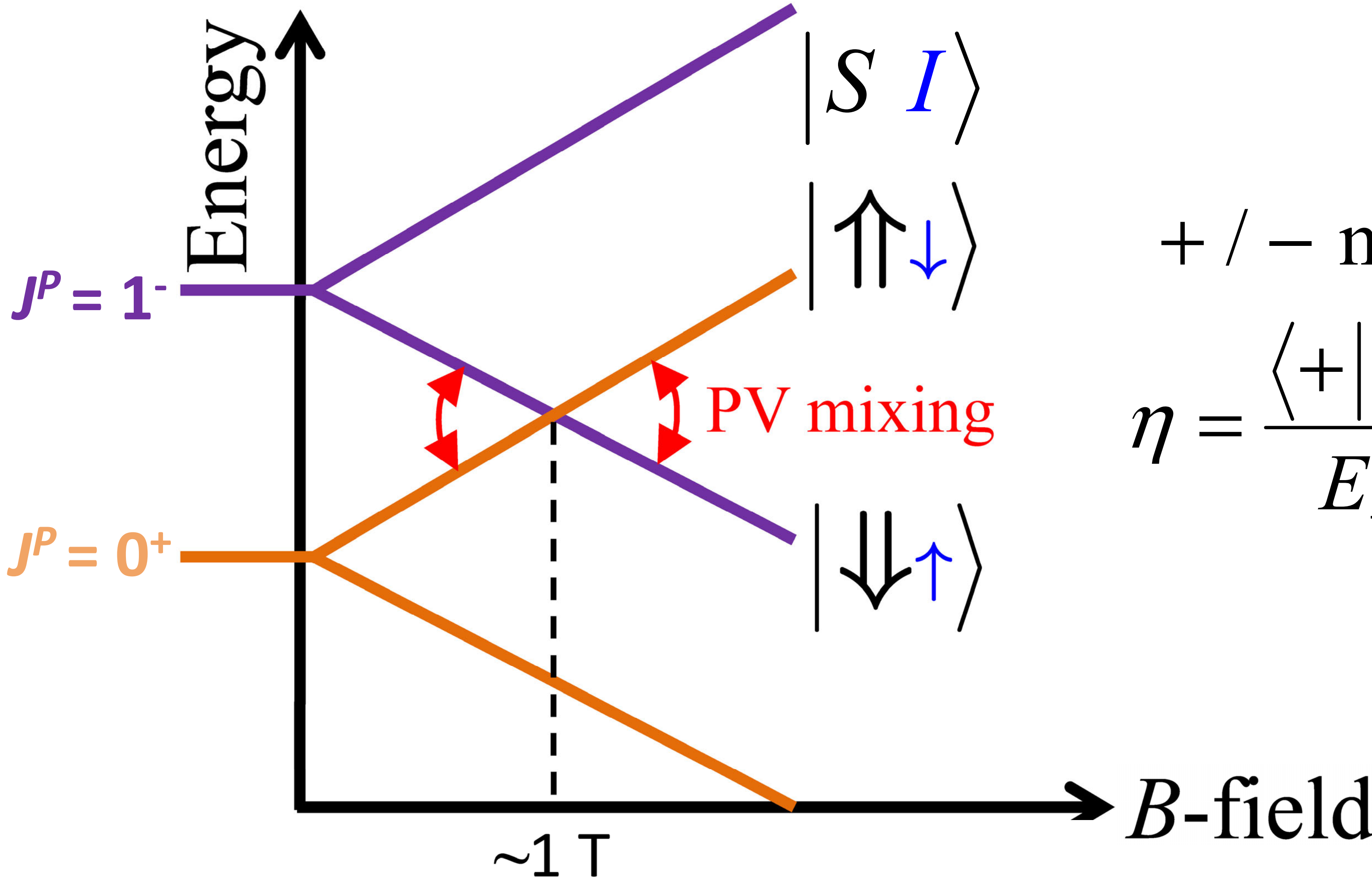


+ / − mixing

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

Naturally small rotational splitting (~10^{-4} eV vs. ~1 eV in atoms)

Amplified NSD-PV mixing in molecules with one unpaired electron

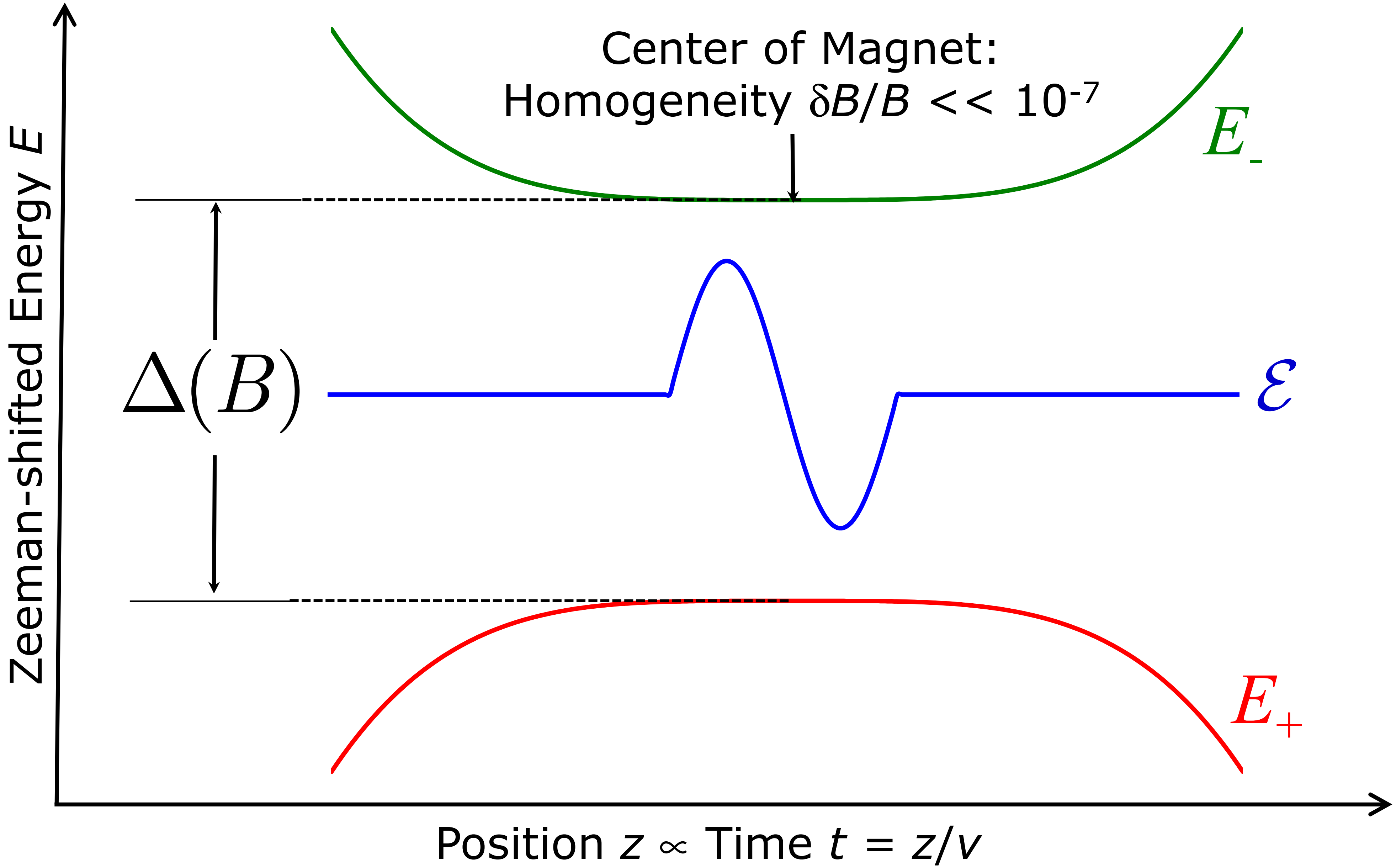


+ / − mixing

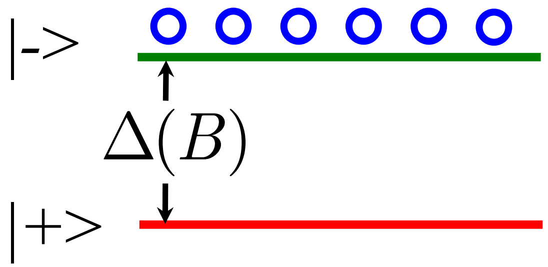
$$\eta = \frac{\langle + | H_{PV} | - \rangle}{E_+ - E_-}$$

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

Stark interference method: apply oscillating $\mathcal{E}$-field to mix nearly-degenerate opposite-parity levels



Detecting PV in near-degenerate levels: AC Stark shift



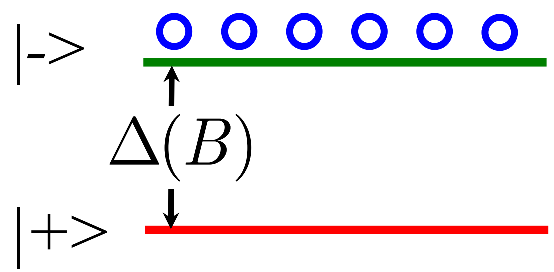
$$H = \begin{pmatrix} 0 & iW + d\mathcal{E}(t) \\ -iW + d\mathcal{E}(t) & \Delta \end{pmatrix}$$

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

Nguyen *et al.*,
PRA **56**, 3453 (1997)

Detecting PV in near-degenerate levels: AC Stark shift

PV mixing iW encodes physics of interest



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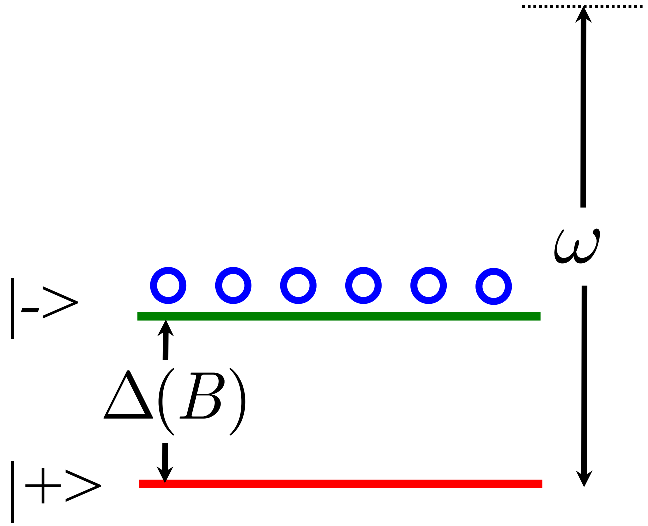

$$H = \begin{pmatrix} 0 & iW + d\mathcal{E}(t) \\ -iW + d\mathcal{E}(t) & \Delta \end{pmatrix}$$

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

$$\mathcal{E}(t) = \mathcal{E}_0 \sin(\omega t)$$

$$\left[\begin{array}{l} \omega \gg \Delta,\ d\mathcal{E}_0; \\ T = 2\pi / \omega \end{array}\right]$$

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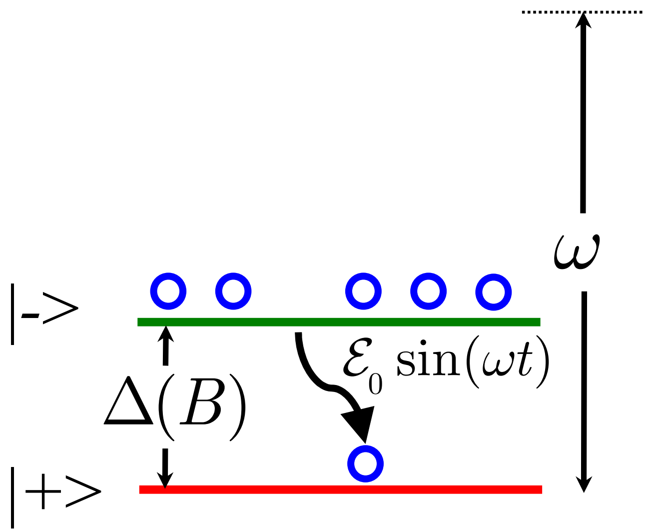

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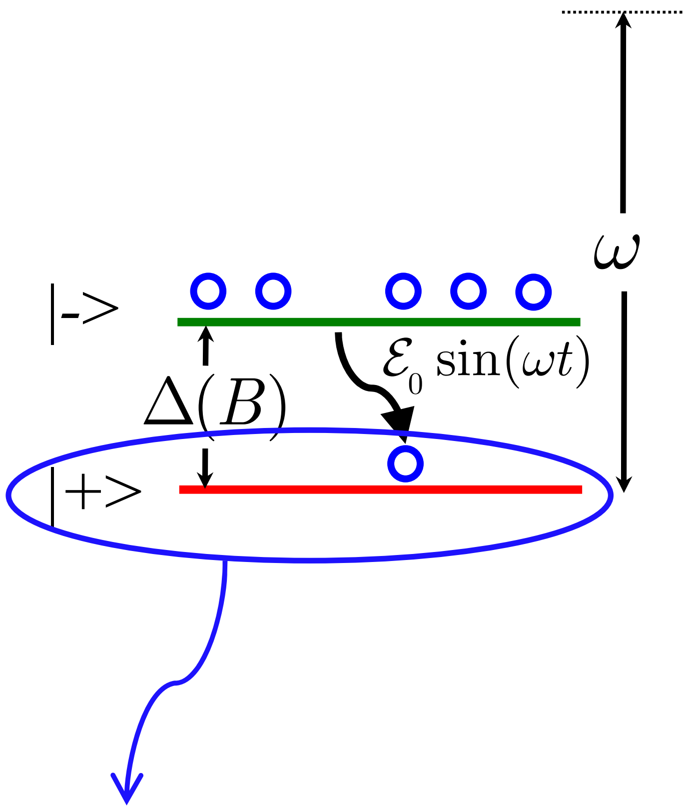

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$$S = \left| \langle + | \psi(T) \rangle \right|^2 = 4\sin^2\left(\frac{\Delta T}{2}\right)\left[\left(\frac{d\mathcal{E}_0}{\omega}\right)^2 + 2\frac{W}{\Delta}\frac{d\mathcal{E}_0}{\omega}\right]$$

