Wick Haxton, UC Berkeley and LBL

Nuclei as Laboratories for Tests of Symmetries

- Hadronic parity violation: weak neutral current
- Time reversal: atomic and nuclear elms
- Dark matter direct detection

Why bother with nuclei?   They are too complicated

- This is a valid point of view: In many cases, our model-based approaches to many-nucleon systems prevent us from assigning meaningful errors to predictions

- But in applications to symmetries, often we are interested in discovery: the underlying question may be a binary one — is there, or is there not…

- Nuclei have their virtues:

They can filter interactions

- *Kinematically:* a remarkable example is $\beta\beta$ decay: because of the nuclear pairing force, in 40+ cases the only open decay channel is second-order weak

- *Through selection rules:* the quantum labels of nuclear states allow us to exploit parity, time reversal, and isospin to isolate interactions of interest
    - we can see the weak force between nucleons by exploiting parity to filter out the much stronger strong and E&M interactions

They can enhance sources of symmetry violation

- *Through nuclear energy degeneracies: mixing of nearby states*
- *By competing symmetry-allowed but suppressed transitions (e.g., E1s in a self-conjugate nucleus) against a symmetry-forbidden strong one (M1)*
- *Through nuclear Fermi motion: proved important in dark matter*
- *Through the nuclear size*

PNC asymmetries of o(1) have been found in nuclear systems, when the natural scale is o(10^{-7})

Nuclear degeneracies related to collective modes in nuclei can enhance electric dipole moments by factors of 10^3 - 10^5

The intrinsic velocities of bound nucleons enhance detection cross sections for many candidates WIMP DM interactions by 10^4

The $A^{2/3}$ growth of the nuclear anapole moment allows this weak radiative correction to dominate tree-level interactions in ^{133}Cs

<u>They provide experimentalists with opportunities</u>

- *We have many nuclei, but only two types of nucleons*

In the literature there are remarkable examples of opportunistic nuclear physicists stringing together ideas to reach important conclusions

My two favorites (oldies but goodies)

- #1 the 1957 Goldhaber-Grodzins-Sunyar experiment exploiting electron capture on Eu^{152m} to prove the neutrino is left-handed

- #2 the 1936 paper of Gamow and Teller where they concluded from Th chain beta decays that Fermi's vector theory of the weak interaction must be augmented by an axial interaction of comparable strength (!)

Despite my (assigned) title…

- Not an overview, but rather just three examples, chosen to illustrate why nuclei are useful in symmetry tests

- But the topics are relevant to current experiments

  - hadronic parity violation: after a 25-year drought, two new results announced this past year

  - electric dipole moments: FRIB's isotope harvesting will open up the possibility of using radioactive species in very competitive experiments

  - dark matter direct detection

hadronic weak interactions: as the weak neutral current is suppressed in $\Delta S \neq 0$ weak processes, neutral current can only be studied in $\Delta S = 0$ reaction

NN and nuclear reactions the only feasible possibilities, isospin is the filter

$$L^{\text{eff}} = \frac{G}{2}\left[J_W^\dagger J_W + J_Z^\dagger J_z\right] + h.c.$$

$$J_W = \cos\theta_C J_W^{\Delta \text{S}=0} + \sin\theta_C J_W^{\Delta S=-1}$$

↕ ΔI=1 ↕ ΔI=1/2

$$L^{eff}_{\Delta S=0} = \frac{G}{\sqrt{2}}\left[\cos^2\theta_C J_W^{0\dagger} J_W^0 + \sin^2\theta_c J_W^{1\dagger} J_W^1 + J_Z^\dagger J_Z\right]$$

↕ symmetric ⇒ ΔI=0,2

↕ ΔI=1 but Cabibbo suppressed

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$$L^{eff}_{\Delta S=0} = \frac{G}{\sqrt{2}}\left[\cos^2\theta_C J_W^{0\dagger} J_W^0 + \sin^2\theta_c J_W^{1\dagger} J_W^1 + J_Z^\dagger J_Z\right]$$

↕ symmetric ⇒ ΔI=0,2 ↕ ΔI=1 but Cabibbo suppressed

leads to the expectation that the weak hadronic neutral current will dominate nuclear experiments sensitive to isovector PNC — this is the only SM current not yet isolated

Largely equivalent DDH, Danilov, and Pionless EFT treatments

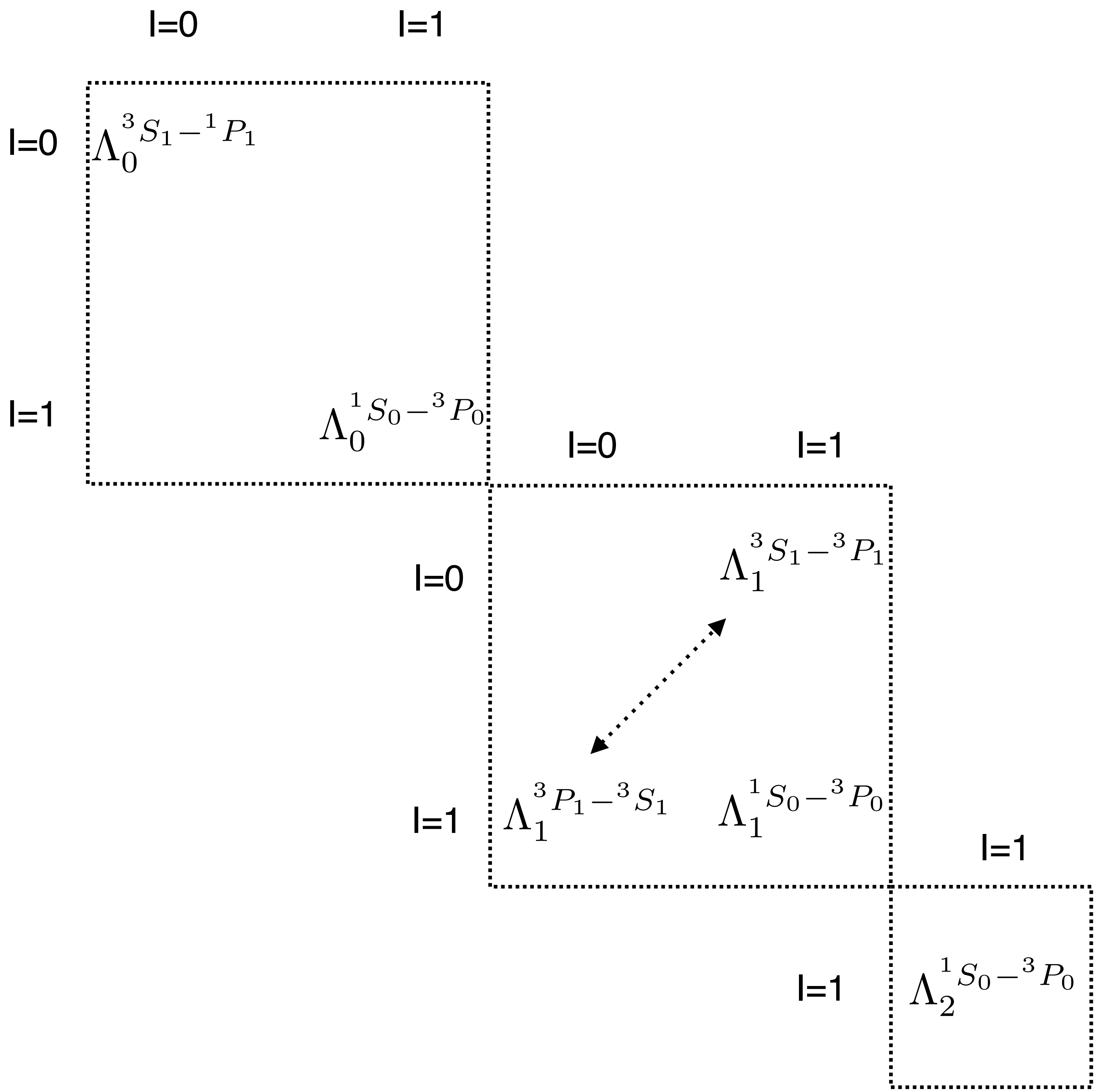
Pionless EFT treatments
- S. L. Zhu et al., Nucl. Phys. A748 (2005) 435
- L. Girlanda, Phys. Rev. C77 (2008) 067001
- D. R. Phillips, M. R. Schindler, and R. P. Springer, Nucl. Phys. A822 (2009) 1

Danilov amplitude or contact interaction expansions
- B. Desplanques and J. Missimer, Nucl. Phys. A300 (1978) 286
- G. S. Danilov, Phys. Lett. 18 (1965) 40 and B35 (1971) 579

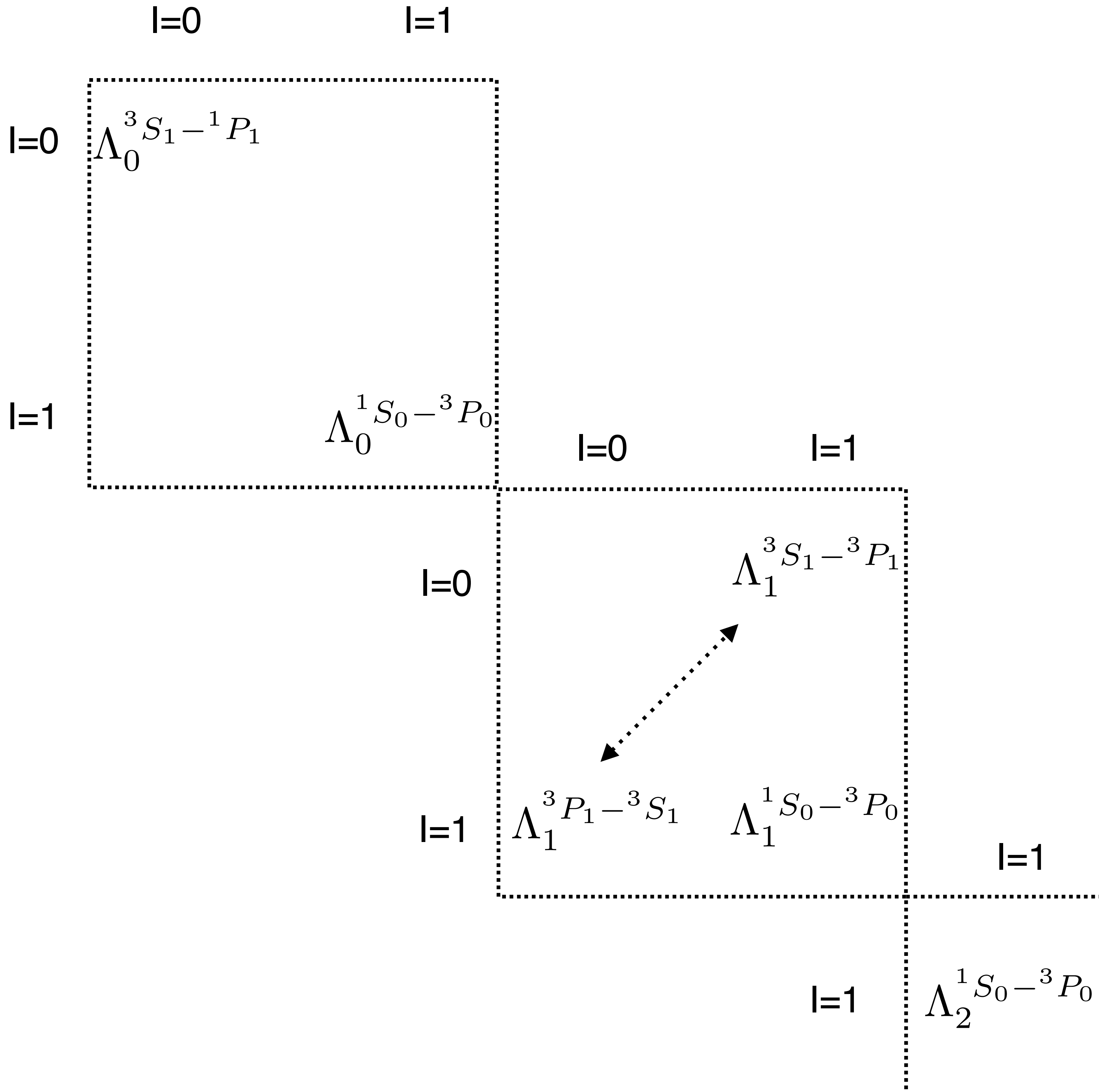
and $1/N_c$ approaches
- D. Phillips, D. Samart, and C. Schat, PRL 114 (2015) 062301
- M. R. Schindler, R. P. Springer, and J. Vanasse, PRC 93 (2016) 025502

Coeff	DDH	Girlanda	Zhu
$\Lambda_{0\ DDH}^{^1S_0-^3P_0}$	$-g_\rho h_\rho^0(2+\chi_V) - g_\omega h_\omega^0(2+\chi_S)$	$2(\mathcal{G}_1+\tilde{\mathcal{G}}_1)$	$2(\mathcal{C}_1+\tilde{\mathcal{C}}_1+\mathcal{C}_3+\tilde{\mathcal{C}}_3)$
$\Lambda_{0\ DDH}^{^3S_1-^1P_1}$	$g_\omega h_\omega^0\chi_S - 3g_\rho h_\rho^0\chi_V$	$2(\mathcal{G}_1\text{-}\tilde{\mathcal{G}}_1)$	$2(\mathcal{C}_1\text{-}\tilde{\mathcal{C}}_1\text{-}3\mathcal{C}_3+3\tilde{\mathcal{C}}_3)$
$\Lambda_{1\ DDH}^{^1S_0-^3P_0}$	$-g_\rho h_\rho^1(2+\chi_V) - g_\omega h_\omega^1(2+\chi_S)$	$\mathcal{G}_2$	$(\mathcal{C}_2+\tilde{\mathcal{C}}_2+\mathcal{C}_4+\tilde{\mathcal{C}}_4)$
$\Lambda_{1\ DDH}^{^3S_1-^3P_1}$	$\frac{1}{\sqrt{2}}g_{\pi NN}h_\pi^1\left(\frac{m_\rho}{m_\pi}\right)^2+g_\rho(h_\rho^1\text{-}h_\rho^{1\prime}) - g_\omega h_\omega^1$	$2\mathcal{G}_6$	$(2\tilde{\mathcal{C}}_6+\mathcal{C}_2\text{-}\mathcal{C}_4))$
$\Lambda_{2\ DDH}^{^1S_0-^3P_0}$	$-g_\rho h_\rho^2(2+\chi_V)$	$-2\sqrt{6}\mathcal{G}_5$	$2\sqrt{6}(\mathcal{C}_5+\tilde{\mathcal{C}}_5)$

isospin structure

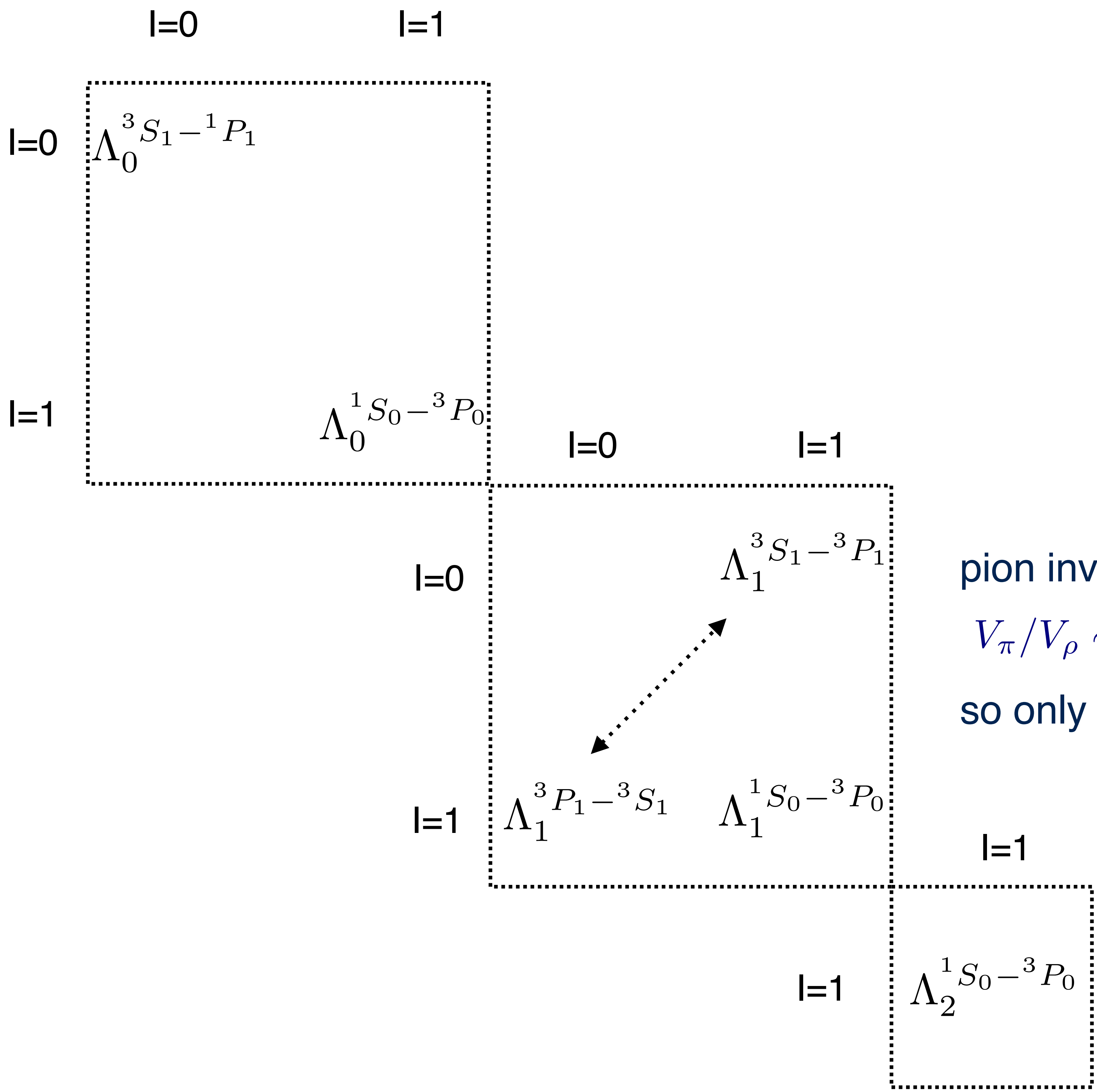


DDH-informed analysis



pp asymmetry only:
“marginalized over”

DDH-informed analysis

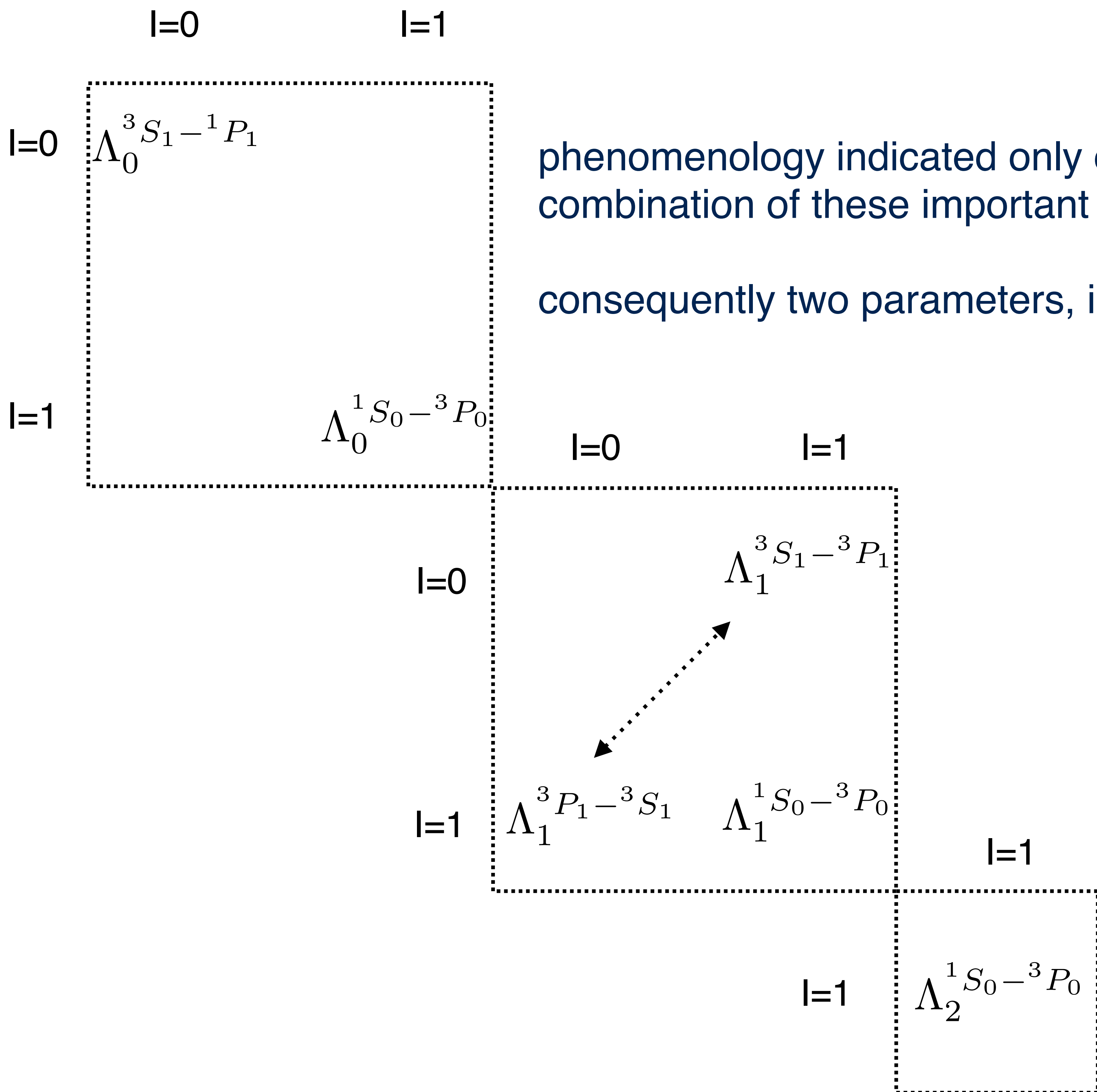


pion involved in both:

$V_\pi / V_\rho \sim m_\rho^2 / m_\pi^2 \sim 30$

so only one parameter, h_1^π

DDH-informed analysis



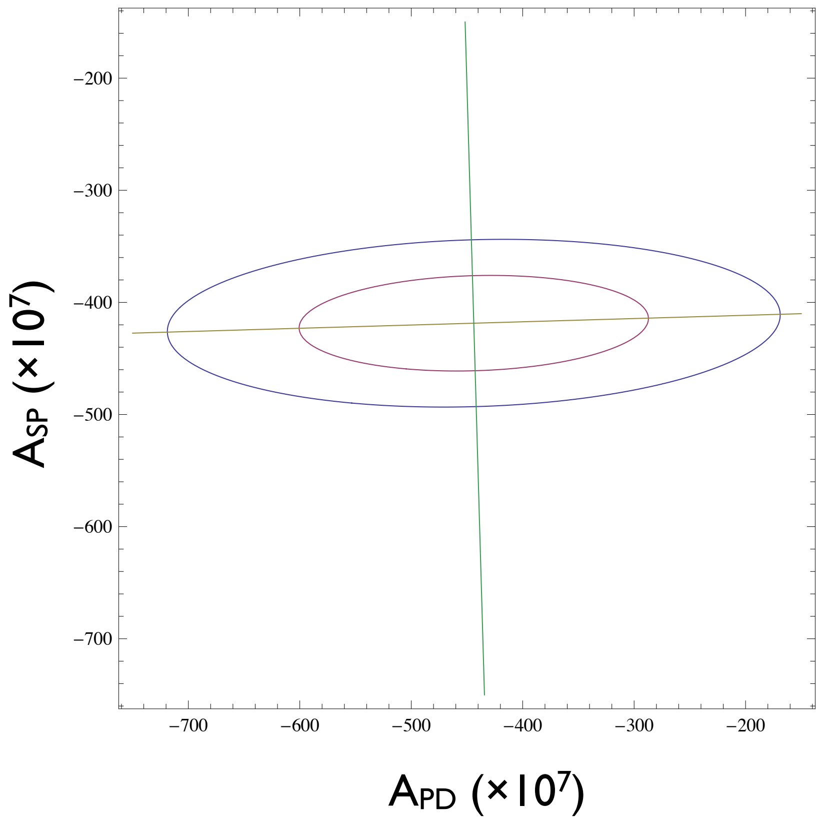
phenomenology indicated only one linear combination of these important :

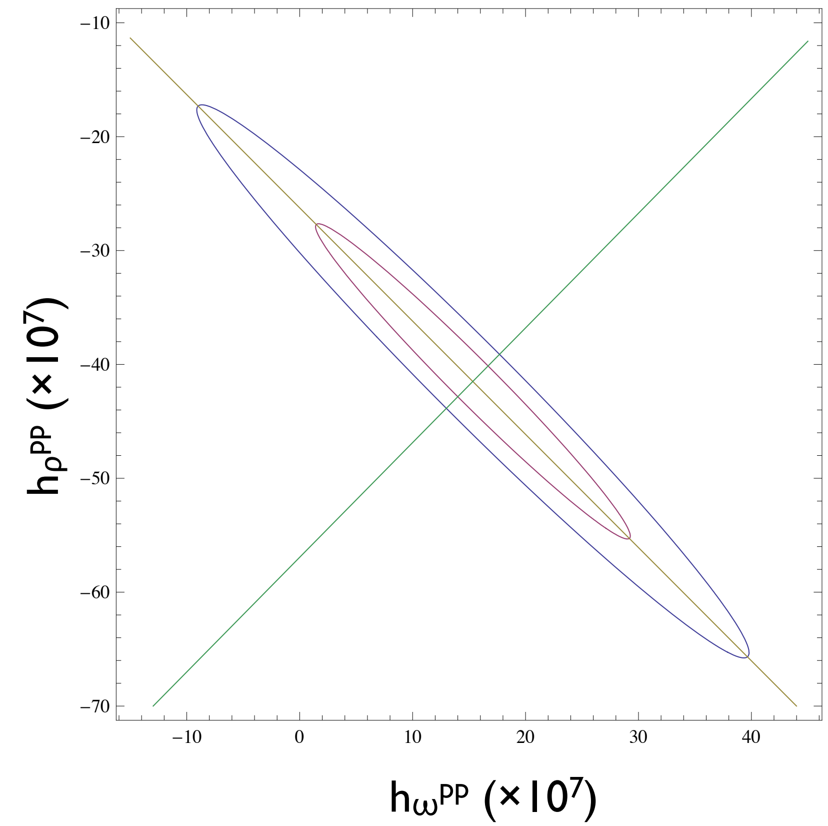
consequently two parameters, isoscalar and h_1^π

<u>Lack of data has been one challenge</u>

$\vec{p}+p$ asymmetry:

at 13.6, 45, 221 MeV





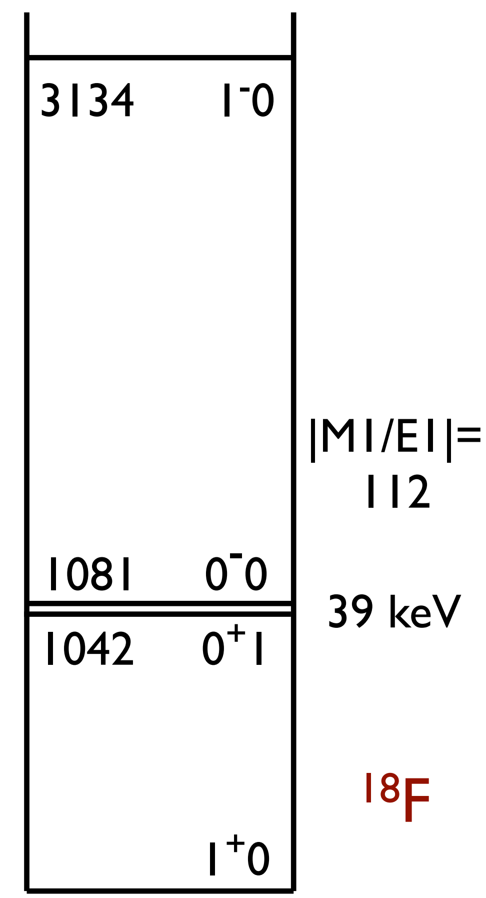
some of the most reliable constraints

$$A_L^{\vec{p}+p}(45\,\text{MeV}) = (-1.57 \pm 0.23) \times 10^{-7}$$

$$A_L^{\vec{p}+\alpha}(46\,\text{MeV}) = (-3.34 \pm 0.93) \times 10^{-7}$$

$$P_\gamma^{^{18}\text{F}}(1081\,\text{keV}) = (12 \pm 38) \times 10^{-5}$$

$$A_\gamma^{^{19}\text{F}}(110\,\text{keV}) = (-7.4 \pm 1.9) \times 10^{-5}$$



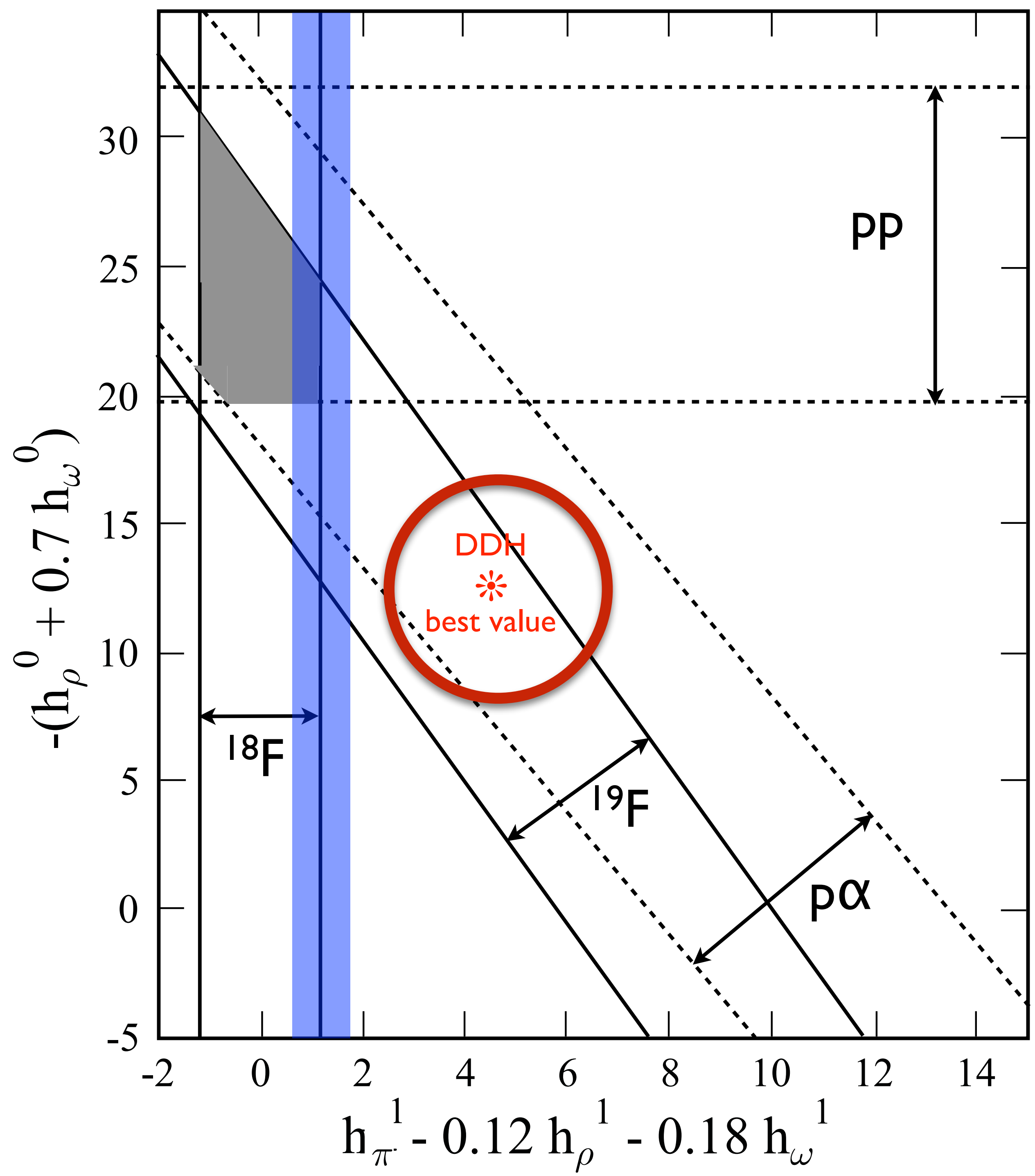
Enhancement #1

Enhancement #2

Isospin filter

Little NP uncertainty

Results of the 2D isoscalar/isovector analysis



Collapses to 1D: Internally inconsistent as we assumed h_1^π dominance

Large Nc Classification

Coeff	DDH	Girlanda	Large N_c
$\Lambda_0^+ \equiv \frac{3}{4}\Lambda_0^{^3S_1-^1P_1} + \frac{1}{4}\Lambda_0^{^1S_0-^3P_0}$	$-g_\rho h_\rho^0(\frac{1}{2}+\frac{5}{2}\chi_\rho) - g_\omega h_\omega^0(\frac{1}{2}-\frac{1}{2}\chi_\omega)$	$2\mathcal{G}_1 + \tilde{\mathcal{G}}_1$	$\sim N_c$
$\Lambda_0^- \equiv \frac{1}{4}\Lambda_0^{^3S_1-^1P_1} - \frac{3}{4}\Lambda_0^{^1S_0-^3P_0}$	$g_\omega h_\omega^0(\frac{3}{2}+\chi_\omega) + \frac{3}{2}g_\rho h_\rho^0$	$-\mathcal{G}_1 - 2\tilde{\mathcal{G}}_1$	$\sim 1/N_c$
$\Lambda_1^{^1S_0-^3P_0}$	$-g_\rho h_\rho^1(2+\chi_\rho) - g_\omega h_\omega^1(2+\chi_\omega)$	$\mathcal{G}_2$	$\sim \sin^2\theta_w$
$\Lambda_1^{^3S_1-^3P_1}$	$\frac{1}{\sqrt{2}}g_{\pi NN}h_\pi^1\left(\frac{m_\rho}{m_\pi}\right)^2 + g_\rho(h_\rho^1 - h_\rho^{1\prime}) - g_\omega h_\omega^1$	$2\mathcal{G}_6$	$\sim \sin^2\theta_w$
$\Lambda_2^{^1S_0-^3P_0}$	$-g_\rho h_\rho^2(2+\chi_\rho)$	$-2\sqrt{6}\mathcal{G}_5$	$\sim N_c \sin^2\theta_w$

Schindler et al.

Large Nc Classification

	Coeff	DDH	Girlanda	Large N_c
LO	$\Lambda_0^+ \equiv \frac{3}{4}\Lambda_0^{{}^3S_1-{}^1P_1} + \frac{1}{4}\Lambda_0^{{}^1S_0-{}^3P_0}$	$-g_\rho h_\rho^0(\frac{1}{2}+\frac{5}{2}\chi_\rho) - g_\omega h_\omega^0(\frac{1}{2}-\frac{1}{2}\chi_\omega)$	$2\mathcal{G}_1 + \tilde{\mathcal{G}}_1$	$\sim N_c$
NNLO	$\Lambda_0^- \equiv \frac{1}{4}\Lambda_0^{{}^3S_1-{}^1P_1} - \frac{3}{4}\Lambda_0^{{}^1S_0-{}^3P_0}$	$g_\omega h_\omega^0(\frac{3}{2}+\chi_\omega) + \frac{3}{2}g_\rho h_\rho^0$	$-\mathcal{G}_1 - 2\tilde{\mathcal{G}}_1$	$\sim 1/N_c$
NNLO	$\Lambda_1^{{}^1S_0-{}^3P_0}$	$-g_\rho h_\rho^1(2+\chi_\rho) - g_\omega h_\omega^1(2+\chi_\omega)$	$\mathcal{G}_2$	$\sim \sin^2\theta_w$
NNLO	$\Lambda_1^{{}^3S_1-{}^3P_1}$	$\frac{1}{\sqrt{2}}g_{\pi NN}h_\pi^1\left(\frac{m_\rho}{m_\pi}\right)^2 + g_\rho(h_\rho^1 - h_\rho^{1\prime}) - g_\omega h_\omega^1$	$2\mathcal{G}_6$	$\sim \sin^2\theta_w$
NLO	$\Lambda_2^{{}^1S_0-{}^3P_0}$	$-g_\rho h_\rho^2(2+\chi_\rho)$	$-2\sqrt{6}\mathcal{G}_5$	$\sim N_c\sin^2\theta_w$

Schindler et al.

The LO/NLO space is isoscalar - isotensor

The isovector space is NNLO: consequently ^{18}F and the new experiment NPDGamma are not redundant, but independent, testing different S-P amplitudes, both of the same order

The old notion of a dominant isoscalar combination is born out, and now motivated

	Coeff	DDH	Girlanda	Large N_c
LO	$\Lambda_0^+ \equiv \frac{3}{4}\Lambda_0^{^3S_1-^1P_1} + \frac{1}{4}\Lambda_0^{^1S_0-^3P_0}$	$-g_\rho h_\rho^0(\frac{1}{2}+\frac{5}{2}\chi_\rho) - g_\omega h_\omega^0(\frac{1}{2}-\frac{1}{2}\chi_\omega)$	$2\mathcal{G}_1 + \tilde{\mathcal{G}}_1$	$\sim N_c$
NNLO	$\Lambda_0^- \equiv \frac{1}{4}\Lambda_0^{^3S_1-^1P_1} - \frac{3}{4}\Lambda_0^{^1S_0-^3P_0}$	$g_\omega h_\omega^0(\frac{3}{2} + \chi_\omega) + \frac{3}{2}g_\rho h_\rho^0$	$-\mathcal{G}_1 - 2\tilde{\mathcal{G}}_1$	$\sim 1/N_c$
NNLO	$\Lambda_1^{^1S_0-^3P_0}$	$-g_\rho h_\rho^1(2+\chi_\rho) - g_\omega h_\omega^1(2+\chi_\omega)$	$\mathcal{G}_2$	$\sim \sin^2\theta_w$
NNLO	$\Lambda_1^{^3S_1-^3P_1}$	$\frac{1}{\sqrt{2}}g_{\pi NN}h_\pi^1\left(\frac{m_\rho}{m_\pi}\right)^2 + g_\rho(h_\rho^1 - h_\rho^{1\prime}) - g_\omega h_\omega^1$	$2\mathcal{G}_6$	$\sim \sin^2\theta_w$
NLO	$\Lambda_2^{^1S_0-^3P_0}$	$-g_\rho h_\rho^2(2+\chi_\rho)$	$-2\sqrt{6}\mathcal{G}_5$	$\sim N_c\sin^2\theta_w$

$$\frac{2}{5}\Lambda_0^+ + \frac{1}{\sqrt{6}}\Lambda_2^{^1S_0-^3P_0} + \left[-\frac{6}{5}\Lambda_0^- + \Lambda_1^{^1S_0-^3P_0}\right] = 419 \pm 43 \qquad A_L(\vec{\mathrm{p}}\mathrm{p})$$

$$1.3\Lambda_0^+ + \left[-0.9\Lambda_0^- + 0.89\Lambda_1^{^1S_0-^3P_0} + 0.32\Lambda_1^{^3S_1-^3P_1}\right] = 930 \pm 253 \qquad A_L(\vec{\mathrm{p}}\alpha)$$

$$\left[\left|2.42\Lambda_1^{^1S_0-^3P_0} + \Lambda_1^{^3S_1-^3P_1}\right|\right] < 340 \qquad P_\gamma(^{18}\mathrm{F})$$

PREVIOUSLY A PUZZLE

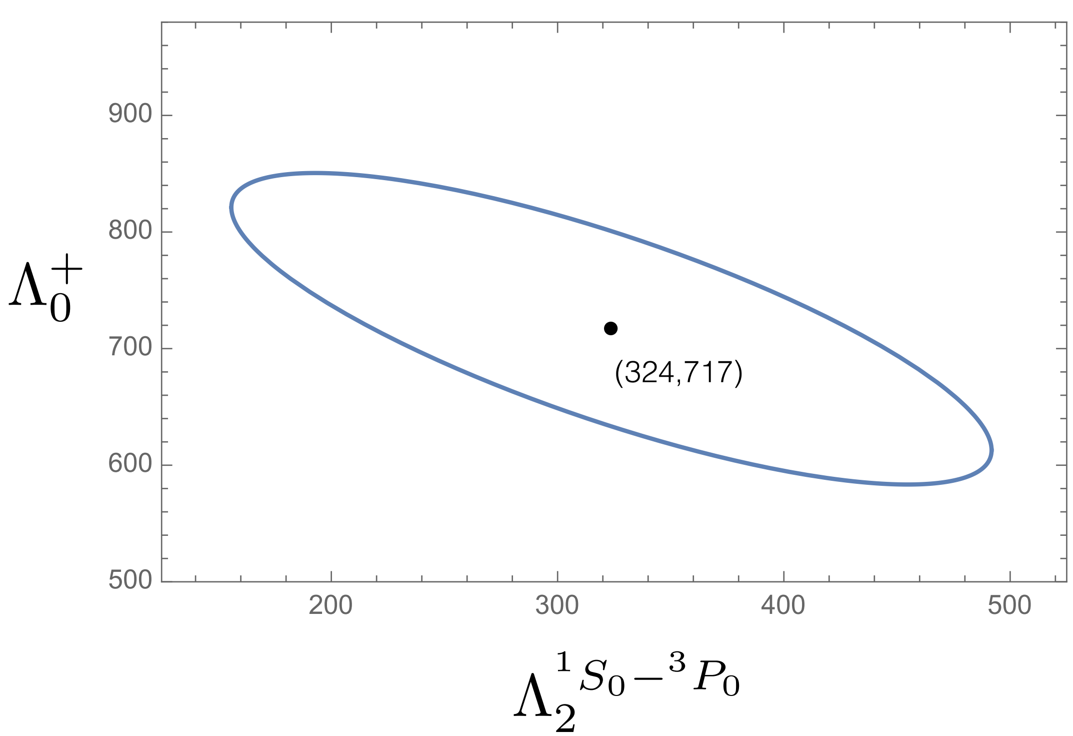
$$0.92\Lambda_0^+ + \left[-1.03\Lambda_0^- + 0.67\Lambda_1^{^1S_0-^3P_0} + 0.29\Lambda_1^{^3S_1-^3P_1}\right] = 661 \pm 169 \qquad A_\gamma(^{19}\mathrm{F})$$

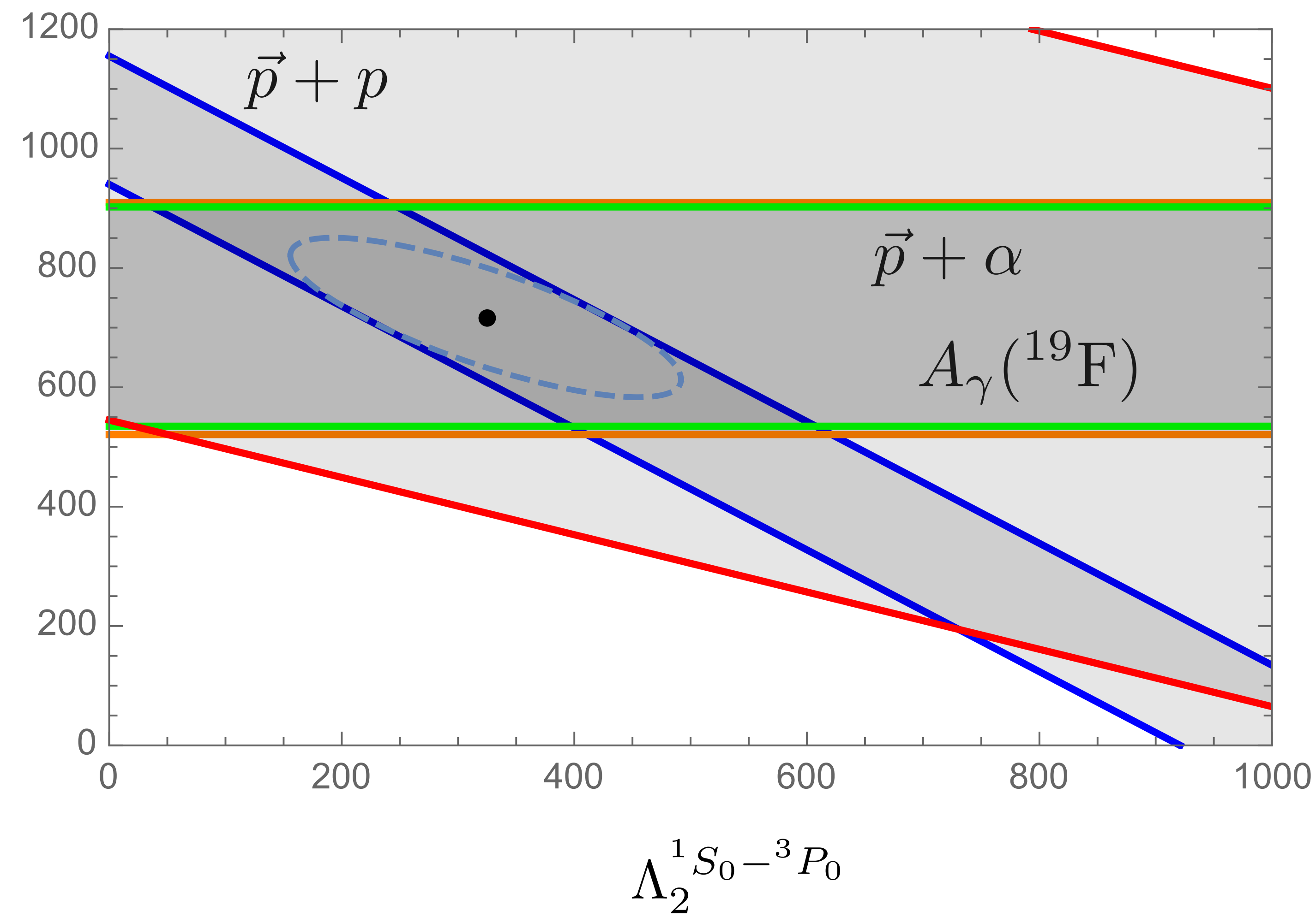
This large Nc analysis is more consistent with the data

$$\left\{ \begin{array}{c} {}^{\rm DDH}\Lambda_0^+ \\ {}^{\rm DDH}\Lambda_2^{^1S_0-^3P_0} \end{array} \right\} = \left\{ \begin{array}{c} 319 \\ 151 \end{array} \right\} \qquad \left\{ \begin{array}{c} {}^{\rm DDH}\Lambda_0^- \\ {}^{\rm DDH}\Lambda_1^{^1S_0-^3P_0} \\ {}^{\rm DDH}\Lambda_1^{^3S_1-^3P_1} \end{array} \right\} = \left\{ \begin{array}{c} -70 \\ 21 \\ 1340 \end{array} \right\}$$