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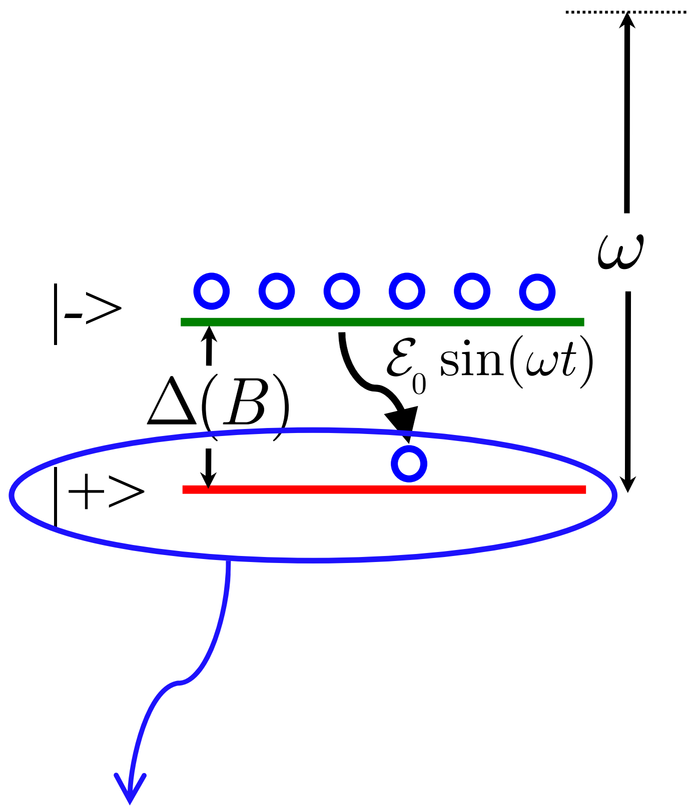

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"Large" Stark Term Even in $\mathcal{E}_0$

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

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

Nguyen *et al.*,
PRA **56**, 3453 (1997)

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 $+\mathcal{E}_0, -\mathcal{E}_0$

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

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

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

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Statistical Uncertainty

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

best sensitivity from large interaction time T

Equivalent to measuring W as generic energy shift at Standard Quantum Limit

N. Fortson, PRL **70**, 2383 (1993)

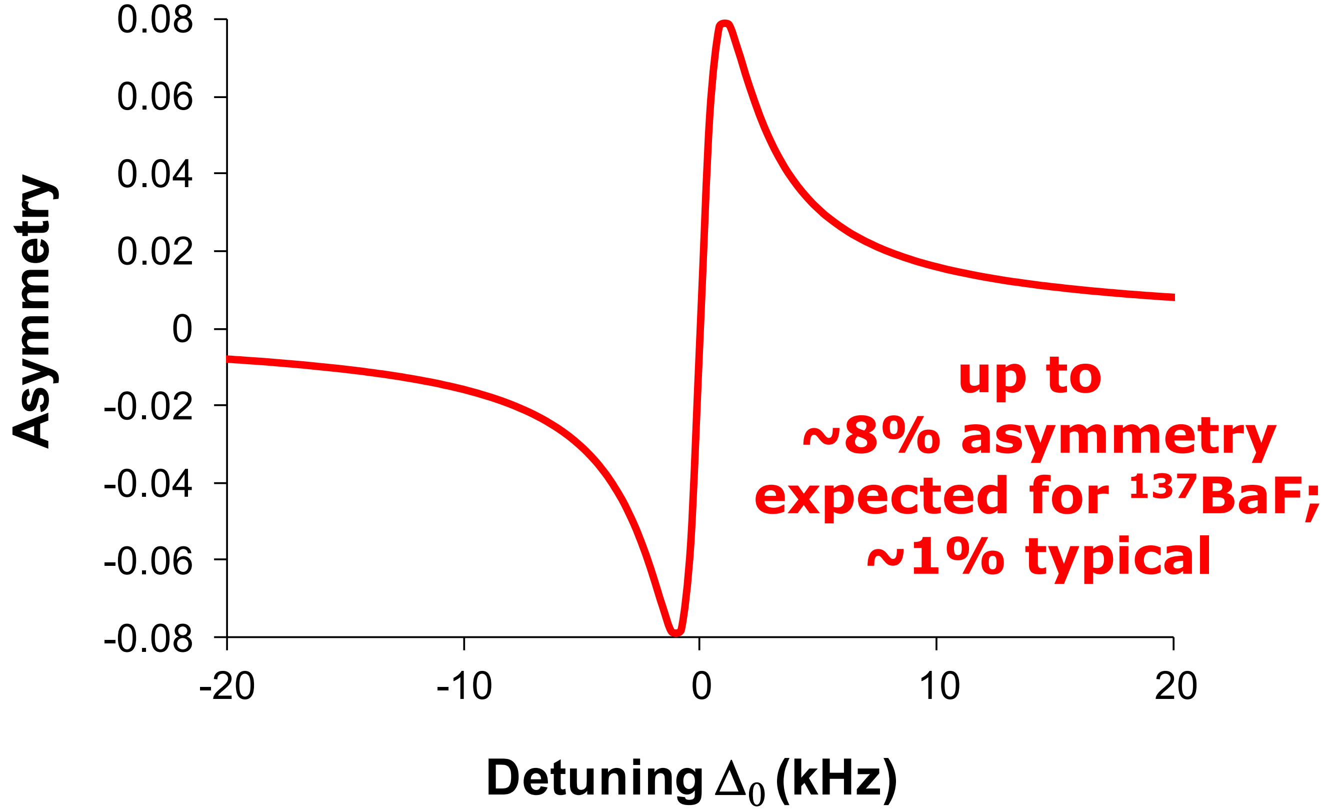
Properties of NSD-PV asymmetry: example with ^{137}BaF

Typical numbers for ^{137}BaF:

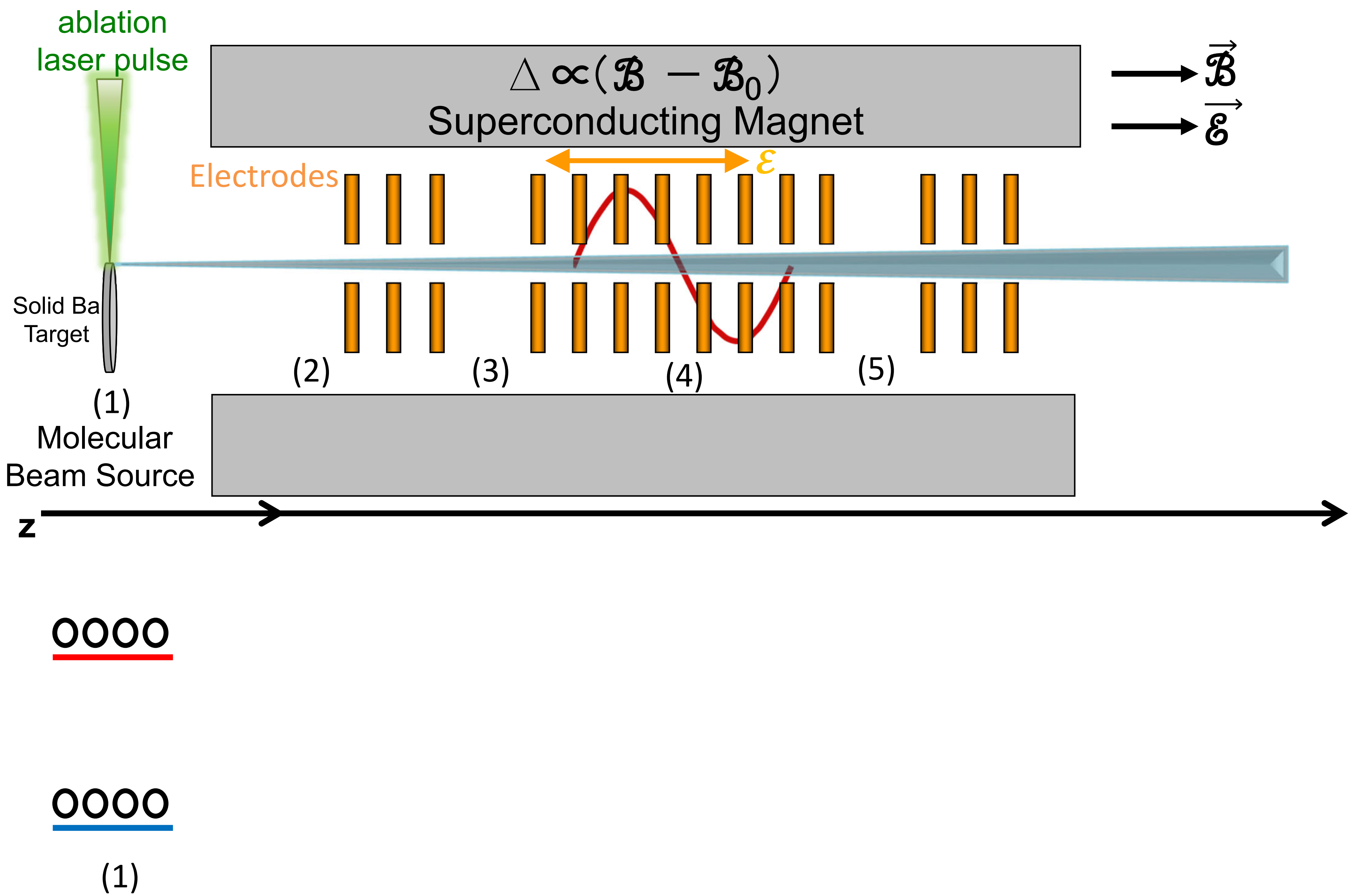
$$\Delta_0 \sim 1/T \sim 2\pi \times 1\ \text{kHz}$$
$$\omega = 2\pi \times 100\ \text{kHz}$$
$$dE_0/\omega = 0.1$$
$$W = 2\pi \times 5\ \text{Hz}$$

PV Invariant

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



ZOMBIES experimental schematic



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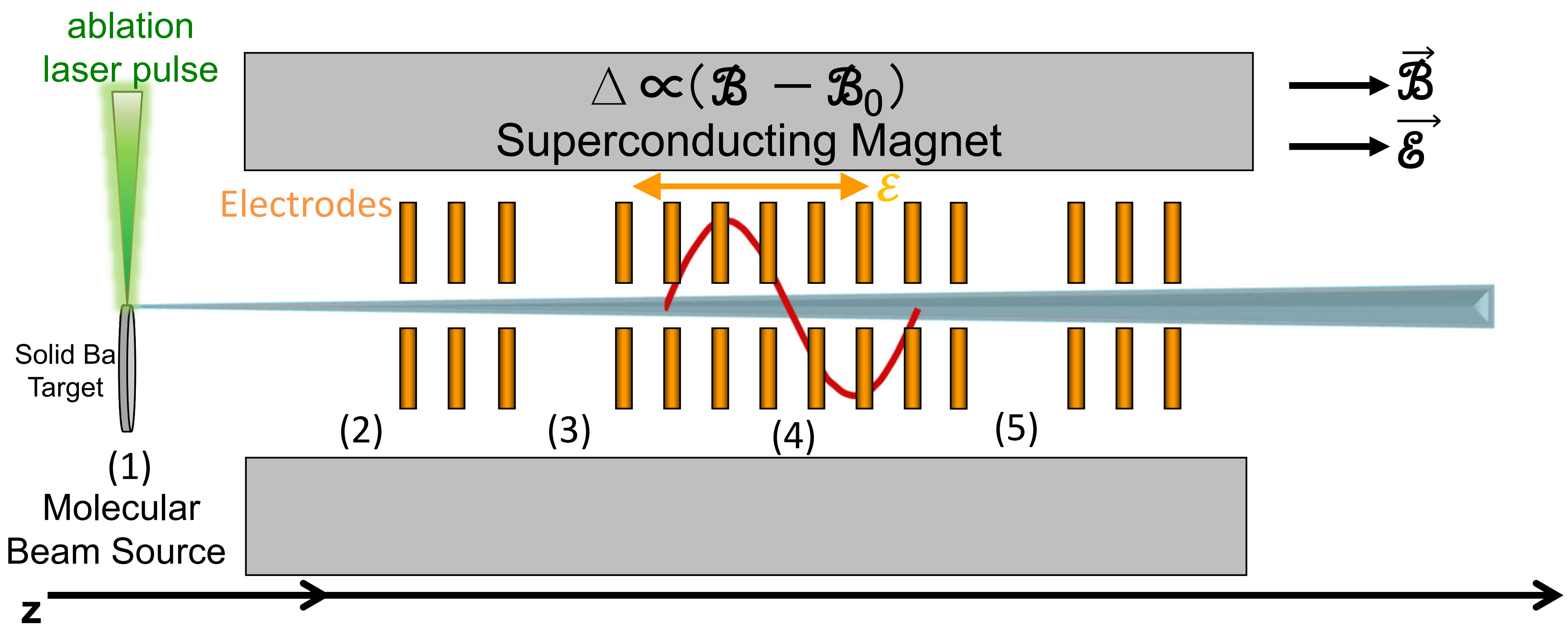

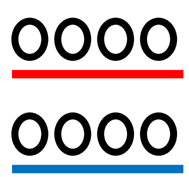

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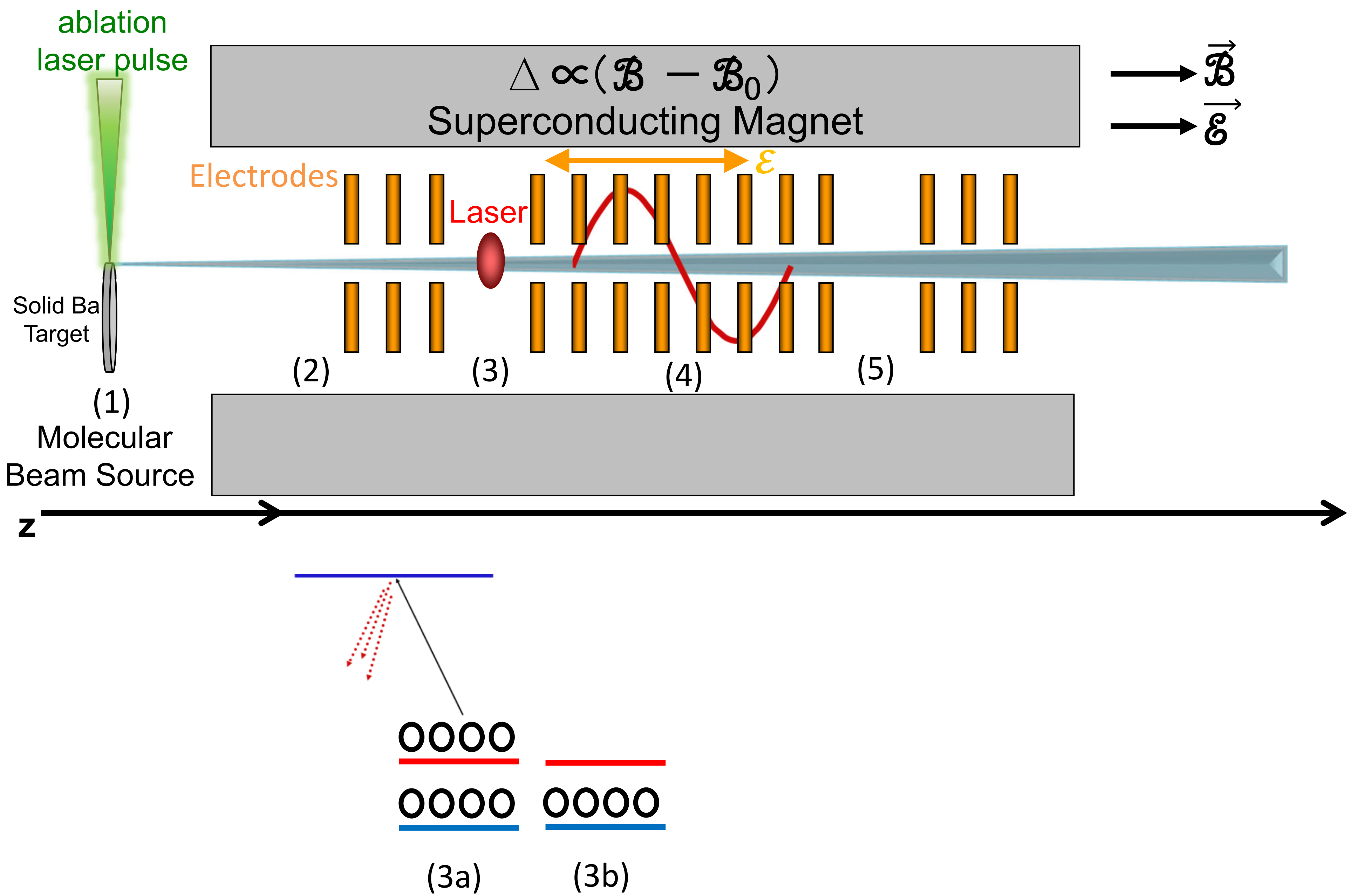
ZOMBIES experimental schematic



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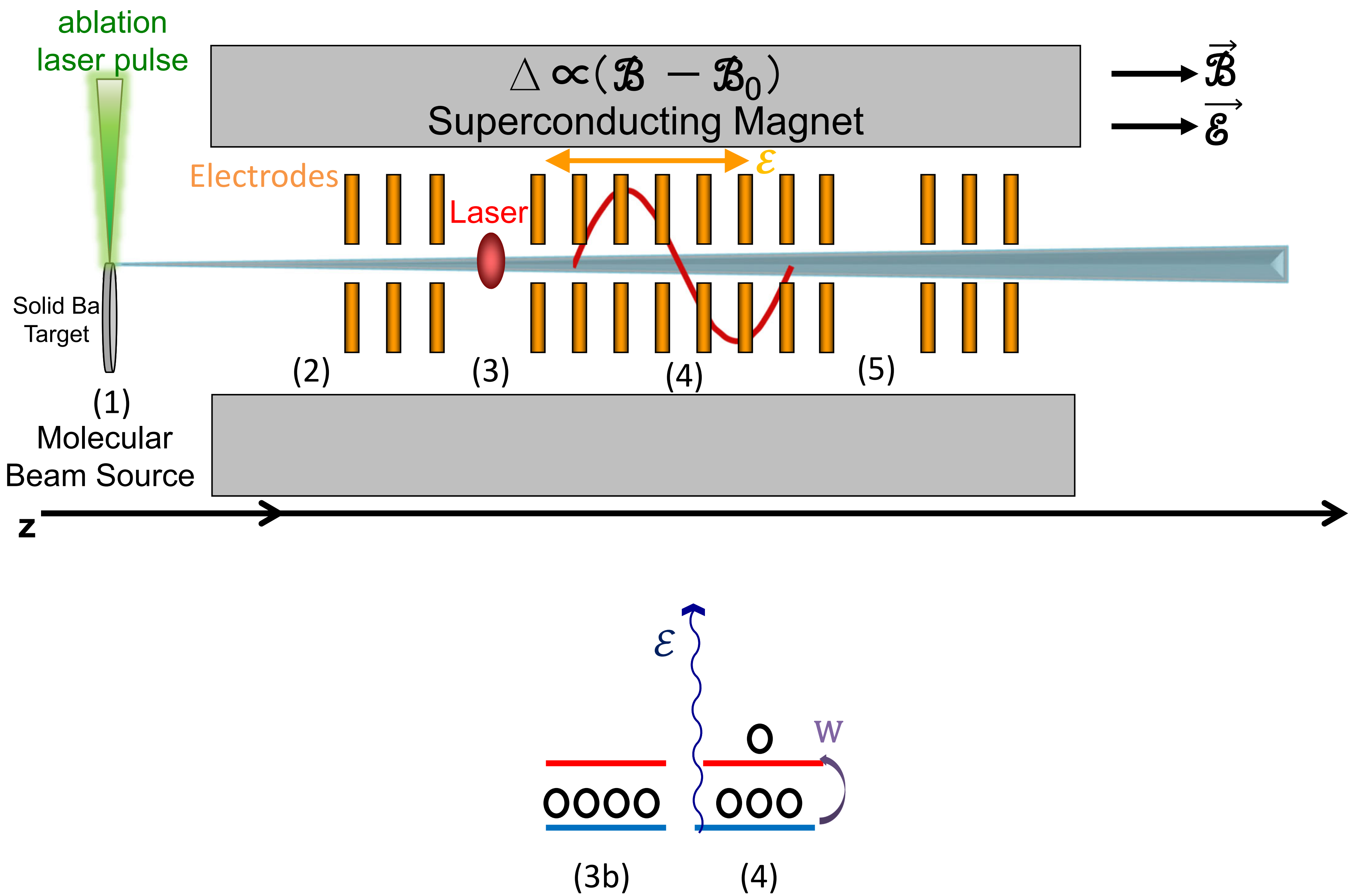

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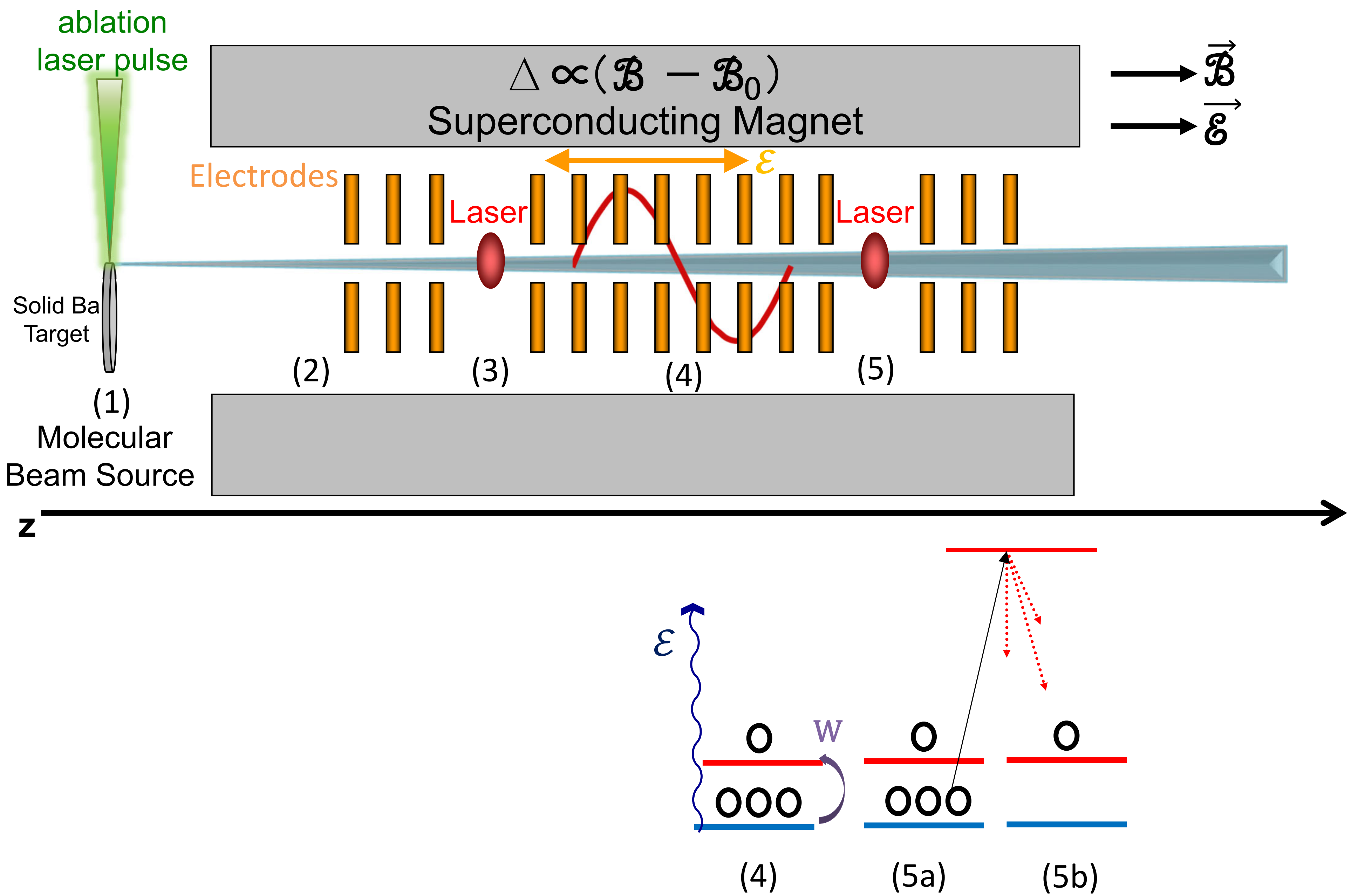

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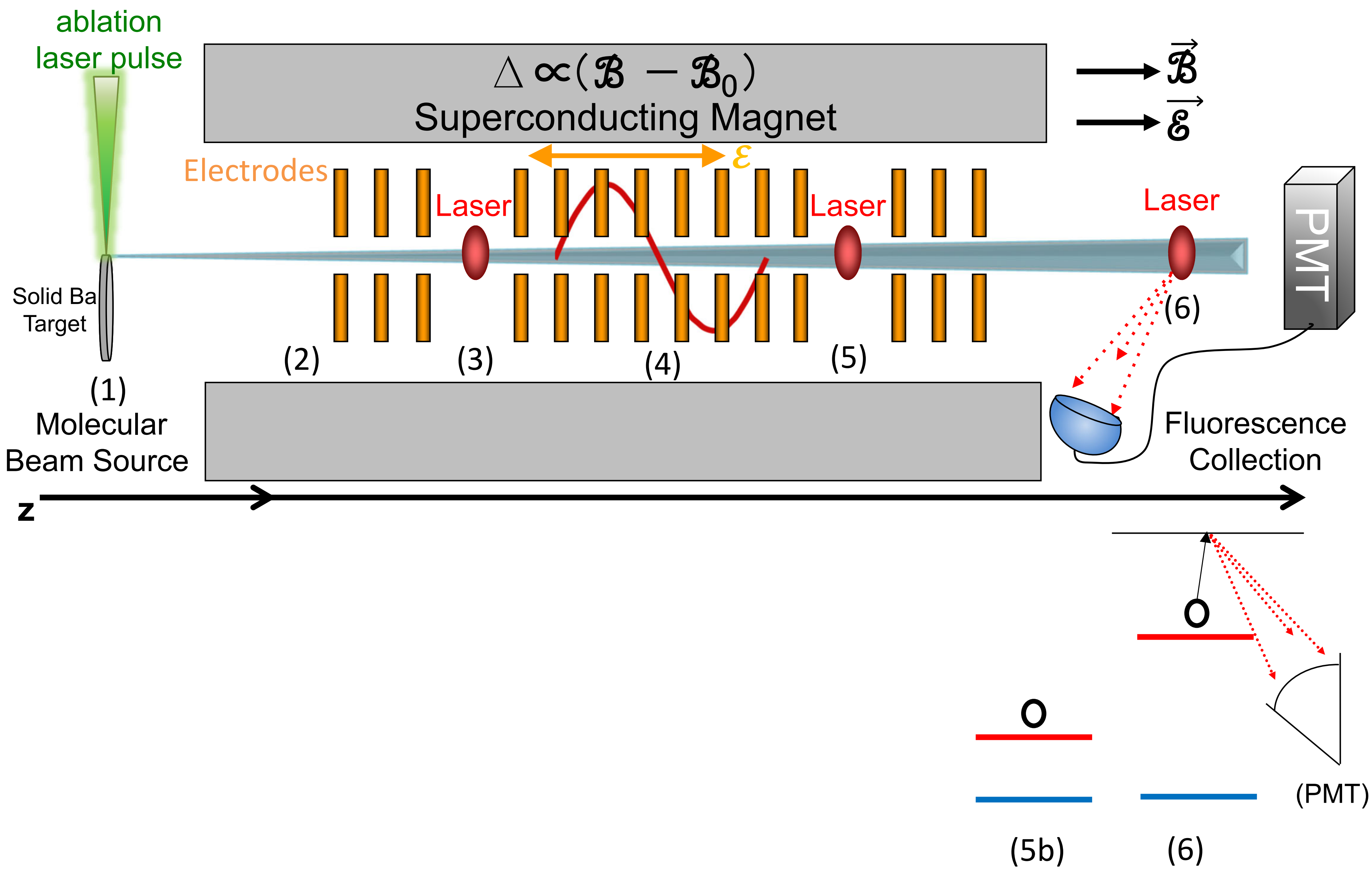
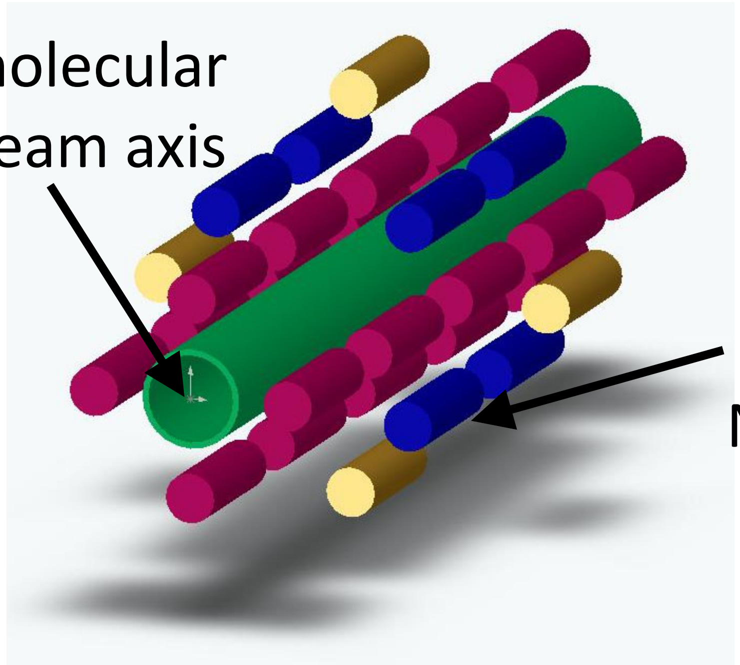