LO/NLO theory consistent with experiment

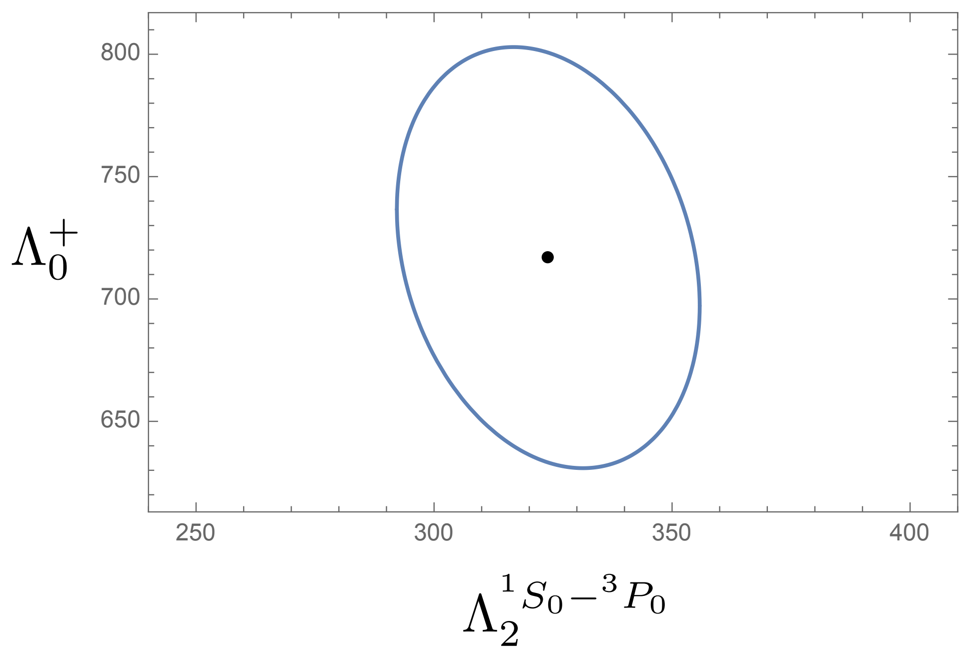
$$\left\{ \begin{array}{c} 717 \\ 324 \end{array} \right\}$$

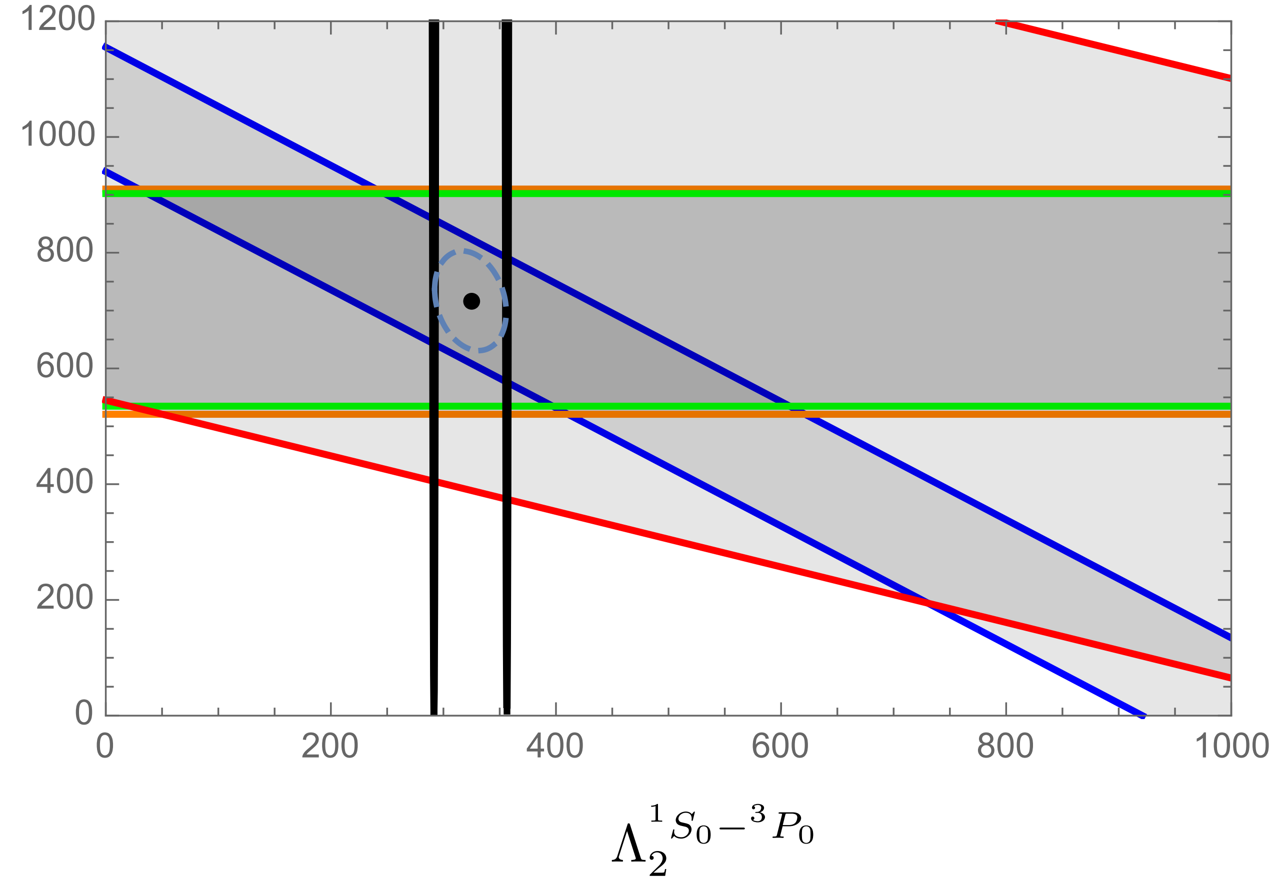




With things beginning to align, one can see the experimental path forward

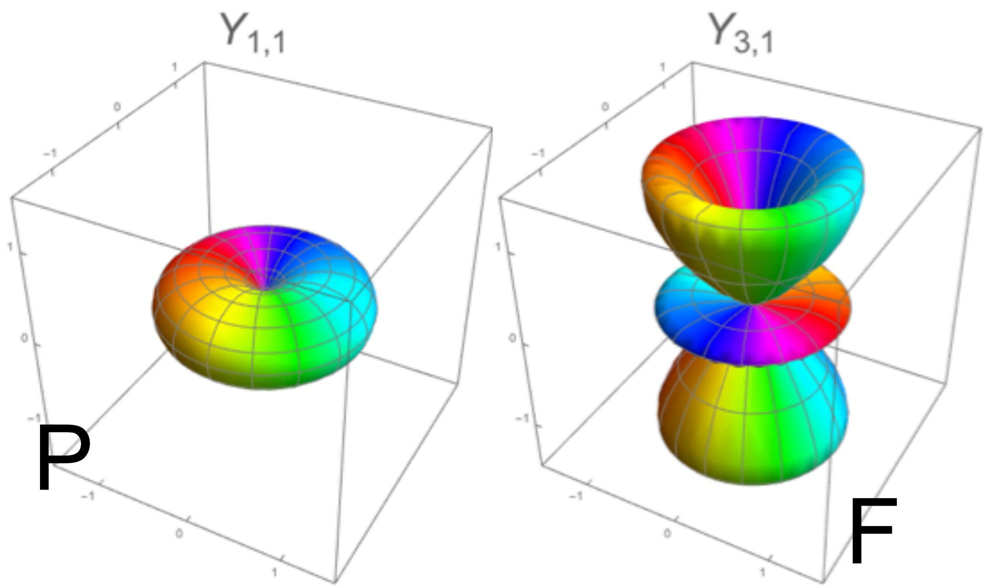
LO couplings: need a 10% measurement to complement $\vec{p} + p$ experimentally, no obvious candidate, but…



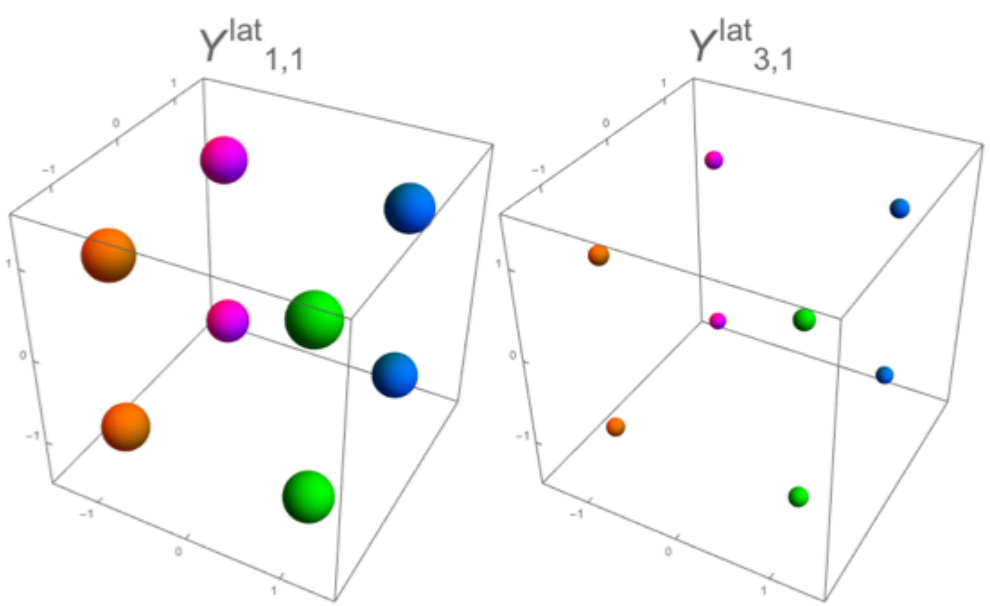


Impact of a 10% LQCD calculation of the I=2 amplitude

<u>LQCD work</u> on HPNC builds on recent efforts to build the technology to use extended nuclear sources required for calculating NN partial waves beyond s-wave

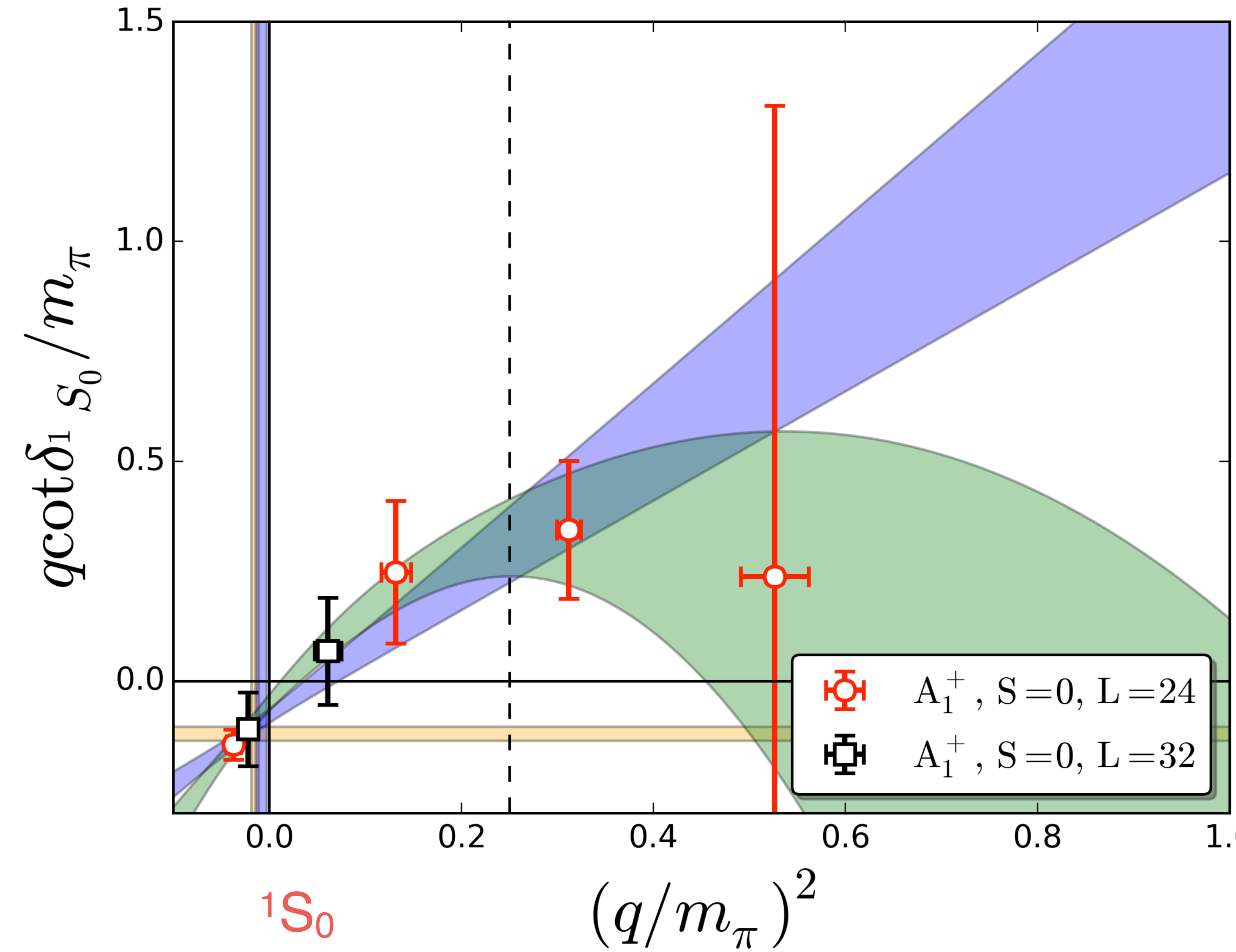


(a) continuum



(b) discretized

Cubic to rotational symmetry



Higher partial waves with extended sources:
E. Berkowitz et al. (CalLat Collab.) arXiv:1508.00886
K. Murano et al. (HAL QCD Collab.) arXiv:1305.2293

HPNC Summary

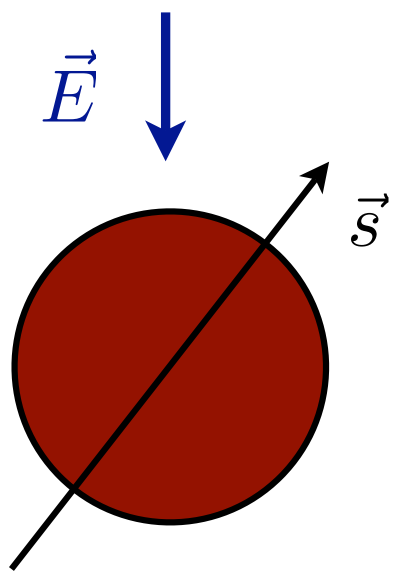
- HPNC progress over the past three decades has until recently been slow
  - only a few new experimental results
  - idea of selecting two LO couplings — isoscalar and h_π^1 — ran into the problem of a small h_π^1