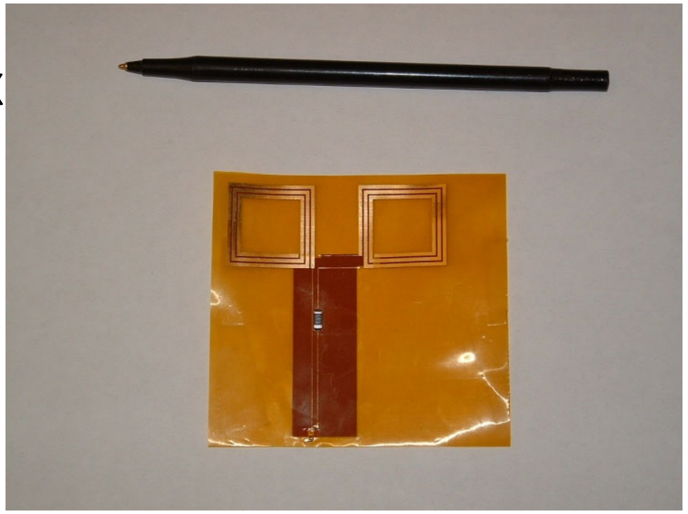
Magnetic field measurement (1st layer)



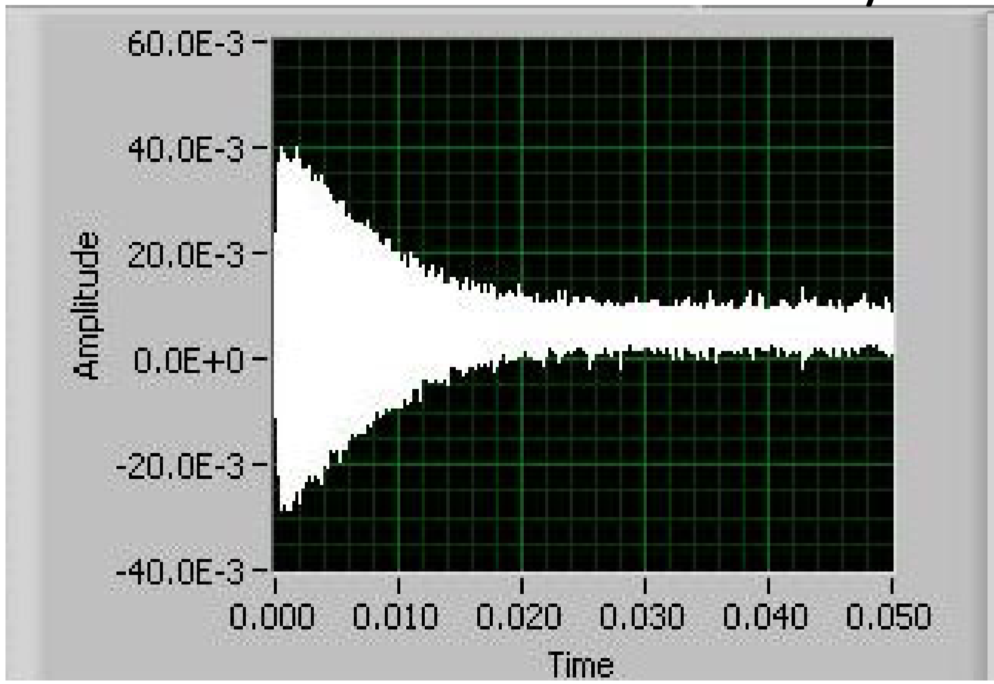
molecular beam axis

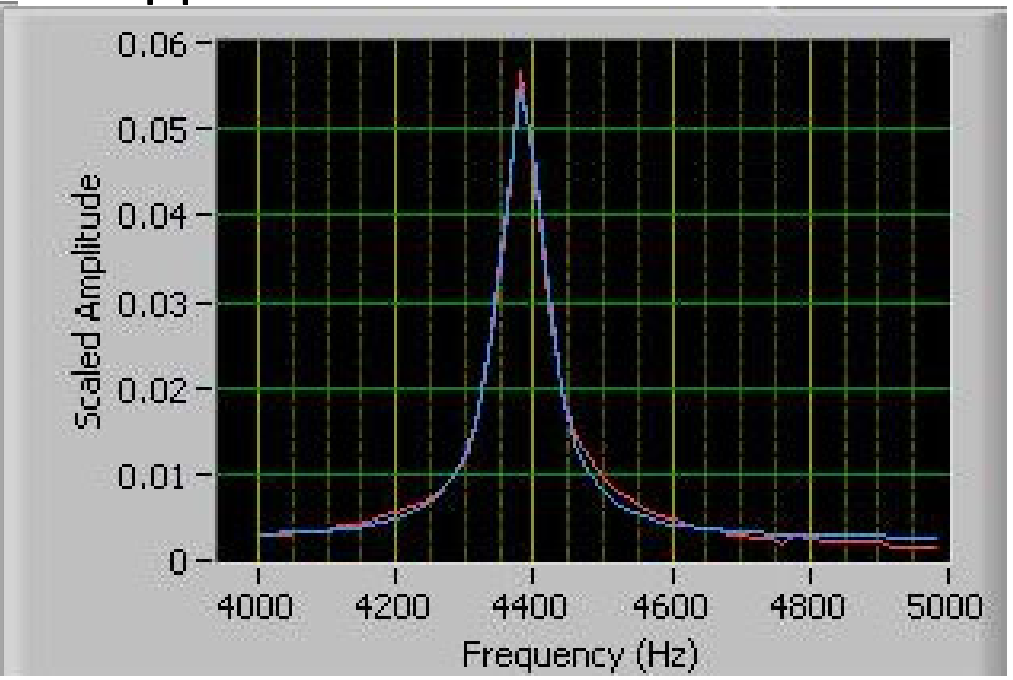
array of 32 NMR B-field probes

broadband probe on flex circuit

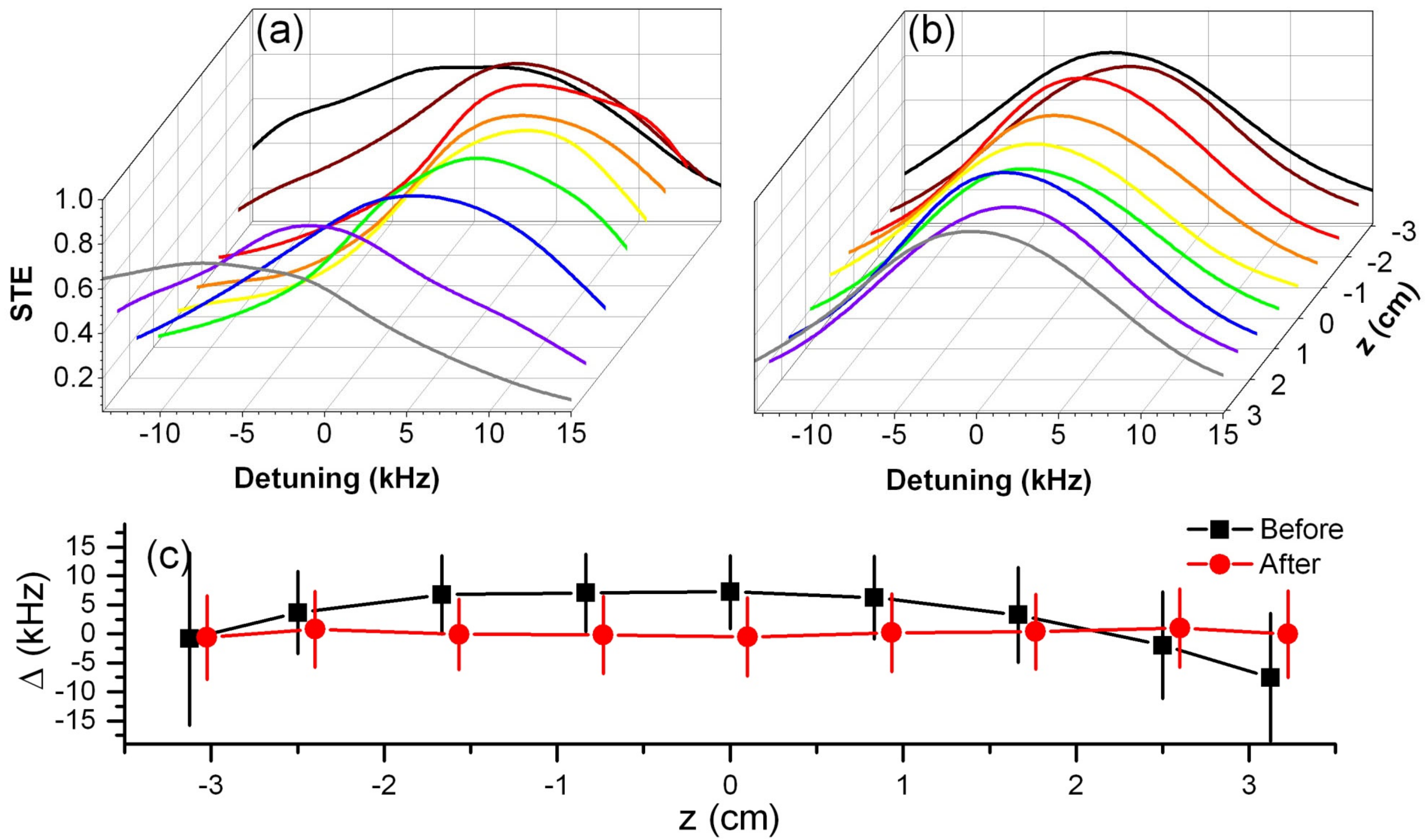


FID trace + FFT fit: $\delta B/B$ = 0.01 ppm in one 60 ms shot





Magnetic field control (2nd layer): results with 52 shim coils

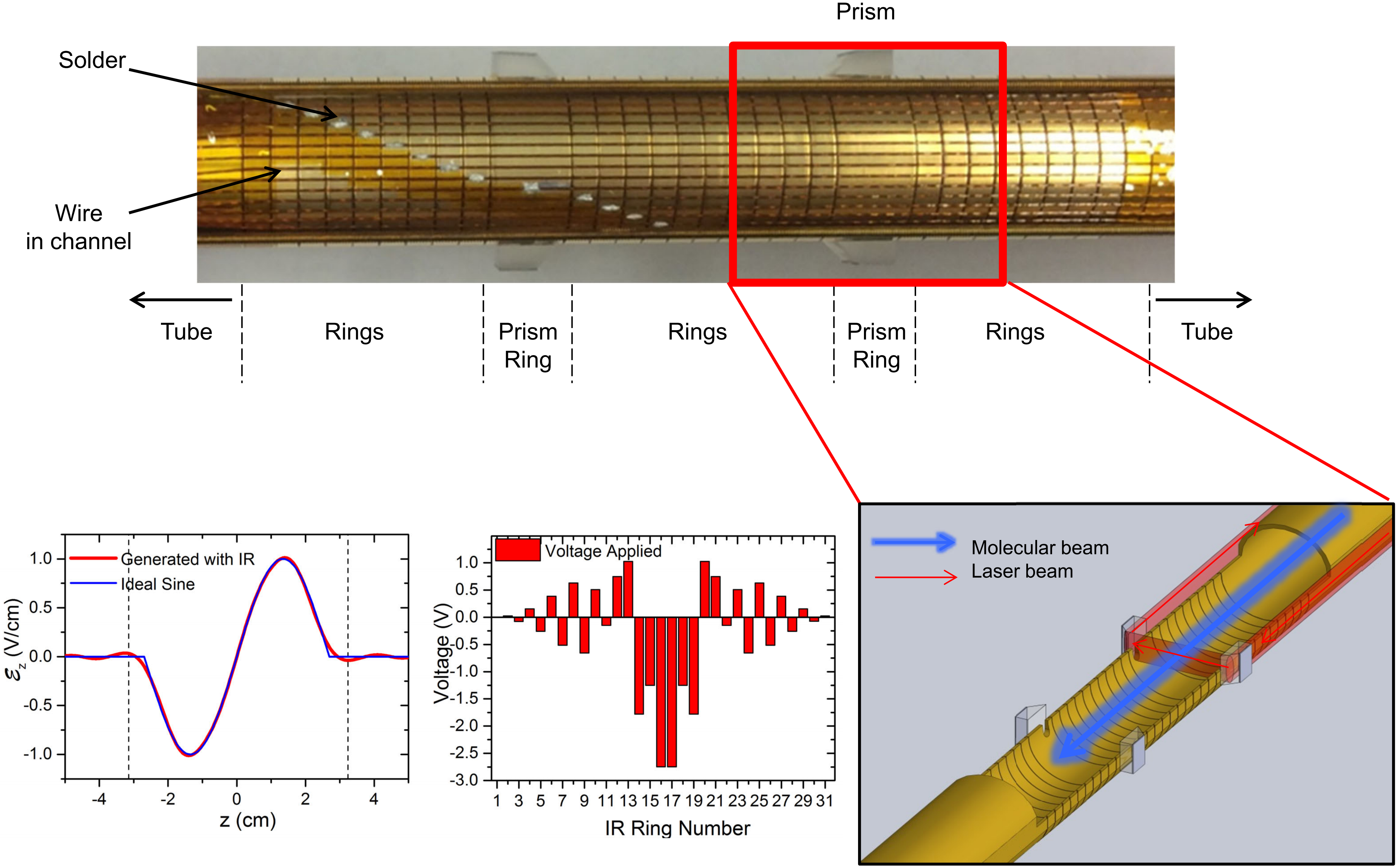


Using molecules for final measurement & shimming:

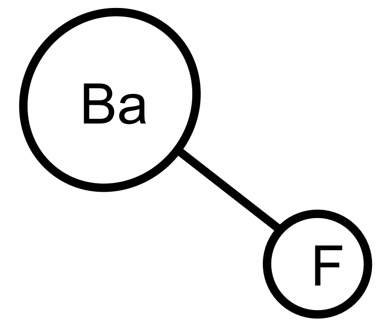
r.m.s. variation $\delta B/B < 20$ ppb [6 cm L. x 1 cm D. cylinder]

$\mathcal{E}$-field control

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



ZOMBIES I: NSD-PV with BaF



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

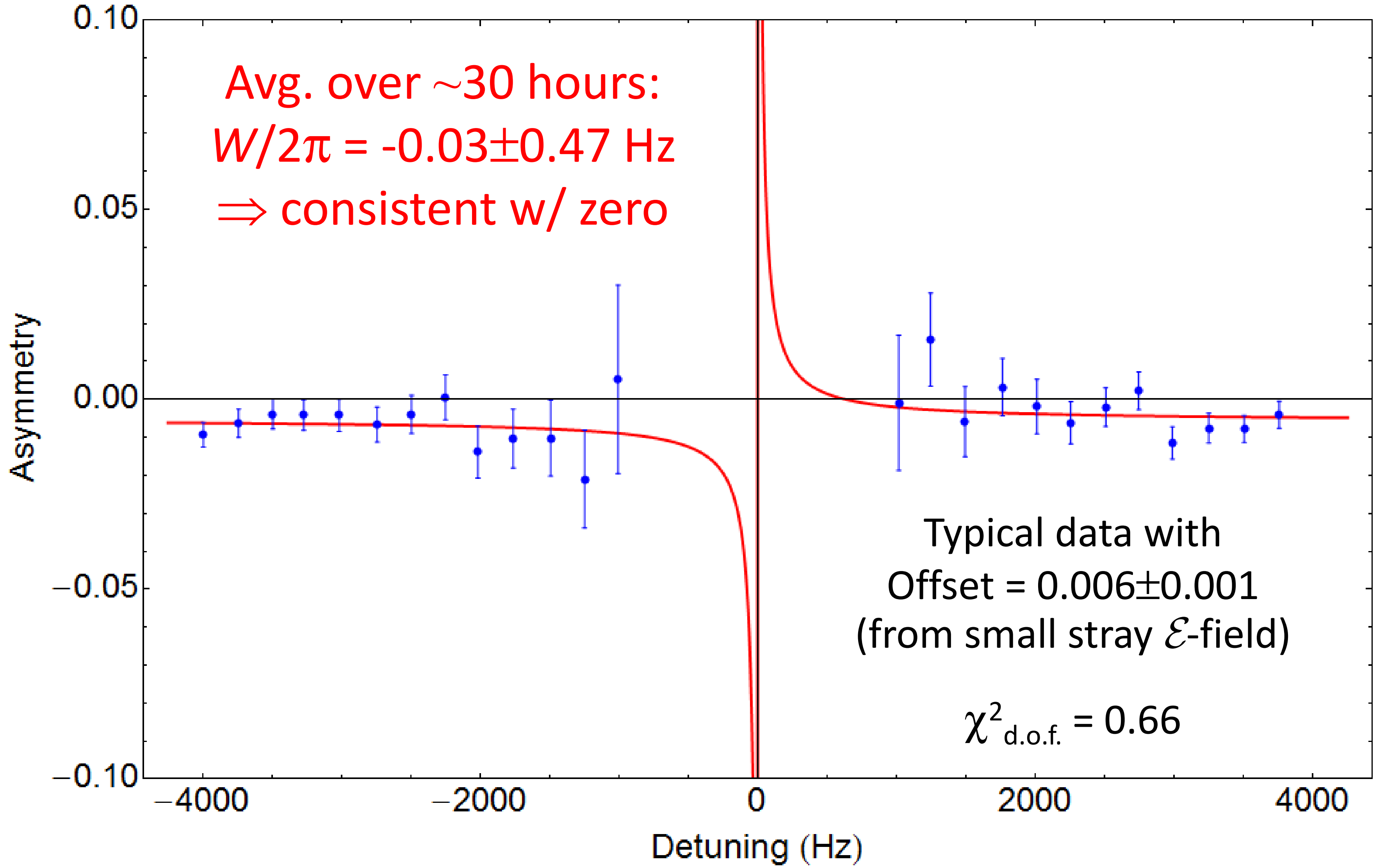
- Odd neutron (vs. ^{133}Cs w/odd proton)
- Heavy → large effect, anapole term dominates
- Large enough natural abundance 11%
- Required lasers = simple, cheap diodes

Completed: proof of principle using ^{138}Ba^{19}F

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

Typical asymmetry data from proof of principle run with $^{138}Ba^{19}F$

Null signal expected for ^{19}F nucleus



Uncertainties in proof-of-principle with ^{138}BaF

Strategy

- Deliberately exaggerate possible imperfections 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 δW_{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

Uncertainties in proof-of-principle with ^{138}BaF

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- Measure effect on extracted NSD-PV matrix element *W* from coupling to ambient imperfections in the experiment

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Total Systematic	-0.04	0.38

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

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

~170 h data
~6x10^7 molecules total

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

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

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

Most useful comparison:

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

E. Altuntas, J. Ammon, S.B. Cahn, DD PRL **120**, 142501 (2018); PRA **97**, 042101 (2018)

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Same experimental uncertainty in ^{137}BaF would mean

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

~10% of predicted value

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

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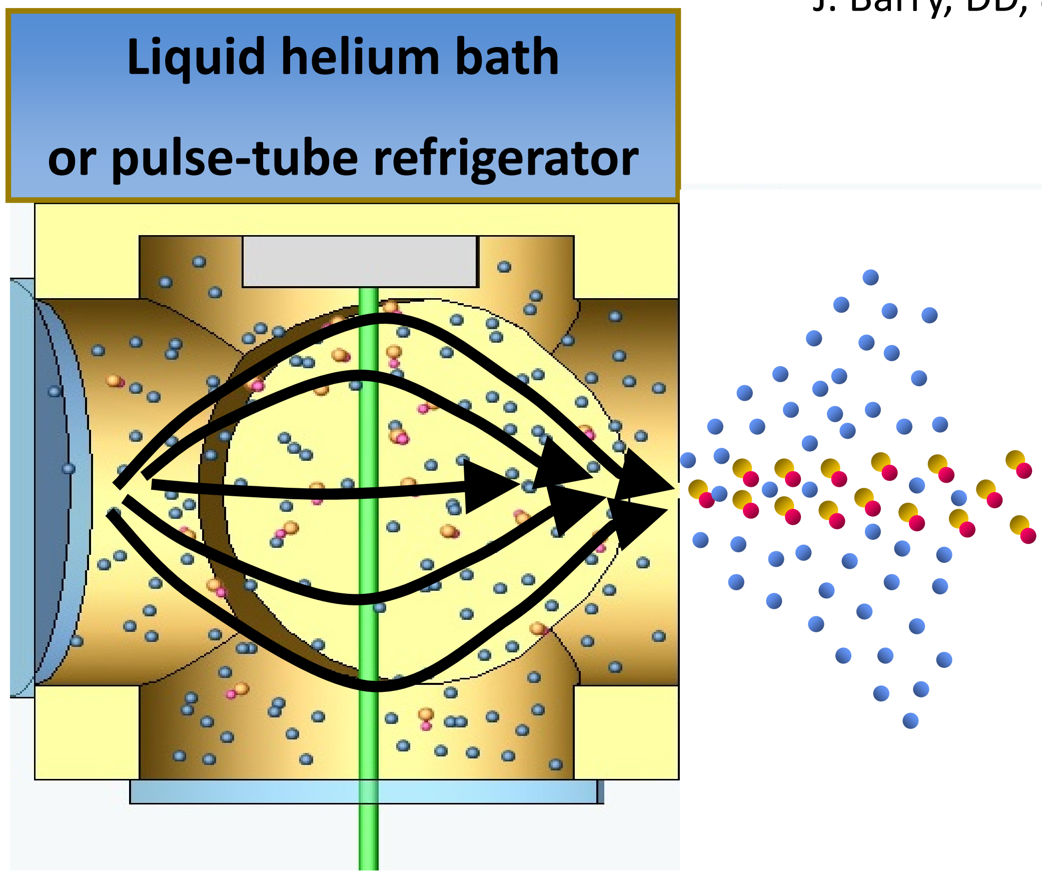
C.S. Wood *et al.*, Science **275**, 1759 (1997)

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

E. Altuntas, J. Ammon, S.B. Cahn, DD PRL **120**, 142501 (2018); PRA **97**, 042101 (2018)

Newly added: Cryogenic Buffer Gas-cooled Beam (CBGB)

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

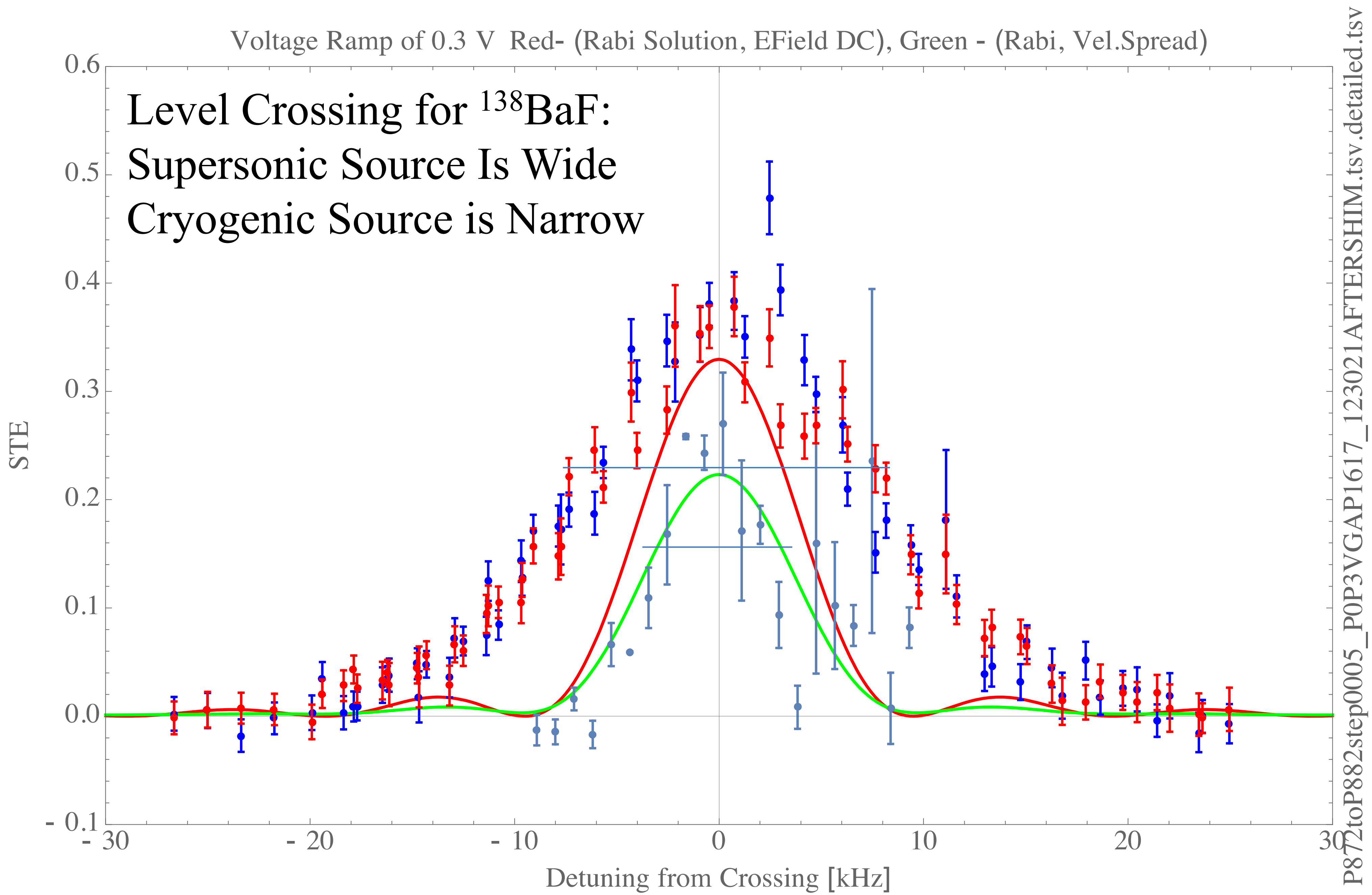


- Inject hot molecules (e.g. via laser ablation)
- Cool w/cryogenic buffer gas @ high density
- Efficient extraction to beam
  via "wind" in cell: $10^{-4} \rightarrow$ 10%-40%
- "Self-collimated" by extraction dynamics
- Rotational cooling in expansion: T $\sim$ 1-4 K
- Moderately slow: $v \sim$ 200 m/s

Low velocity → interaction time ~ ***3×*** larger;
Beam brightness ~ ***2×*** larger flux observed SO FAR (but expected 10-100x....?)
Will enable magnetic focusing ⇒ ~ ***10×*** flux