- now have NPDGamma, n+^{3}He: analysis in the large-Nc framework underway
  - it may be that these results are too imprecise to have much impact

- This progress coincides with the advent of high flux cold neutron beams, including the coming ESS
  - so one can envision a period of progress

Electric Dipole Moments and CP Violation

Permanent electric dipole moments of an elementary particle or a composite s requires requires both P and T violation



$$H_{edm} = d\ \vec{E} \cdot \vec{s}$$

$$\vec{E}(t \to -t) \to \vec{E}$$
$$\vec{s}(t \to -t) \to -\vec{s}$$

$$\Rightarrow H_{edm} \to -H_{edm}$$

Two important motivations for edm searches

CP phases show up generically in the Standard Model and its extensions

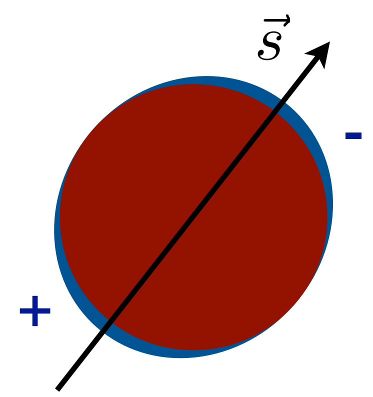
The need for additional sources of CP violation to account for baryogengesis

Experimental sensitivity: The dipole moment of a classical distribution

$$\vec{d} = \int d^3x \; \vec{x} \; \rho(\vec{x})$$

Limit* $d(^{199}\mathrm{Hg}) < 7.5 \times 10^{-30}$ e cm (95% c.l.) corresponds to a strain over atom of 10^{-19} — comparable to what LIGO achieves over a 4 km interferometer arm

E.g., expand the atom to the size of the earth: equivalent to a shell of excess charge (difference between + and - charge at the poles) of thickness $\sim 10^{-4}$ angstroms



The limit on the precession in the applied field (10^{-5} V/m) corresponds to a sensitivity to a difference in the energies of atom levels of $\sim 10^{-26}$ eV

* B Graner et al. (Seattle group), PRL 116 (2016) 161601

General classification of electromagnetic moments:

Multipole	P-even, T-even	P-odd, T-odd	P-odd, T-even	P-even, T-odd
$\langle C_J^M \rangle$	even $J \geq 0$	odd $J \geq 1$	x	x
$\langle M_J^M \rangle$	odd $J \geq 1$	even $J \geq 2$	x	x
$\langle E_J^M \rangle$	x	x	odd $J \geq 1$	even $J \geq 2$

edm is the C1 moment; other P- and T-odd moments include M2, C3, …, and are present for J ≥ 1

General current for a spin-1/2 fermion:

$$\langle p | J_\mu^{\rm em} | p \rangle = \bar{N}(p') \left(F_1 \gamma_\mu + F_2 \sigma_{\mu\nu} q^\nu + \frac{a(q^2)}{M^2} (\not{q} q_\mu - q^2 \gamma_\mu)\gamma_5 + d(q^2) \sigma_{\mu\nu} q^\nu \gamma_5 \right) N(p)$$

Charge — Magnetic — Anapole — Electric Dipole

Experiments:

e/p/n edm experiments break into three general categories

- —neutron or electron beam/trap/fountain edm experiments
- —paramagnetic (unpaired electrons) atoms or molecules with sensitivity to the electron edm
- —diamagnetic atoms (electrons paired, nonzero nuclear spin) with sensitivity to p and n edm and to CPNC nuclear interactions

Key limits, from neutral systems, in units of e cm

Particle	edm limit	system	SM prediction*
e	8.7×10^{-29}	atomic TlO	10^{-38}
p	**2.0×10^{-25}**	Hg vapor cell	10^{-31}
n	2.9×10^{-26}	ultracold n	10^{-31}
^{199}Hg	**7.5×10^{-30}**	Hg vapor cell	10^{-33}

*CKM phase

n: Baker et al, PRL 97 (2006) 131801; Pendlebury et al., PRD 92 (2015) 9092003
e: J. Baron et al., Science 343 (2014) 269
Hg: B. Graner et al., PRL 116 (2016) 161601

Experiments:

e/p/n edm experiments break into three general categories

- neutron or electron beam/trap/fountain edm experiments
- paramagnetic (unpaired electrons) atoms or molecules with sensitivity to the electron edm
- diamagnetic atoms (electrons paired, nonzero nuclear spin) with sensitivity to p and n edm and to CPNC nuclear interactions

Key limits, from neutral systems, in units of e cm

Potential window for discovery

Particle	edm limit	SM prediction*
e	8.7×10^{-29}	10^{-38}
p	**2.0×10^{-25}**	10^{-31}
n	2.9×10^{-26}	10^{-31}
^{199}Hg	**7.5×10^{-30}**	10^{-33}

*CKM phase

n: Baker et al, PRL 97 (2006) 131801; Pendlebury et al., PRD 92 (2015) 9092003
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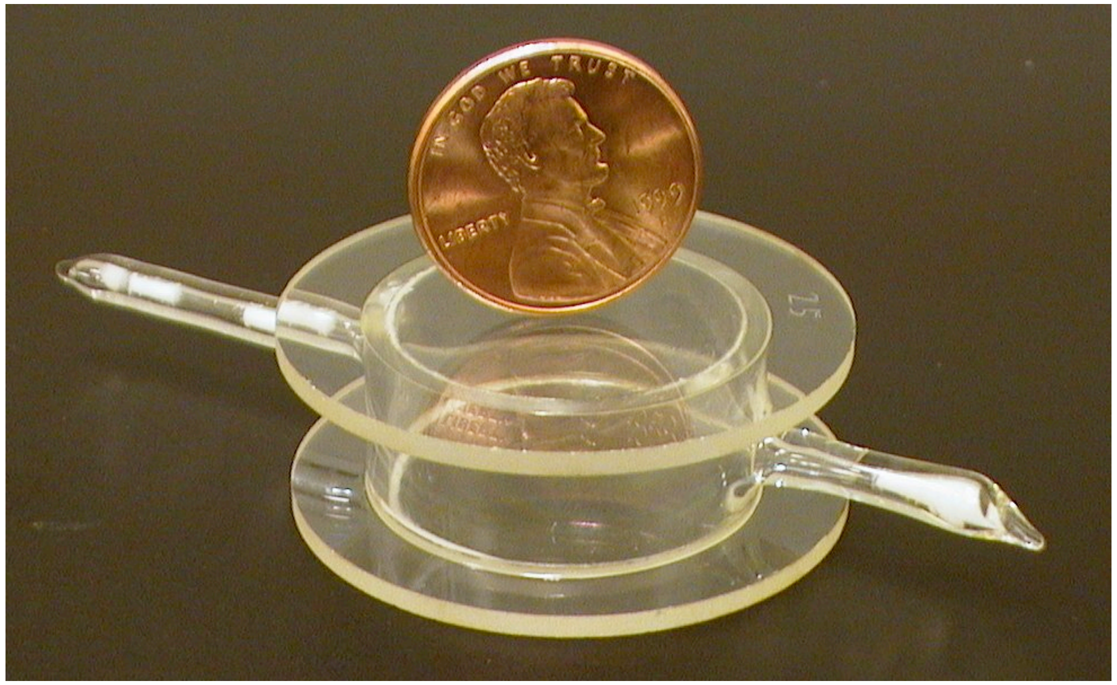
Hg: B. Graner et al., PRL 116 (2016) 161601

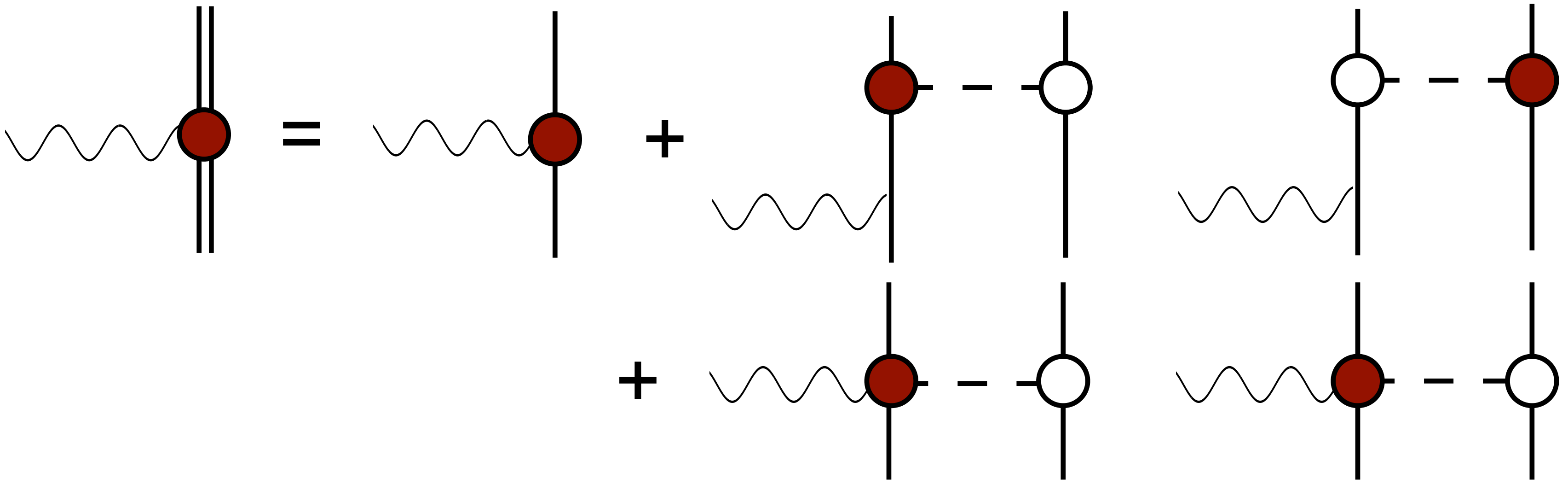
^{199}Hg vapor cells:



- Number of ^{199}Hg atoms: 10^{14}
- Leakage currents at 10 kV: 0.5 – 1 pA
- N_2 + CO buffer gas (500 Torr)
- Paraffin wall coating
- Spin relaxation time: 100 – 200 sec

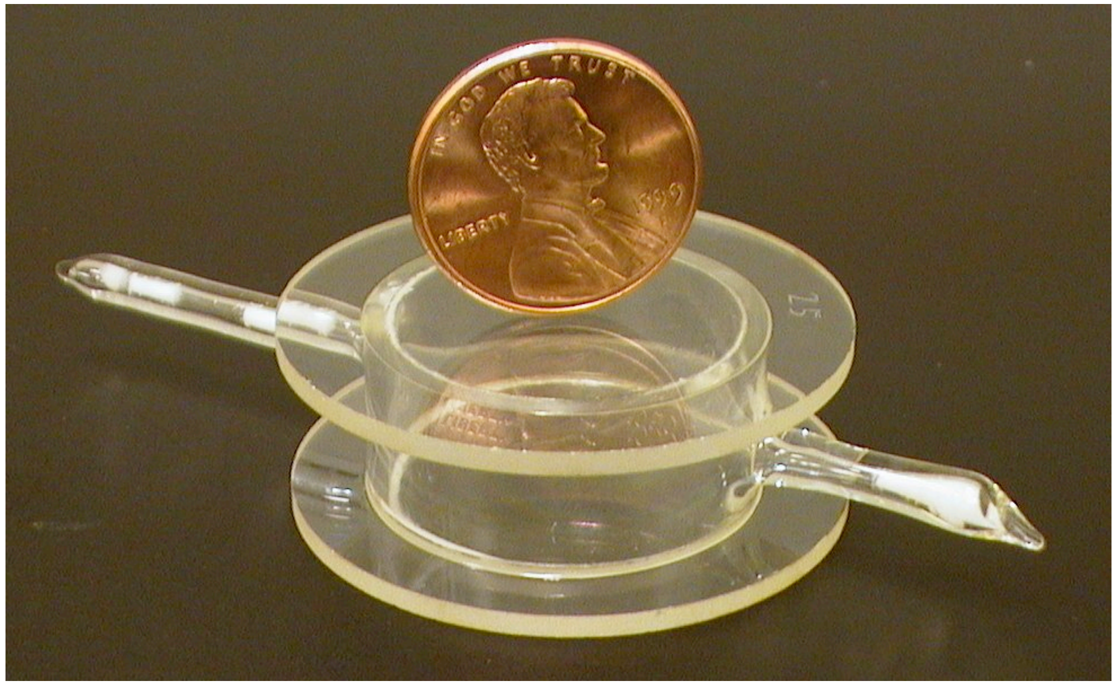
(Heckel's workshop presentation)

Nuclear edm:



nuclear edm = 1-body + polarization + exchange current

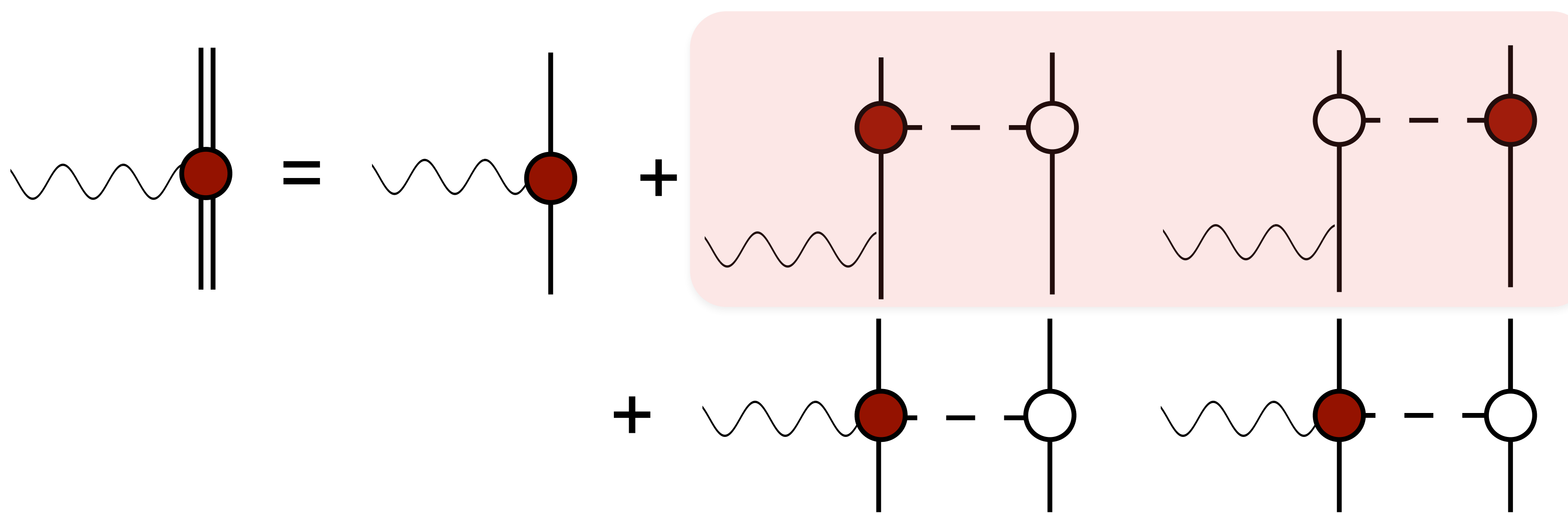
^{199}Hg vapor cells:



– Number of ^{199}Hg atoms: 10^{14}
– Leakage currents at 10 kV: 0.5 – 1 pA
– N_2 + CO buffer gas (500 Torr)
– Paraffin wall coating
– Spin relaxation time: 100 – 200 sec

(Heckel's workshop presentation)

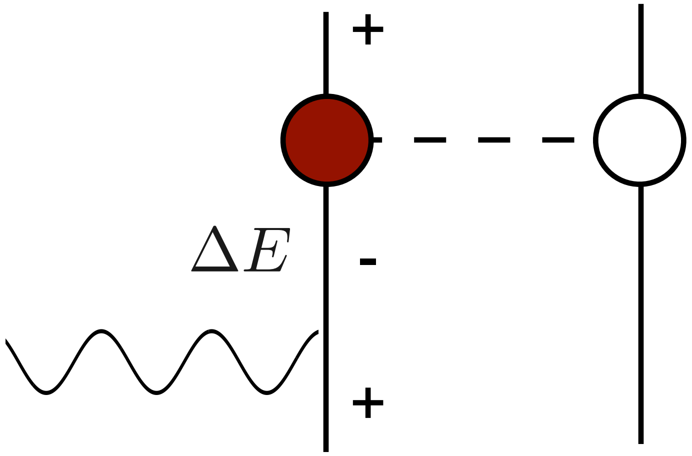
Nuclear edm:



nuclear edm = 1-body + polarization + exchange current

smallest energy denominator is the typically nuclear $\sim \hbar\omega$ (nuclear size)

Dimensional estimate of the nuclear edm (good news):



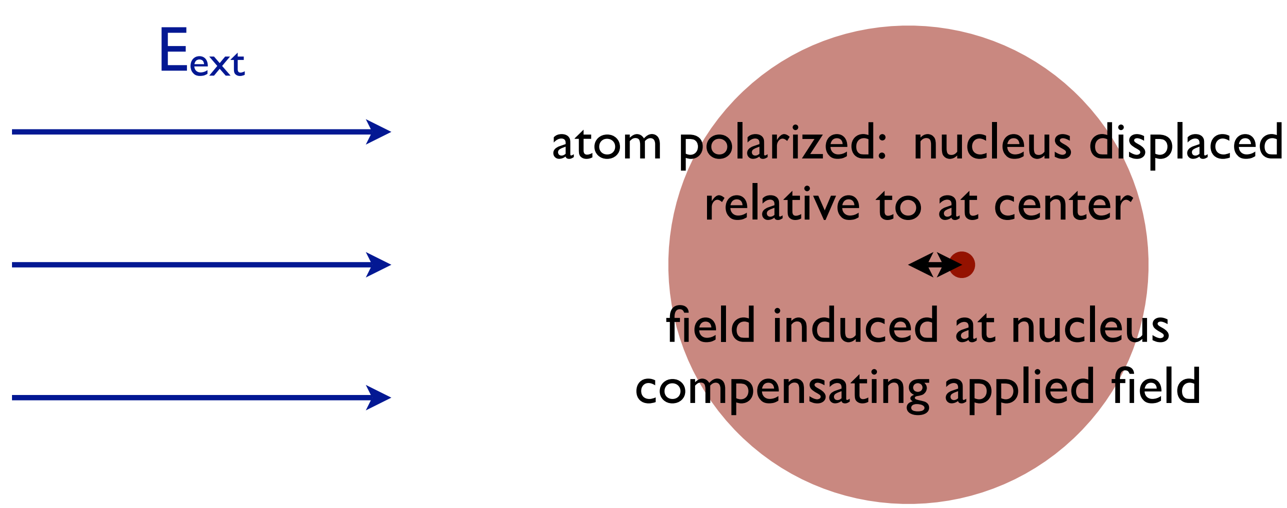
$$d_{\rm Nuclear} \sim 10 d_n \frac{\hbar\omega}{\Delta E} \sim 10 d_n \text{ typically}$$

a small ΔE can greatly enhance $d_{\rm Nuclear}$

the potential can generally be related to d_n

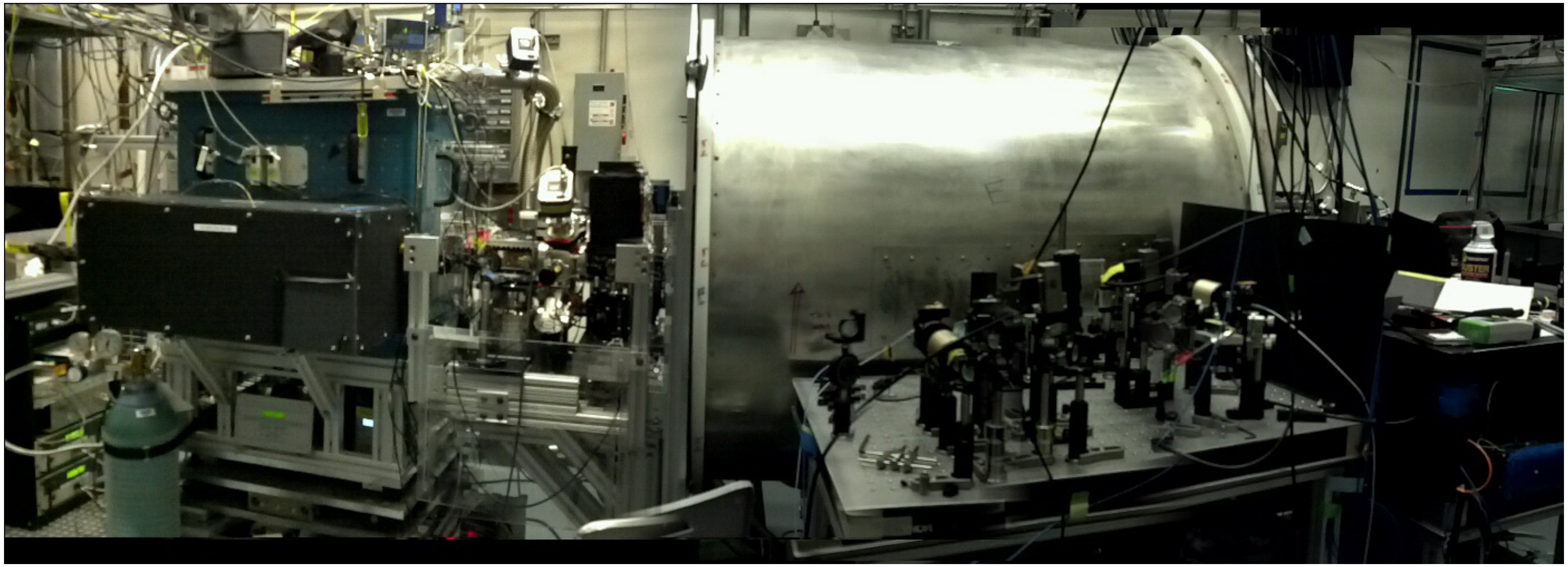
e.g., $$V^{\theta}_{12} = -0.9\ d_n\ m_\pi^2\ \vec{\tau}\cdot\vec{\tau}\ \left(\vec{\sigma}(1) - \vec{\sigma}(2)\right)\cdot\hat{r}\ \frac{e^{-m_\pi r}}{m_\pi r}\left[1 + \frac{1}{m_\pi r}\right]$$

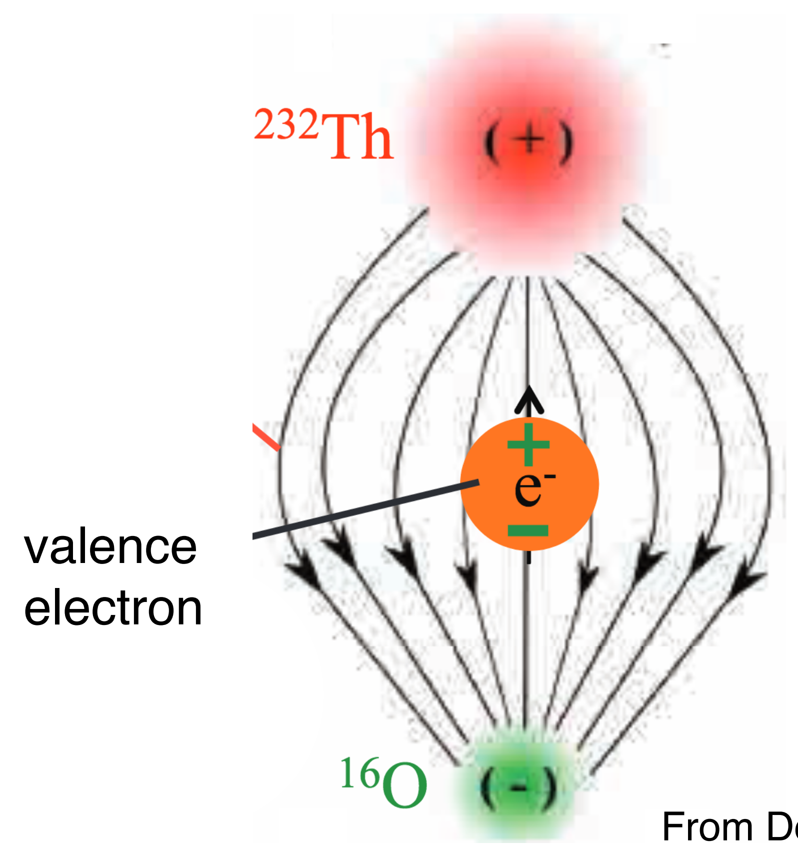
Schiff screening: Interaction energy of a non relativistic point nucleus with a nonzero edm, inside a neutral atom, is zero (bad news)



reduction in edm sensitivity $\sim (R_N/R_A)^2 \sim 10^{-3}$ in heavy atoms

ACME ThO electron edm experiment





From Doyle, KITP Workshop

instead of a loss due to shielding, a great gain is obtained from the extreme internal fields found in polar molecules

$\sim 10^3$ volts/cm in the lab vs.

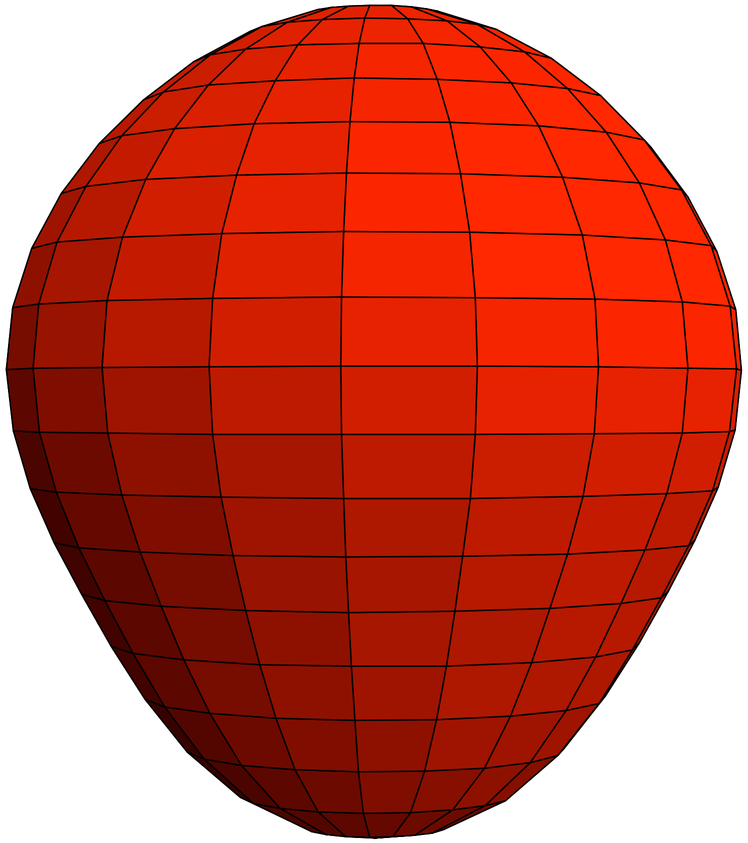
$\sim 10^{11}$ volts/cm in ThO huge fields

Nuclear Enhancements

From collective motion: In rotational nuclei, intrinsic state breaks spherical symmetry, deformed into a football, restored by the “Goldstone mode of rotations

Octupole deformation: deformed intrinsic state and its parity reflection can be combined

$$|\text{even}\rangle = |+\rangle + |-\rangle$$
$$|\text{odd}\ \rangle = |+\rangle - |-\rangle$$



Deformation violates P and T, symmetry restored by collective motion, yielding parity doublets that strongly mix through P-odd operators

⇒ CPNC polarization enhancement

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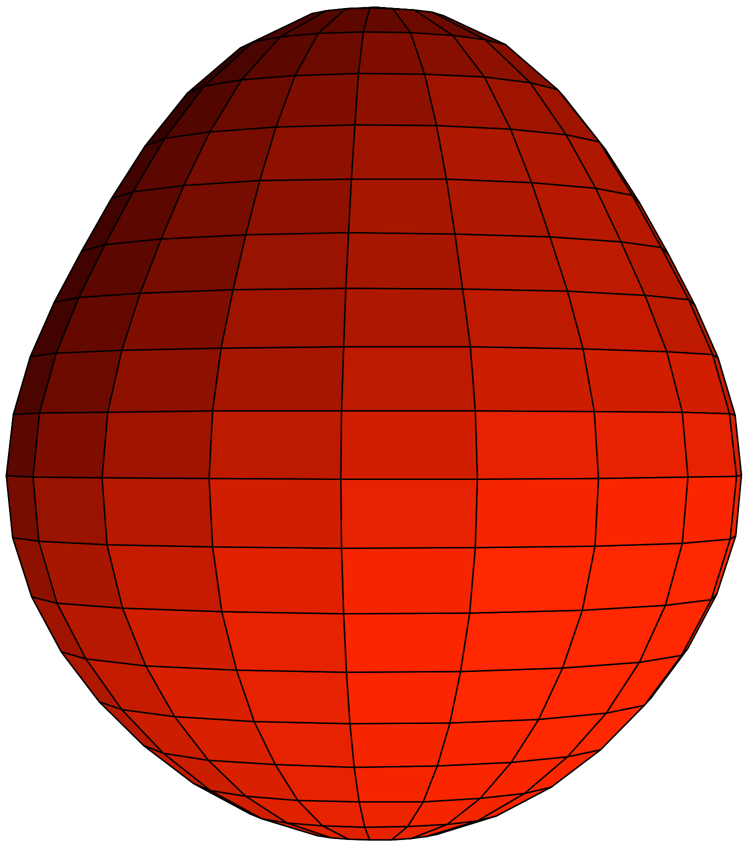