Gain in NSD-PV statistical sensitivity: 5x now, >30× anticipated

Demonstrated: Better Energy Resolution with CBGB



ZOMBIES: general-purpose technique, applicable to many isotopes

PRL **100,** 023003 (2008) PHYSICAL REVIEW LETTERS week ending 18 JANUARY 2008

Using Molecules to Measure Nuclear Spin-Dependent Parity Violation

D. DeMille,[1] S. B. Cahn,[1] D. Murphree,[1] D. A. Rahmlow,[1] and M. G. Kozlov[2]

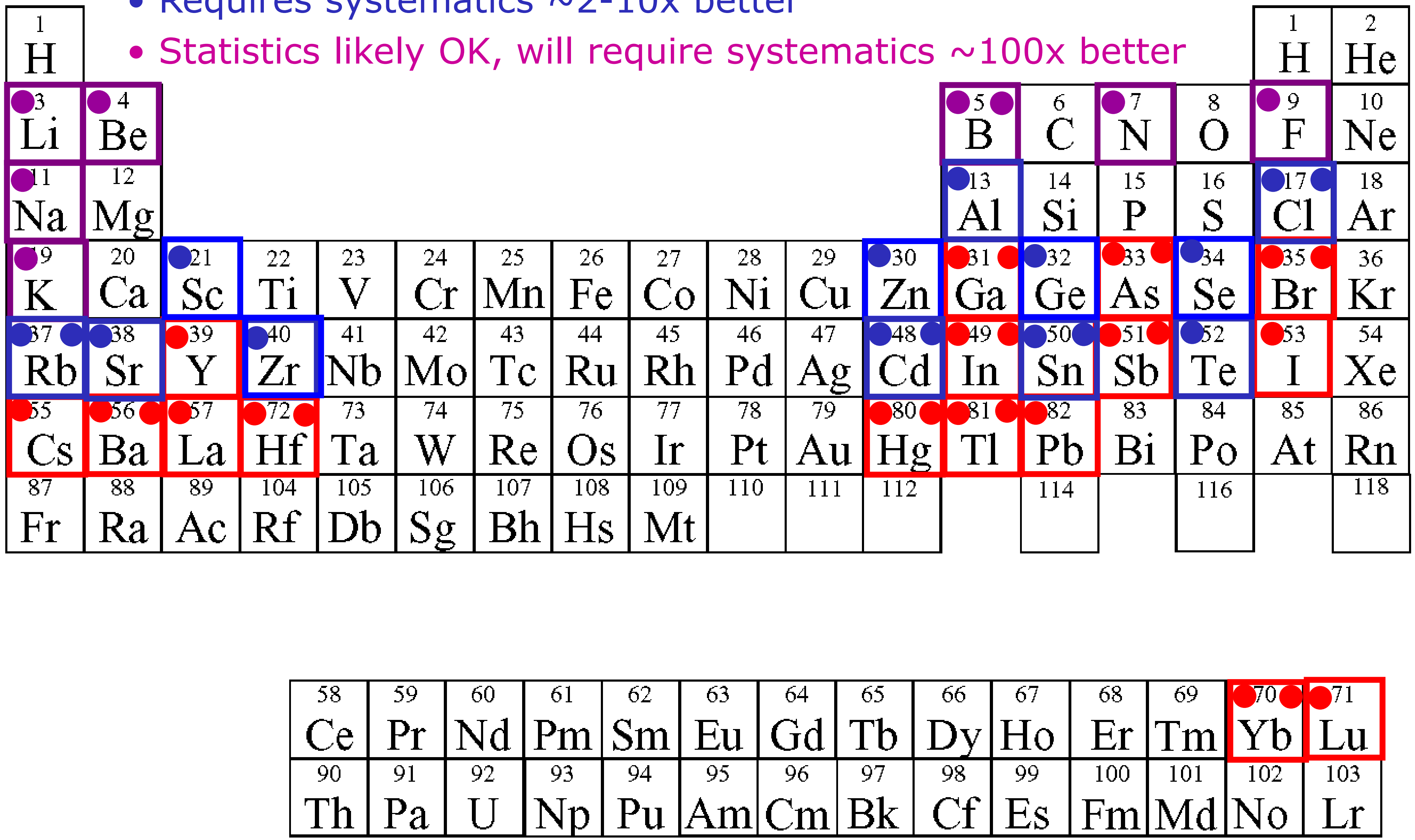
Nucleus	I	ν	ℓ	n.a. (%)	$100\kappa'_a$	$100\kappa'_2$	Species	B_e (MHz)	$\mathcal{B}_0^{(m)}$ (T)	W_P (Hz)	$\tilde{C}^{(m)}$	$W^{(m)}$ (Hz)
$^{87}Sr_{38}$	9/2	N	4	7.0	−3.6	−5.0	SrF	7515	0.62	65	−0.40	2.2
$^{91}Zr_{40}$	5/2	N	2	11.2	−3.5	−5.0	ZrN	14468	1.20	99	−0.40	3.4
$^{137}Ba_{56}$	3/2	N	2	11.2	+4.2	+3.0	BaF	6480	0.32	164	−0.44	−5.2
$^{171}Yb_{70}$	1/2	N	1	14.3	+4.1	+1.7	YbF	7246	0.33	729	−0.52	−22
$^{27}Al_{13}$	5/2	P	2	100	−11.2	+5.0	AlS	8369	0.52	10	−0.42	0.3
$^{69}Ga_{31}$	3/2	P	1	60.1	−19.6	+5.0	GaO	8217	0.49	61	−0.43	3.8
$^{81}Br_{35}$	3/2	P	1	49.3	−21.8	+5.0	MgBr	4944	0.34	18	−0.42	1.3
$^{139}La_{57}$	7/2	P	4	99.9	+34.7	−3.9	LaO	10578	0.25	222	−0.43	−29

Improved understanding of molecular structure since 2008

→ even more viable molecule species to study many different nuclei

Viable nuclei for anapole/NSD-PV measurement with ZOMBIES

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



Beyond ZOMBIES: next-gen NSD-PV measurements with light nuclei

PRL **100,** 023003 (2008) PHYSICAL REVIEW LETTERS week ending 18 JANUARY 2008

Using Molecules to Measure Nuclear Spin-Dependent Parity Violation

D. DeMille,[1] S. B. Cahn,[1] D. Murphree,[1] D. A. Rahmlow,[1] and M. G. Kozlov[2]

F at lower v [31]. Alternatively, it might be possible to increase T using trapped molecular ions [32]. Such improvements, plus more spectral data for similar molecular species, could widen the list of accessible nuclei. For light molecules and nuclei, *ab initio* electronic and nuclear structure calculations may be possible at accuracies better than those envisioned here. Ultimately, the method might extend to direct measurement of κ' for ^{1}H and ^{2}H. For

See Ronald Garcia-Ruiz plenary talk this morning

Towards measurements of symmetry-violating nuclear properties using single molecular ions in a Penning trap
J Karthein, D DeMille, J Dilling, R Garcia Ruiz, N Hutzler, P Mohapatra, Scott Moroch, Ryan Ringle, Silviu-Marian Udrescu
Bulletin of the American Physical Society 66 2021

- MUCH longer interaction time, MUCH smaller experimental volume, very advanced techniques w/single ions in Penning traps

→ MUCH better sensitivity (sufficient for p,d…?)
AND
ability to probe short-lived radioactive isotopes

First glimmers: reliable HPV→NSD-PV calculations in nuclei?

PHYSICAL REVIEW A **102**, 052828 (2020)

Editors' Suggestion

Nuclear spin-dependent parity-violating effects in light polyatomic molecules

Yongliang Hao,[1] Petr Navrátil,[2] Eric B. Norrgard,[3] Miroslav Iliaš,[4] Ephraim Eliav,[5] Rob G. E. Timmermans,[1] Victor V. Flambaum,[6] and Anastasia Borschevsky[1,*]

III. NO-CORE SHELL-MODEL NUCLEAR CALCULATIONS

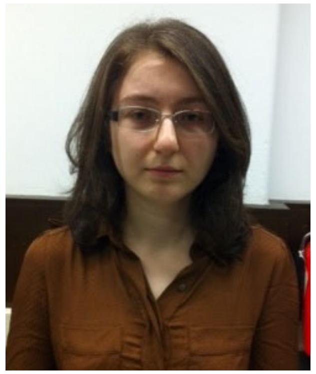
	^{9}Be	^{13}C	^{14}N	^{15}N	^{25}Mg
I^π	$3/2^-$	$1/2^-$	1^+	$1/2^-$	$5/2^+$
$\mu^{\text{exp.}}$	−1.177[a]	0.702[b]	0.404[c]	−0.283[d]	−0.855[e]
			NCSM calculations		
μ	−1.05	0.44	0.37	−0.25	−0.50
κ_A	0.016	−0.028	0.036	0.088	0.035
$\langle s_{p,z}\rangle$	0.009	−0.049	−0.183	−0.148	0.06
$\langle s_{n,z}\rangle$	0.360	−0.141	−0.1815	0.004	0.30
κ_{ax}	0.035	−0.009	0.0002	0.015	0.024
κ	0.050	−0.037	0.037	0.103	0.057

- First No-Core Shell Model calculations of anapole moments and V_eA_N effects
- Significant differences from single-particle SM estimates
- Magnetic moment as benchmark

present calculations, we can be optimistic that uncertainties of nuclear calculations for light nuclei can be reduced to ∼10% once the above improvements are implemented. The NCSM

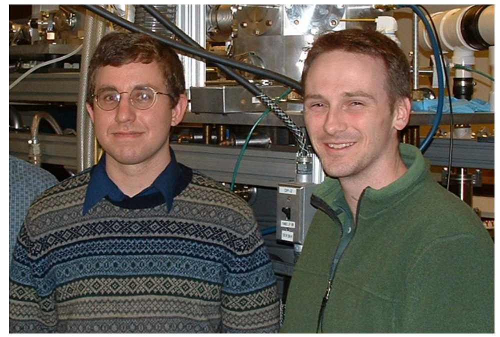
ZOMBIES Past & Present

Emine Altuntas



Jeffrey Ammon

David Rahmlow,
Dennis Murphree

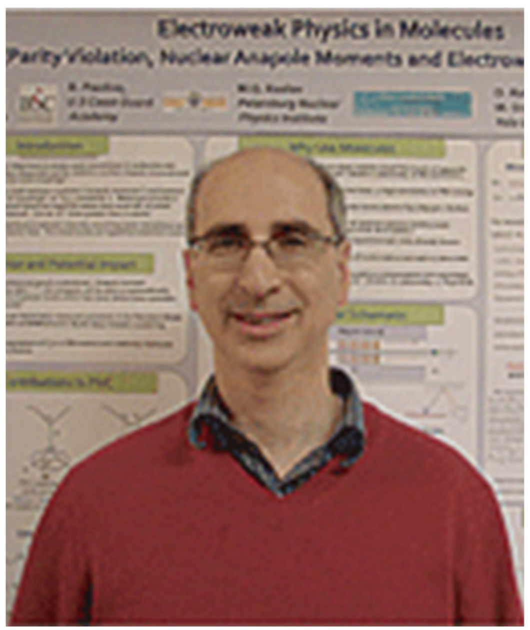


Dr. Yulia
Gurevich

Dr. Emil
Kirilov

Dr. Max
Beyer

Sidney Cahn
(Yale)



Sidney Cahn
(Yale)

Dr. Mangesh
Bhattarai

Tanvi Deshmukh

ZOMBIES: Summary & Outlook

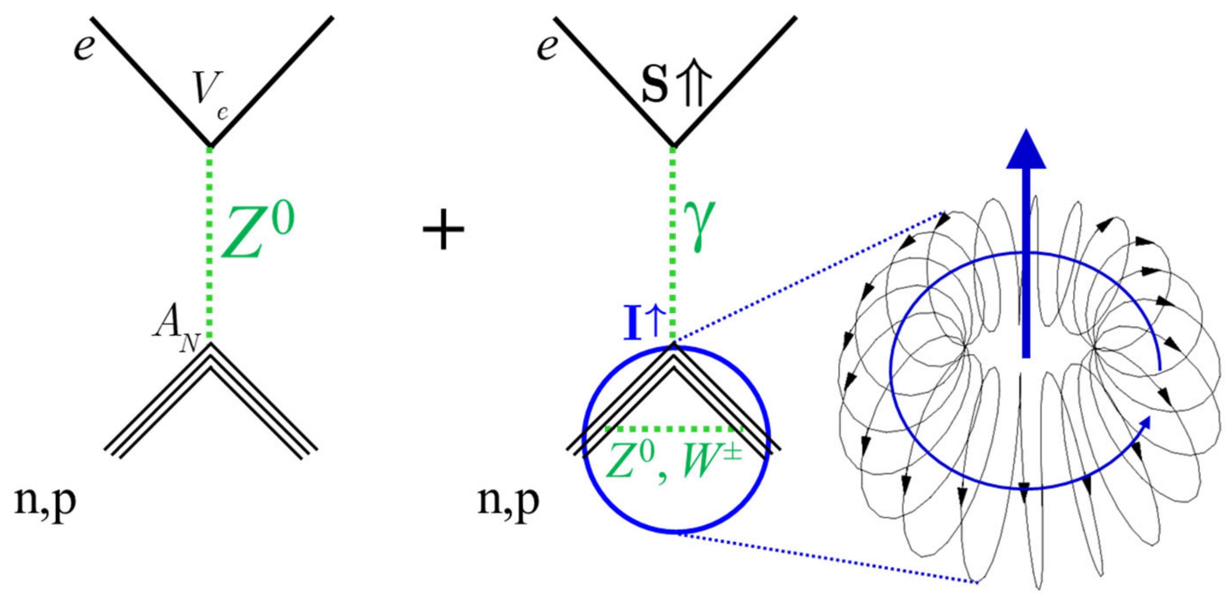
--**New era in NSD-PV:** anapole + $V_e A_N$ measurements beginning

--Sensitivity & accuracy of molecular systems likely to
enable measurements on many nuclei, including lighter isotopes, with <10% uncertainty

--Complementary to other hadronic PV experiments & SoLID/PVDIS @ JLab

--NSD-PV poised to open new window to
unified understanding of hadronic PV & semileptonic neutral-current PV,
in strongly-interacting environment, across wide range of scales

Argonne NATIONAL LABORATORY

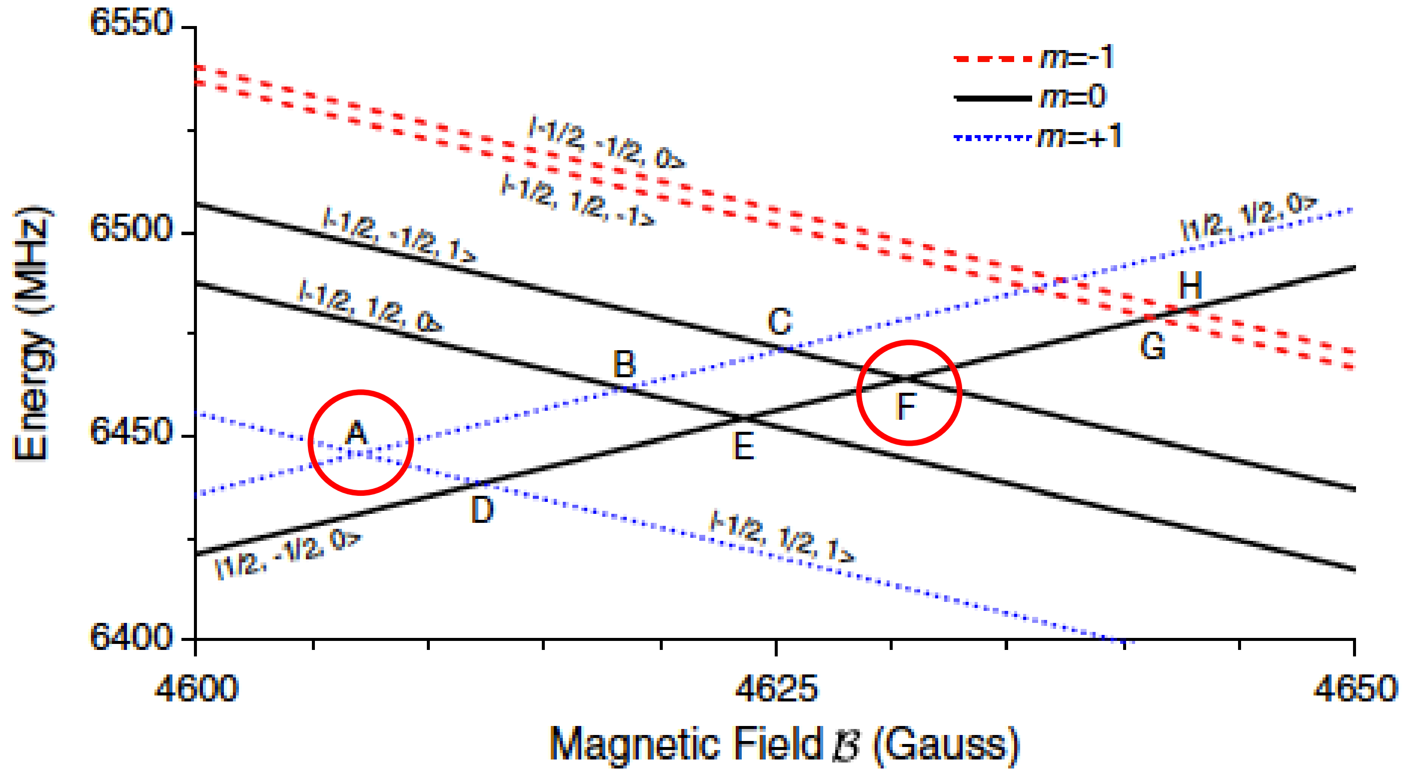


THE UNIVERSITY OF CHICAGO 1890

Extra Slides

ZOMBIES Re-assembly Underway at Argonne!

Different level crossings to suppress systematics



$|m_S, m_I, m_N>$

S: electron spin

I: nuclear spin

N: rotation

n: molecular axis

$$W \equiv \langle + \uparrow | H_{PV} | - \downarrow \rangle$$

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

Measured quantity, different for each crossing

Molecular wavefunctions: same at all crossings, **accurately computed**

NSD-PV parameters: same at all crossings

Angular factor:

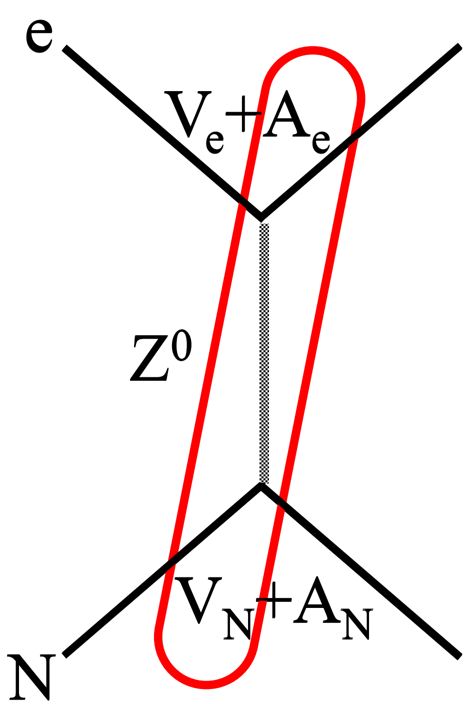
- Different for each crossing (sign & magnitude)
- Analytically calculable

Ongoing or proposed anapole-sensitive experiments with atoms

- Mainz: ^{171}Yb, ^{173}Yb atoms (similar to JILA Cs experiment)
- FrPNC @ TRIUMF: ^{xxx}Fr atoms (laser cooled & trapped)
- Mainz: new ideas using NMR signals for light nuclei….?
- Mainz + ANL: use CeNTREX apparatus in different mode (AC $\mathcal{E}$-field)…?

Mechanisms for atomic/molecular parity violation

Axial electron-vector nucleon interaction



Coherent coupling
to all nuclei =
"weak charge"
$Q_W = -N + (1-4\sin^2\theta_W)Z$

A_eV_N interaction →
atomic Hamiltonian

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

axial vector
associated with electron

short-range
Yukawa potential

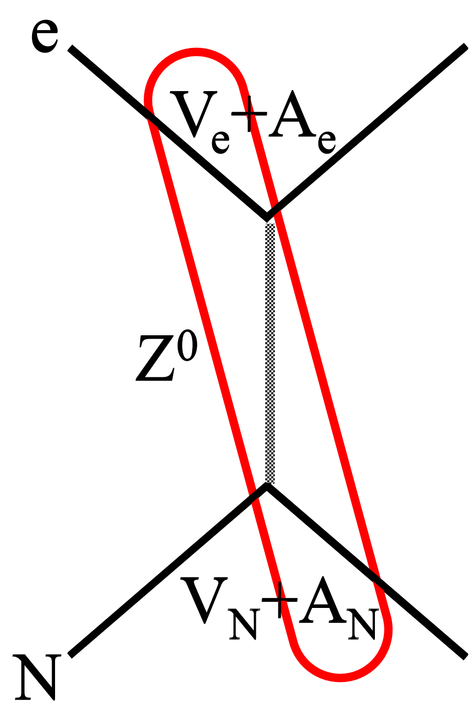
Q_W measured to 0.4%
[C. Wieman group, 1997]

& 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 electron-axial nucleon interaction



Coupling ONLY
to unpaired nucleon
coupling constant C_2

V_eA_N interaction → 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)

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_ρ^1	h_ρ^2	h_ω^0	h_ω^1
$A_L^{pp}(13.6)$	-0.93 ± 0.21		0.043	0.043	0.017	0.009	0.039
$A_L^{pp}(45)$	-1.57 ± 0.23		0.079	0.079	0.032	0.018	0.073
$A_L^{pp}(221)$	0.84 ± 0.34		−0.030	−0.030	−0.012	0.021	
$A_L^{p\alpha}(46)$	-3.34 ± 0.93	−0.340	0.140	0.006		−0.039	−0.002
$P_\gamma(^{18}\mathrm{F})$	1200 ± 3860	4385		34			−44
$A_\gamma(^{19}\mathrm{F})$	-740 ± 190	−94.2	34.1	−1.1		−4.5	−0.1
$\langle \|\|A_1\|\| \rangle / e$, Cs	800 ± 140	60.7	−15.8	3.4	0.4	1.0	6.1
$\langle \|\|A_1\|\| \rangle / e$, Tl	370 ± 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

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

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

- ~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

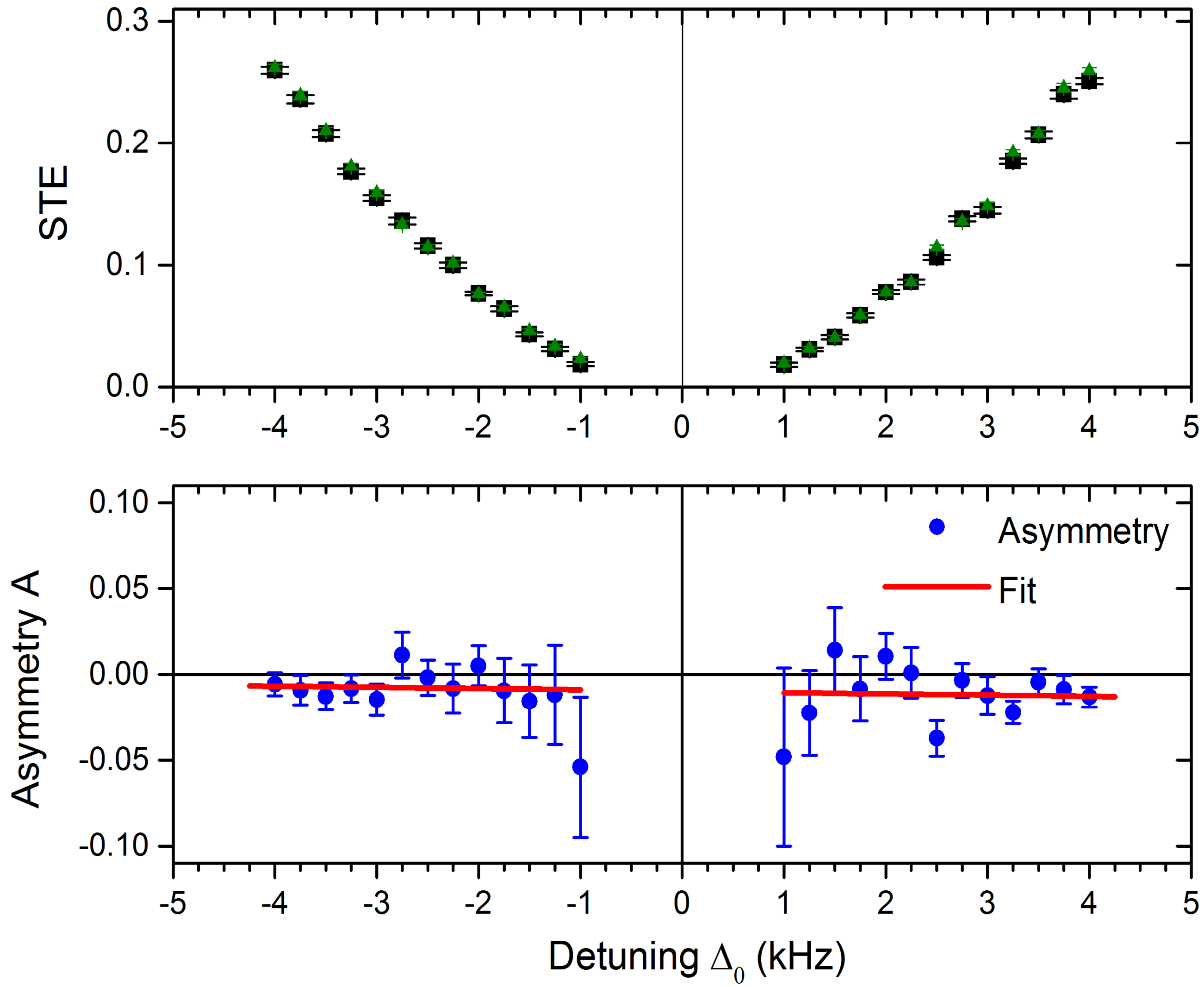
$$\kappa'_a \approx \frac{9}{10}\frac{\alpha\mu}{mr_0}A^{2/3}g_{eff} \approx .05\, g_{eff}\left(\frac{A}{50}\right)^{2/3}$$

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

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



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

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

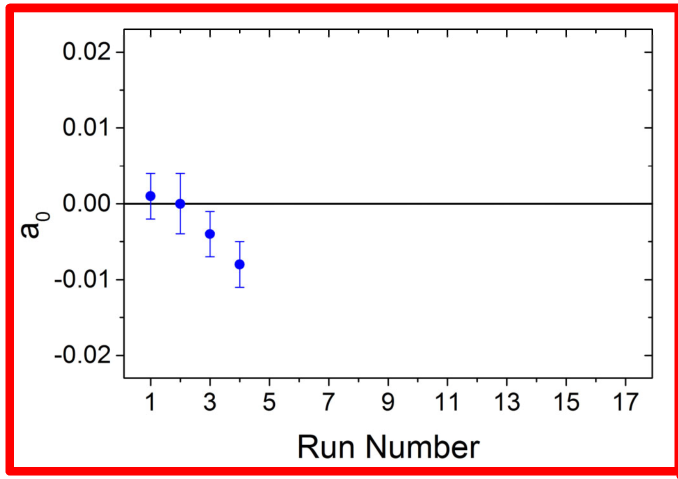
Fit to function

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

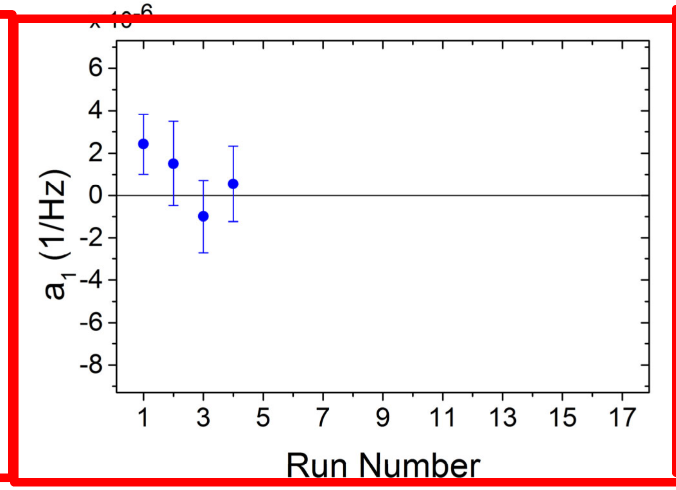
NSD-PV data with $^{138}Ba^{19}F$

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

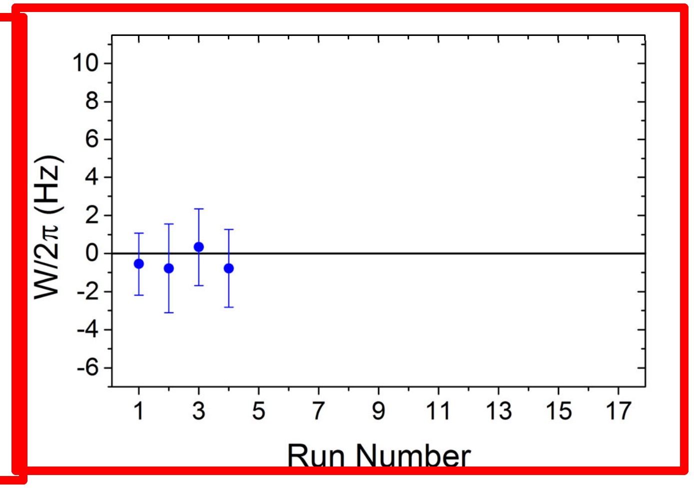
from stray $\mathcal{E}$-fields alone

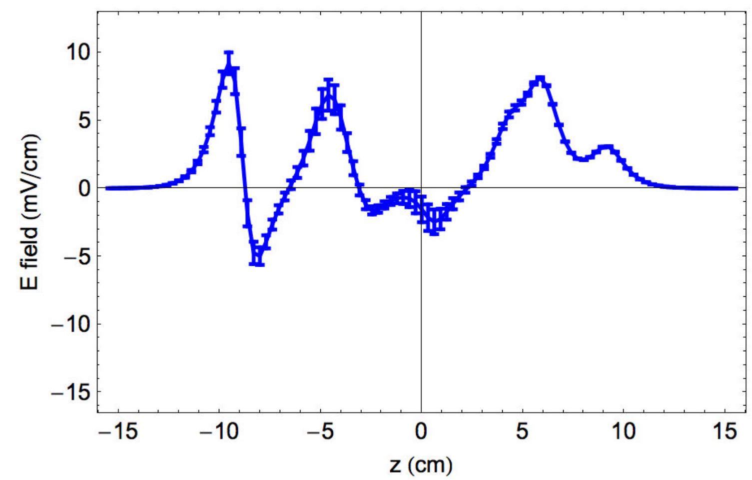


From combined stray $\mathcal{E}$-fields & $\mathcal{B}$-field gradients



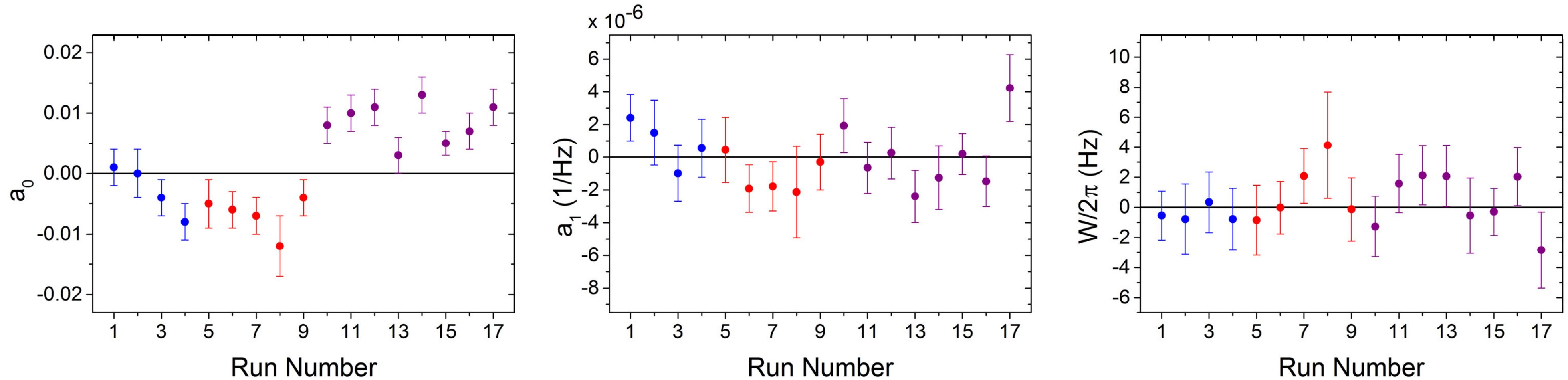
NSD-PV

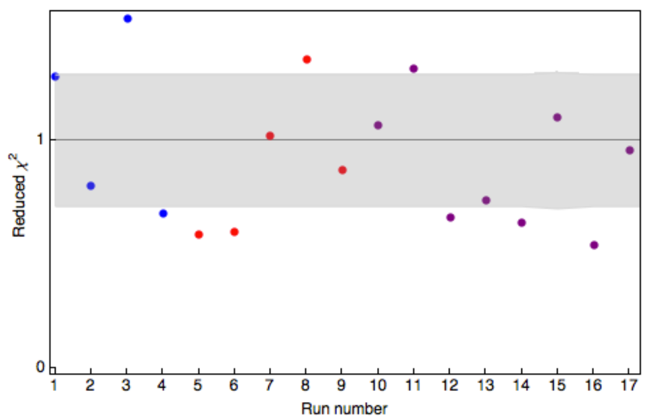




- stray $\mathcal{E}$-fields always below 15mV/cm

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

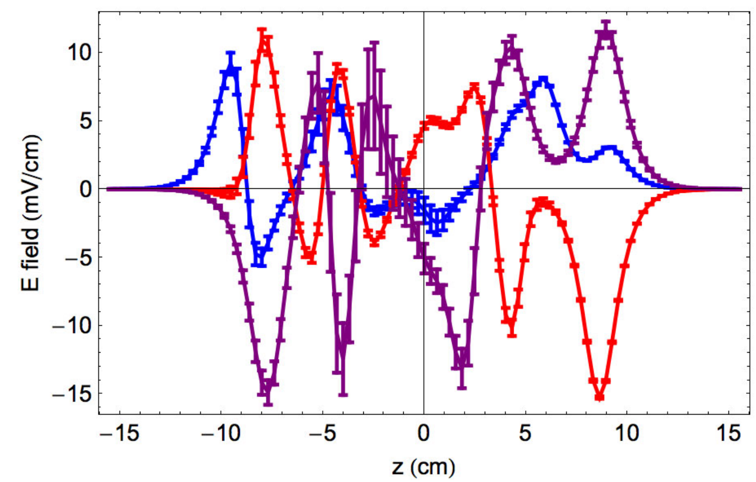




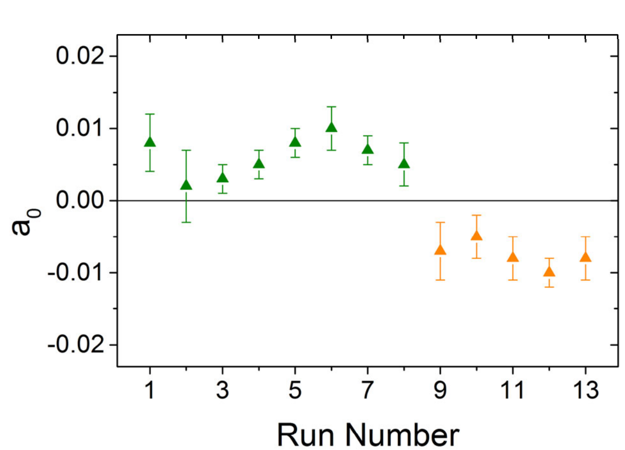
Weighted average $\rightarrow \dfrac{W}{2\pi} = 0.32 \pm 0.49_{\text{stat}}$ Hz

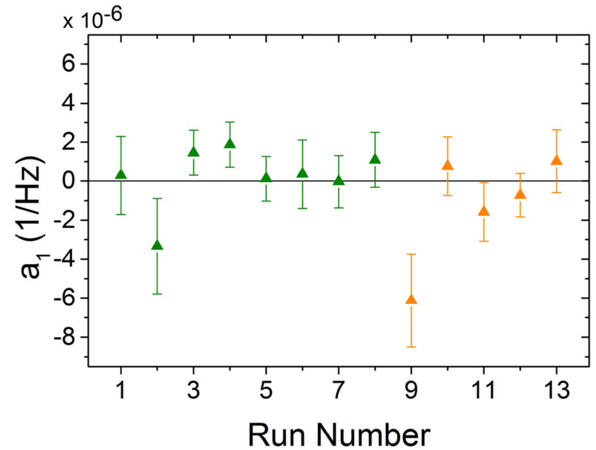
$$a_1 = \left(-1.27 \pm 4.02_{\text{stat}}\right) * 10^{-7} \; 1/\text{Hz}$$

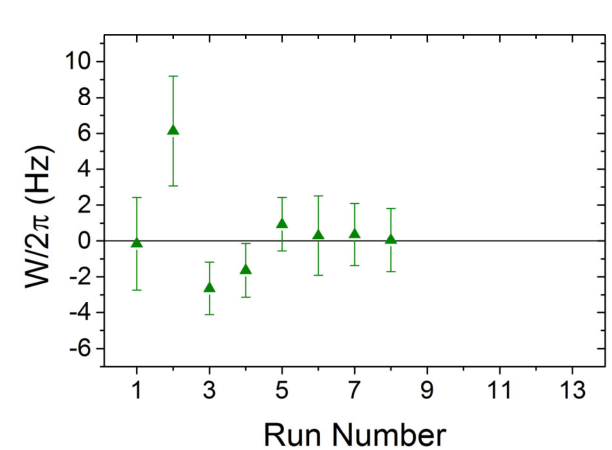
- ^{138}BaF expected $W = 0$
- Measured with 3 different stray $\mathcal{E}$-fields (all below 15 mV/cm)
- a_1 terms consistent with zero: no systematics

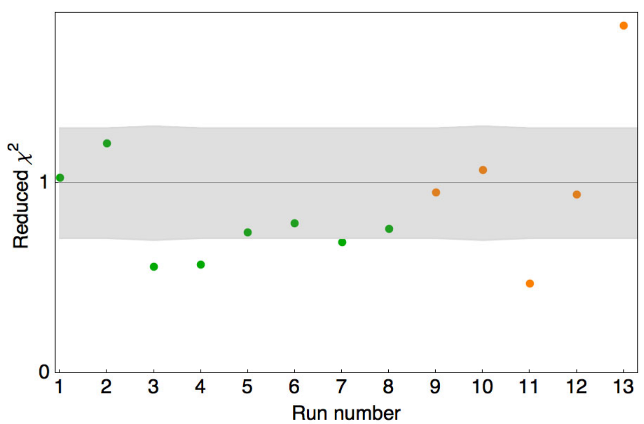


NSD-PV data with $^{138}Ba^{19}F$: 2nd crossing W→-W



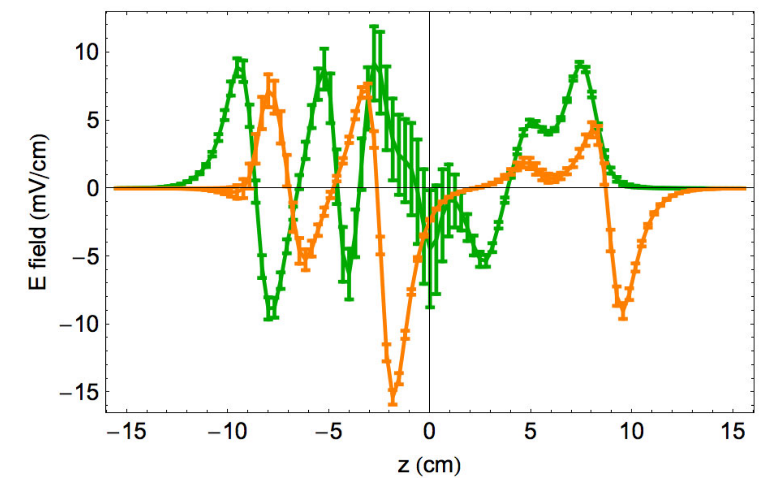






Weighted average $\rightarrow \frac{W}{2\pi} = 0.05 \pm 0.51_{stat}$ Hz

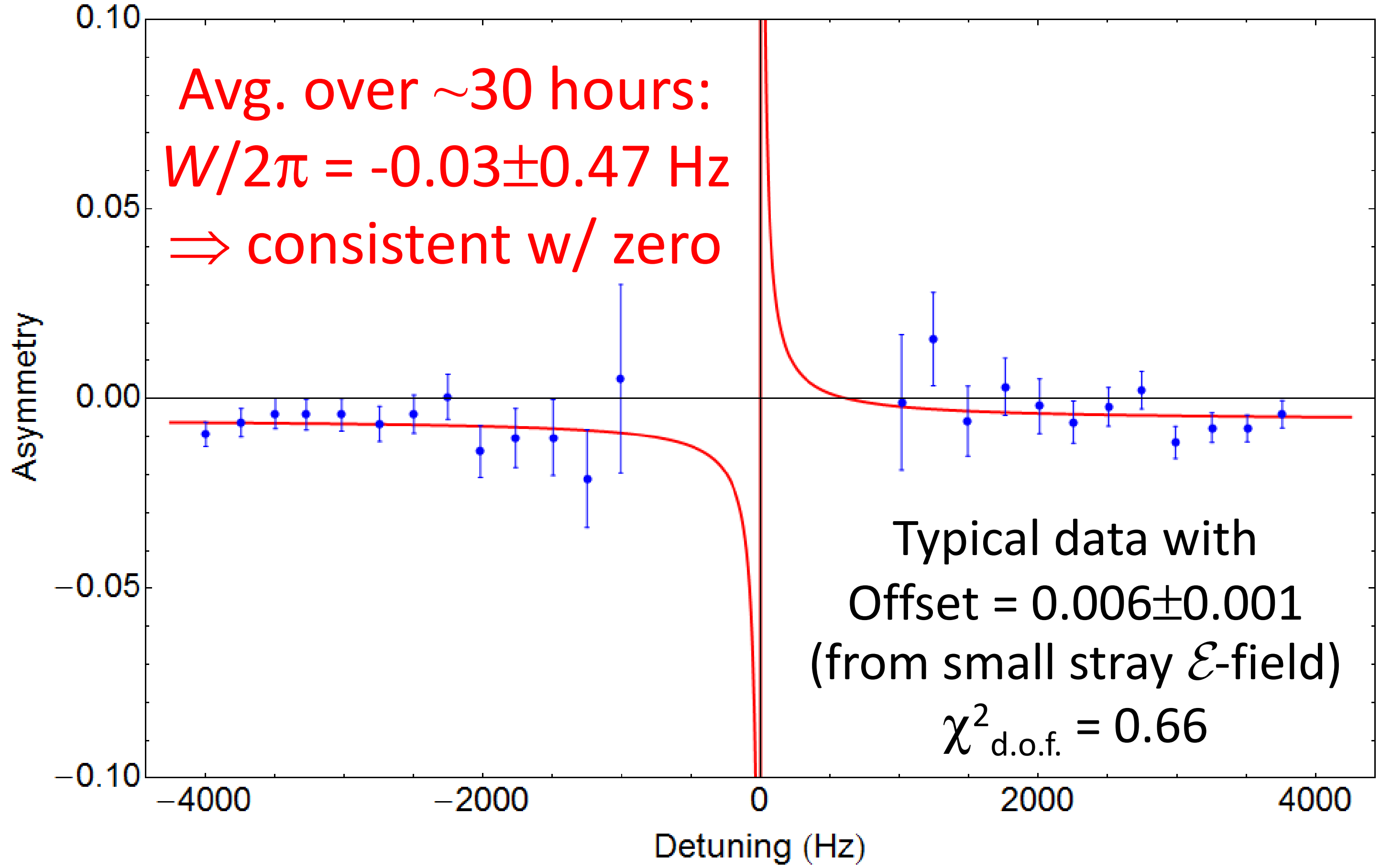
$$a_1 = \left(-1.69 \pm 3.98_{stat}\right) * 10^{-7}\ 1/\text{Hz}$$



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

Recent PV data with $^{138}Ba^{19}F$

Proof of concept run (null signal expected for ^{19}F nucleus)



Statistical uncertainty δW = 0.5 Hz [~30 hours data]

- ~60× more sensitive than best atomic experiment (Wieman, ^{133}Cs)
  - Sufficient to measure effect in many heavy nuclei

& several light nuclei w/anticipated technical upgrades

Questions/requests for theorists

--Calculations with new HPV parameterization

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

--Quantitative uncertainties on calculations!

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

--Is consistency check between isotopes in heavier nuclei useful?
--special cases of particular interest?
(e.g. ^{19}F… can it be calculated accurately?)

--Can anapole measurements (with known inputs) shed light
on other related calculations e.g. Schiff moment, $0\nu\beta\beta$ decay, …?

--Generally: modern theory perspective on anapole moments
URGENTLY needed (>10 years since last nuclear theory paper)