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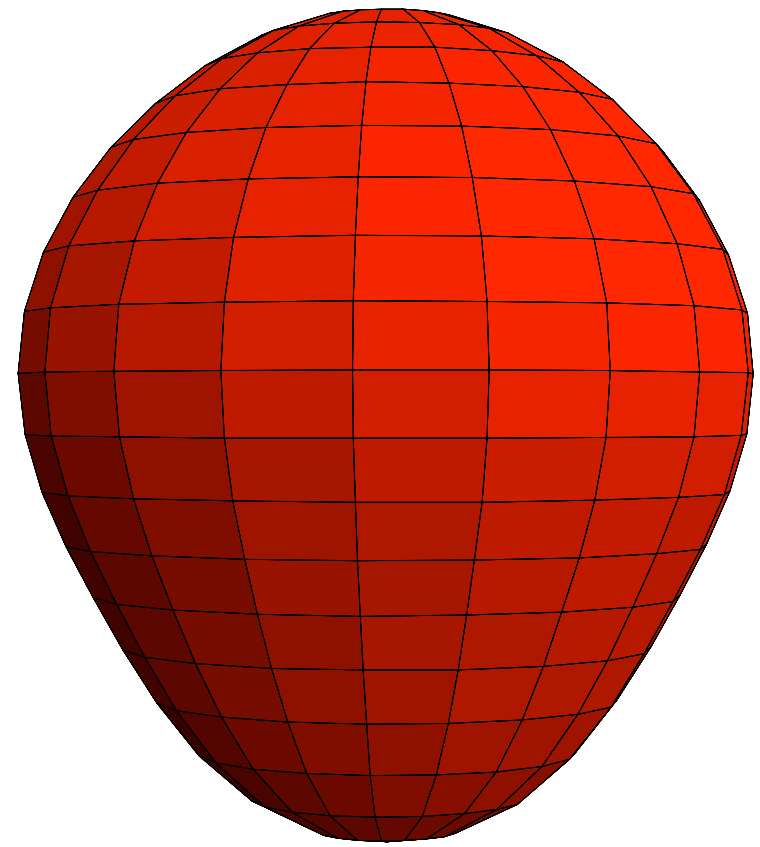
*WH and Henley, PRL 51 (1983) 1937
Sushkov, Flambaum, Khriplovich, JETP 60 (1984) 873



Argonne group work on trapped ^{225}Ra has established an upper bound of

$$< 1.4 \times 10^{-23} \text{ e cm (95\% c.l.)}$$

M. Bishof et al., arXiv:1606.0493

theory: Dzuba et al, PRA 66 (2002) 012111
Auerbach et al., PRL 76 (1996) 4316
Dobaczewski, Engel PRL 94 (2005) 232502

FRIB and the strange case of ^{229}Pa

WH and Henley paper: First study of nuclear enhancements

There was a spectacular case of enhancement identified in that study, the 160 eV parity doublet in ^{229}Pa ($5/2^+ \leftrightarrow 5/2^-$) — a factor > 10^4

Half life of 1.5d, decays by electron capture

But the was no source of ^{229}Pa that could satisfy the needs of a practical experiment

FRIB includes an isotopes harvesting program, focused on medical isotopes

In a parasitic mode, the production of ^{229}Pa is anticipated to be high, 10^{10} atoms/sec

Harvesting over several hours would thus yield in excess of 10^{14} atoms/day

^{225}Ra comparisons: first edm study with a radioactive nucleus

Existing example of use of a radioactive isotope (14.9 d) produced off-site, utilizing a magneto optical trap: 10^{14} atoms used over the experiment's lifetime

Achieved a bound of $< 1.4 \times 10^{-23}$ e cm

Projected statistical sensitivity of the experiment may be $\sim 10^{-28}$ e cm

^{225}Ra provides a factor 100 advantage over ^{199}Hg: 55 keV degeneracy

^{229}Pa provides a factor of 250 advantage over ^{225}Ra: 160 eV degeneracy

While there have been exotic suggestions by experimentalists that a ^{229}Pa experiment in the solid state, based on actinide optical crystals … might be wise to just follow the Ra steps

… The ^{229}Pa nuclear edm, but not its Schiff moment, has been calculated

The strange case of ^{229}Pa

The doublet parity mixing means there is a contribution to the edm proportional to

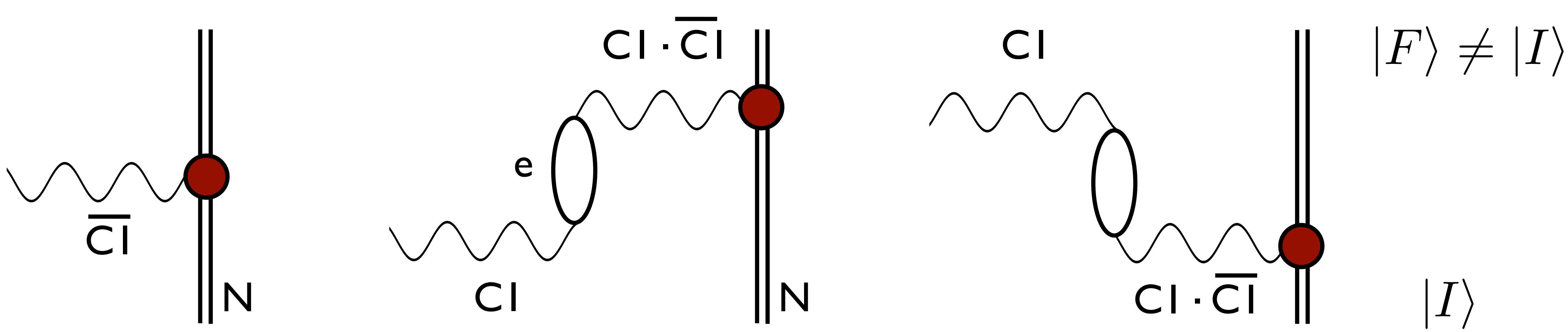
$$\sim \epsilon_{CP} \; \langle 5/2^- | C1 | 5/2^+ \rangle$$

and the C1 matrix element can be taken from the lifetime of the $5/2^-$ state

This state decays by internal conversion 100% due to its low energy:
standard tables of IC coefficients (atomic HF) needed matrix element

It is large (additional enhancement): 14 times the naive Nilsson model estimate

But the Schiff theorem has a generalization for dynamic transitions



if the wavelength of the photon is long on the atomic scale: yes in this crazy case

Does this photo absorption argument also work for IC?

Applied an atomic RPA code: the RPA corrections change the HF result by a factor of 50, suppressing the decay

But the lifetime is measured, so to keep this fixed, the C1 amplitude must be further enhanced by $\sqrt{50}$

Becomes 80 times the s.p. Nilsson model estimate

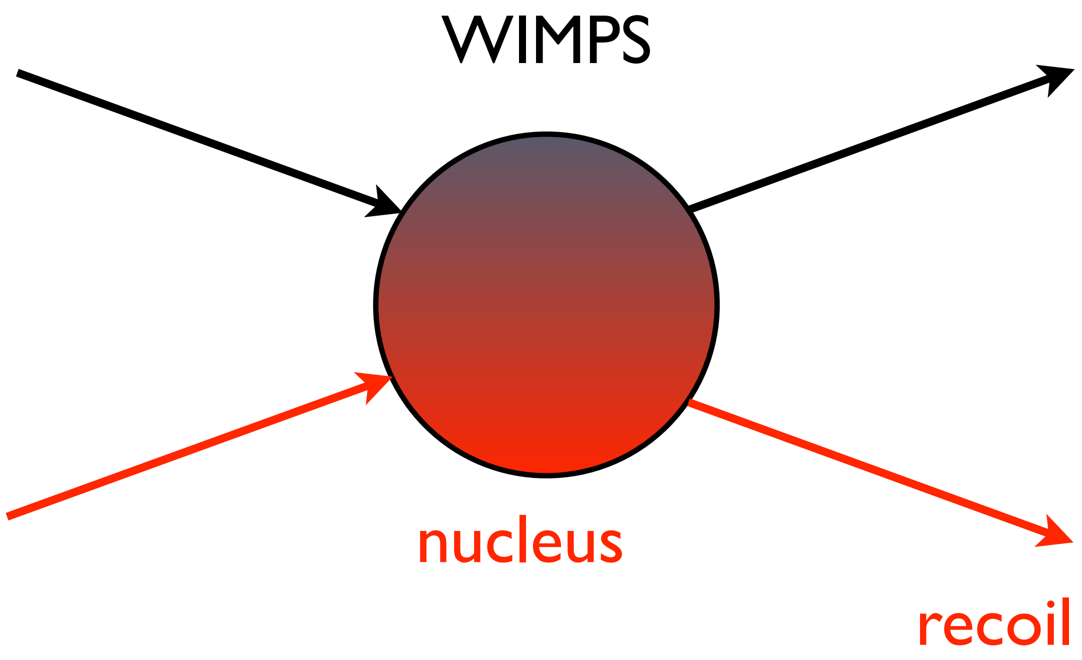
It seems extreme … large enhancement both because of the degeneracy, and because of the crazy C1 strength

It would be great if true

Enhanced C3 and C1 strengths accompany octupole deformation: perhaps the extreme degeneracy and the extreme C1 strengths are reflections of the same physics… *to be continued*

Direct detection of WIMPs

- collider searches
- indirect detection: astrophysical signals
- direct detection



The parameters for the scattering are a bit unusual

- WIMP velocity relative to our rest frame is quite small $\sim 10^{-3}$

- if mass is on the weak scale, WIMP momentum transfers in elastic scattering can be large, up to 200 MeV/c:

  $R_{NUC} \sim 1.2\, A^{1/3}$ f $\Longrightarrow$ $q_{max}\, R \sim 3.2 \Leftrightarrow 6.0$ for F $\Leftrightarrow$ Xe
  the WIMP can “see” the structure of the nucleus

- WIMP kinetic energy ~ 30 keV: elastic scattering is the only open channel, unless the first nuclear excited state is quite near the g.s.

Laura Baudis's WWW Search Map

Xe: Xenon 100/1T; LUX/LZ; XMASS; Zeplin; NEXT

Si: CDMS; DAMIC

Ge: COGENT; Edelweiss; SuperCDMS; TEXONO; CDEX; GERDA; Majorana

NaI: DAMA/LIBRA; ANAIS; DM-ice; SABRE; KamLAND-PICO

CsI: KIMS

Ar: DEAP/CLEAN; ArDM; Darkside

Ne: CLEAN

C/F-based: PICO; DRIFT; DM-TPC

CF_3I: COUP

Cs2: DRIFT

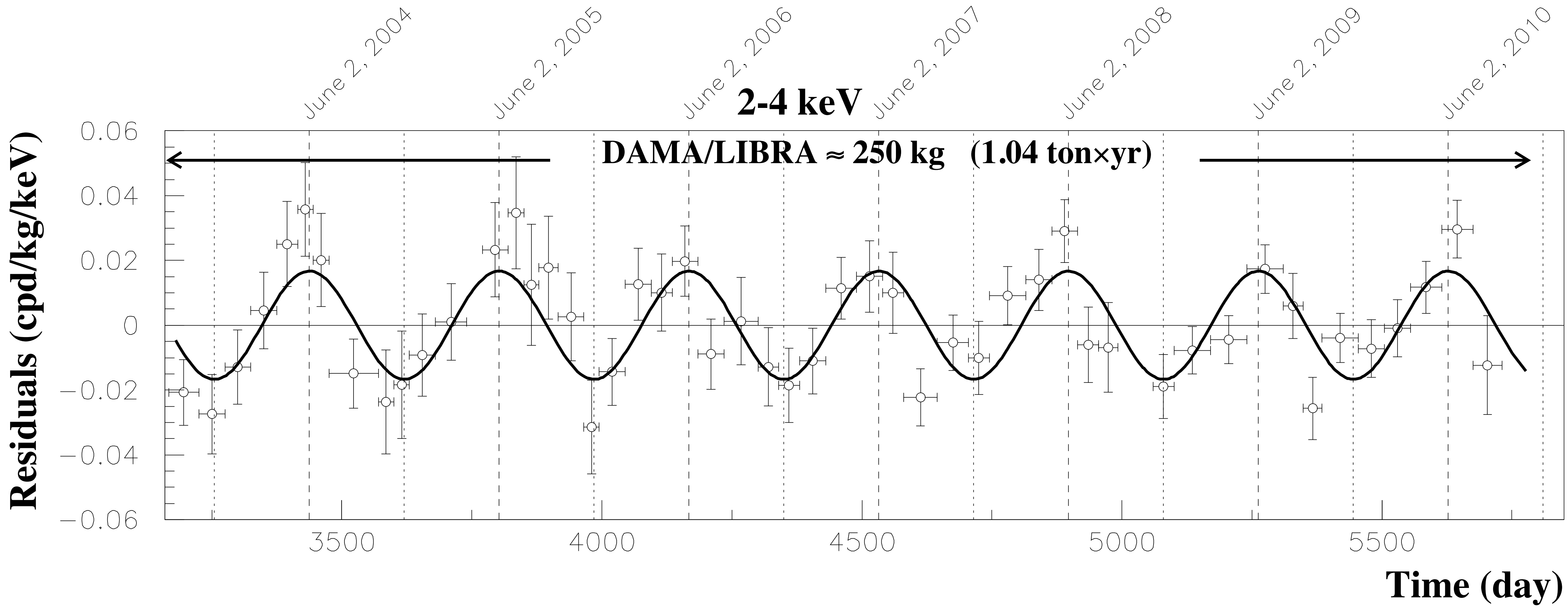
TeO2: CUORE

CaWO4: CRESST

A large variety of nuclei with different spins, isospin, masses

unpaired valence nucleons carrying a variety of values of the orbital angular momentum

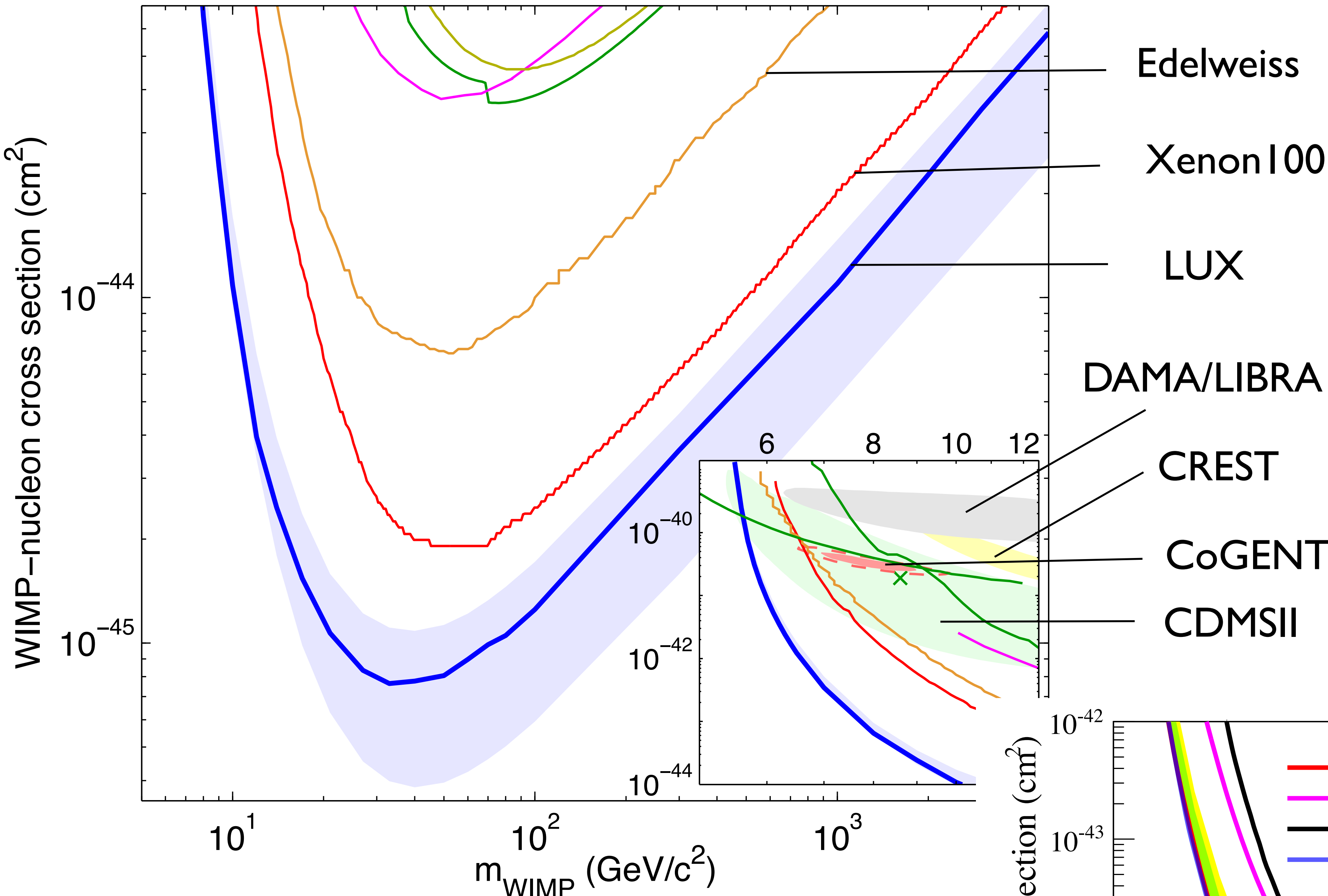
$$\vec{j} = \vec{\ell} + \vec{s}$$



One persistent claim of a signal:

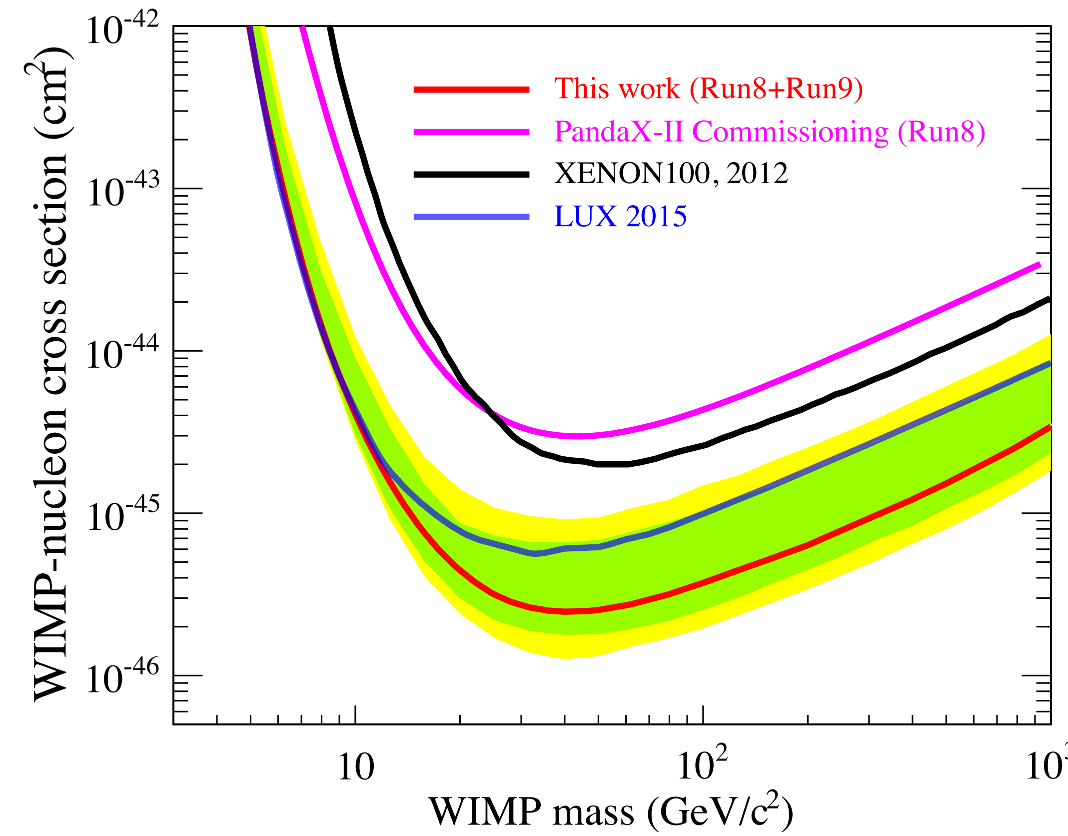
DAMA/LIBRA: 9.3σ annual fluctuation, attributed to the variation of a DM signal due to effects Earth's velocity as we travel through a WIMP sea

$M_{WIMP} \sim 10$ GeV → $E_R^{max} \sim 10$ keV

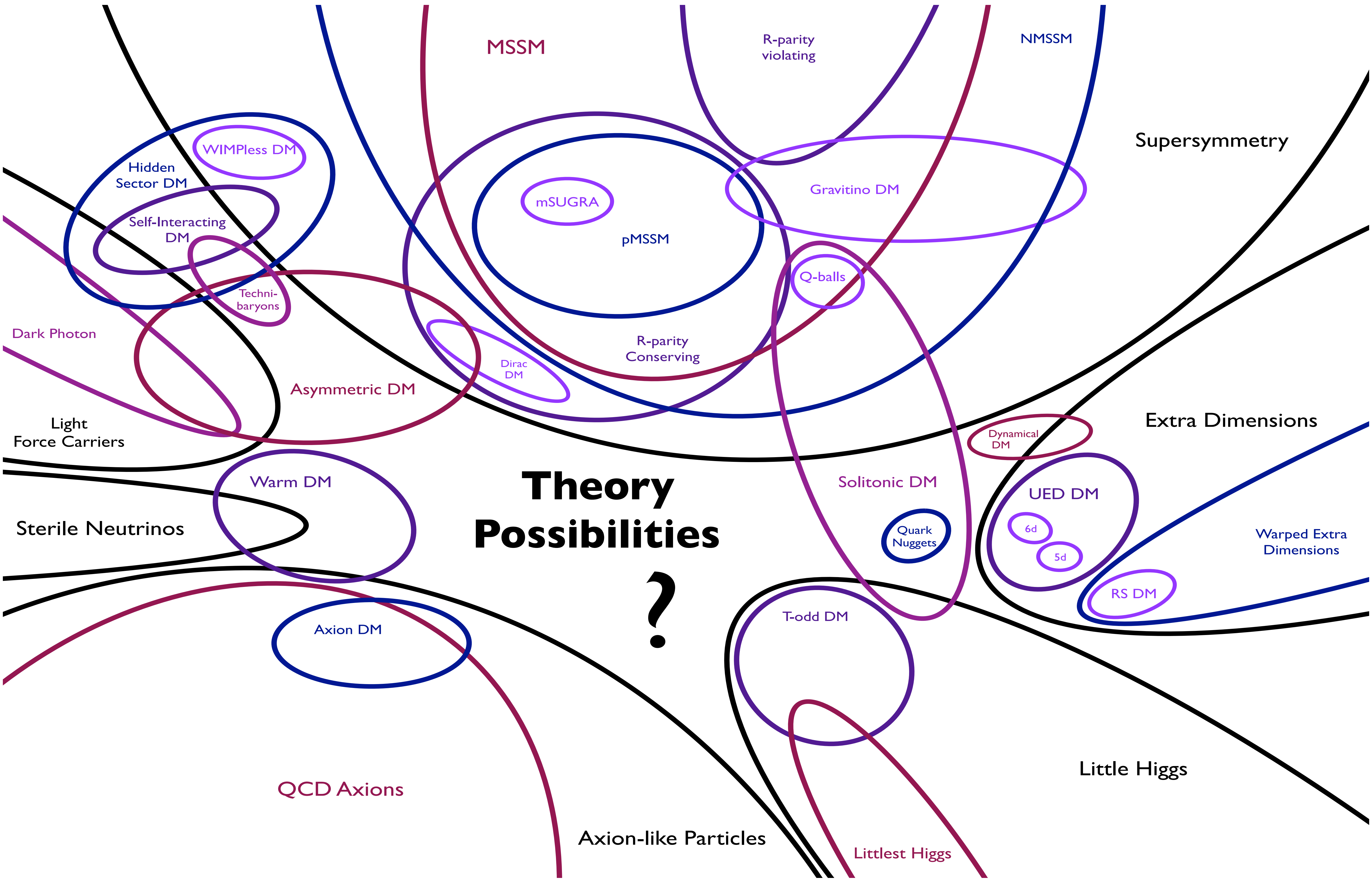


<u>Excluded by others</u>

LUX, PRL 116 (2016) 161301 (for an update)
Xenon 1t has first results



PandaX, PRL 117 (2016) 121303
PandaX SD coming out



from Tim Tait

- Experiments are frequently analyzed and compared in a formalism in which the nucleus is treated as a point particle

$$\text{S.I.} \quad \Rightarrow \quad \langle g.s.| \sum_{i=1}^{A} (a_0^F + a_1^F \tau_3(i)) \; |g.s.\rangle$$

$$\text{S.D.} \quad \Rightarrow \quad \langle g.s.| \sum_{i=1}^{A} \vec{\sigma}(i) \; (a_0^{GT} + a_1^{GT} \tau_3(i)) \; |g.s.\rangle$$

- Is this an adequate formalism for comparing experiments?

- Does is properly encode what you can learn about the universe of UV theories from direct detection experiments…?

UV to Nucleon Scale to an Exclusive Nuclear Process

□ A familiar electroweak interactions problem: What is the form of the elastic response for a nonrelativistic theory with vector and axial-vector interactions?

charges:

	even	odd
vector	C_0	C_1
axial	C_0^5	C_1^5

currents:

	even	odd	even	odd	even	odd
axial spin	L_0^5	L_1^5	$T_2^{5\mathrm{el}}$	$T_1^{5\mathrm{el}}$	$T_2^{5\mathrm{mag}}$	$T_1^{5\mathrm{mag}}$
vector velocity	L_0	L_1	T_2^{el}	T_1^{el}	T_2^{mag}	T_1^{mag}
vector spin − velocity	L_0	L_1	T_2^{el}	T_1^{el}	T_2^{mag}	T_1^{mag}

Response constrained by good parity and time reversal of nuclear g.s.

	even	odd
vector	C_0	
axial		C_1^5

	even	odd	even	odd	even	odd
axial spin		L_1^5		$T_1^{5\text{el}}$	$T_2^{5\text{mag}}$	
vector velocity	L_0		T_2^{el}			T_1^{mag}
vector spin − velocity	L_0		T_2^{el}			T_1^{mag}

Response constrained by good parity and time reversal of nuclear g.s.

	even	odd
vector	C_0	
axial		

	even	odd	even	odd	even	odd
axial spin		L_1^5		$T_1^{5\mathrm{el}}$		
vector velocity						T_1^{mag}
vector spin − velocity	L_0		T_2^{el}			

General I talk about the Galilean ET formalism we developed to explain these responses: now in use by LUX, CDMX, PandaX

but here … focus just on the concept of nuclear velocity enhance,ent

Six is not two: so we are missing something …

What is missing is the universe of theories with derivative couplings, so interactions involving velocities

Are derivative couplings not relevant (e.g.,not measurable in current experiments)?

Direct detection can be reformulated in a complete way in Galilean effective theory, where the variables are

$$S_\chi,\ S_N,\ v^\perp \equiv v_{\rm WIMP} - v_N,\ \frac{q}{M}$$

Another (but actually the same) question is: *what is the scale that goes with q?*

If we remember our scales, $v_{\rm WIMP}$ relative to our target nucleus is only $\sim 10^{-3}$
So a velocity-dependent amplitude would contribute to cross sections at $\sim 10^{-6}$
Ignoring velocities sounds rather reasonable…

Effective theory instructs one to construct all the possible operators out to some order

Let's take an example: consider

$$\sum_{i=1}^{A} \vec{S}_\chi \cdot \vec{v}^\perp(i)$$

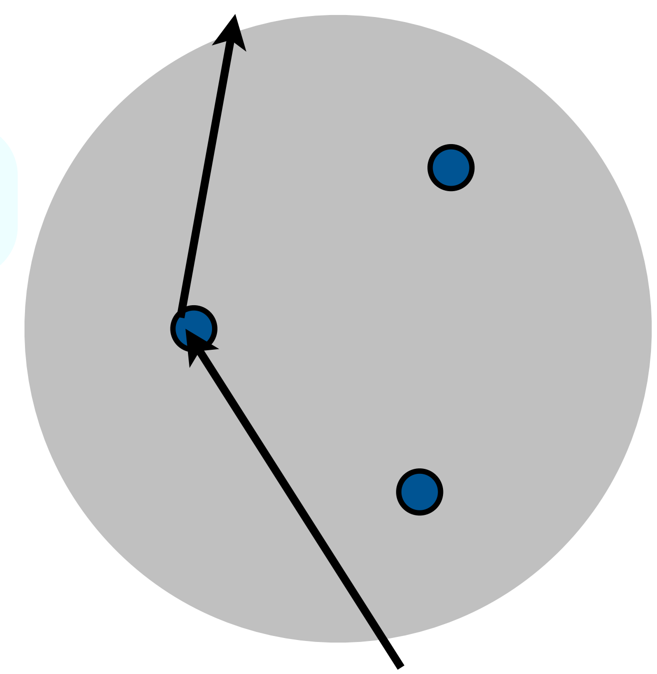
the velocity is defined by Galilean invariance

$$\vec{v}^\perp(i) \equiv \vec{v}_\chi - \vec{v}_N$$

- In the point-nucleus limit $\vec{S}_\chi \cdot \vec{v}_{\mathrm{WIMP}} \sum_{i=1}^{A} 1(i)$

  so a S.I. interaction suppressed by $\vec{v}_{\mathrm{WIMP}} \sim 10^{-3}$

- But in reality the nucleus is not a point



$$\{\vec{v}^\perp(i), i = 1, \cdots, A\} \leftrightarrow \{\vec{v}_{\mathrm{WIMP}};\ \vec{\dot{v}}, i = 1, \cdots, A-1\}$$

$$\vec{\dot{v}}(i) \sim 10^{-1} >> \vec{v}_{\mathrm{WIMP}}$$

- The $\vec{\dot{v}}(i)$ carry odd parity and cannot contribute by themselves to elastic nuclear matrix elements.

- But in elastic scattering, momentum transfers are significant. The full velocity operator is

$$e^{i\vec{q}\cdot\vec{r}(i)} \; \vec{\dot{v}}(i) \quad \text{where} \quad \vec{q}\cdot\vec{r}(i) \sim 1$$

- We can combine the two vector nuclear operators $\vec{\dot{v}}(i),\ \vec{r}(i)$ to form a scalar, vector, and tensor. Expanding the exponential, take the vector case

$$iq\vec{r}\times\vec{\dot{v}} = i\frac{q}{m_N}\;\vec{r}\times\vec{\dot{p}} = -\frac{q}{m_N}\vec{\ell}$$

So velocity-dependent interactions generate much larger contributions to the scattering and several new operators and responses: current generation experiments are probing these

$$\dot{v} \sim 10^{-1} \sim \frac{q}{m_N}$$

and there is our ET mass: Fermi momentum enhancement

The point-nucleus world is what we thought we could probe

But the derivative coupling world is completely available to current detectors

$$R_M^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}) = c_1^\tau c_1^{\tau'} + \frac{j_\chi(j_\chi+1)}{3}\left[\frac{\vec{q}^2}{m_N^2}\vec{v}_T^{\perp 2} c_5^\tau c_5^{\tau'} + \vec{v}_T^{\perp 2} c_8^\tau c_8^{\tau'} + \frac{\vec{q}^2}{m_N^2} c_{11}^\tau c_{11}^{\tau'}\right]$$

$$R_{\Phi''}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}) = \frac{\vec{q}^2}{4m_N^2} c_3^\tau c_3^{\tau'} + \frac{j_\chi(j_\chi+1)}{12}\left(c_{12}^\tau - \frac{\vec{q}^2}{m_N^2} c_{15}^\tau\right)\left(c_{12}^{\tau'} - \frac{\vec{q}^2}{m_N^2} c_{15}^{\tau'}\right)$$

$$R_{\Phi'' M}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}) = c_3^\tau c_1^{\tau'} + \frac{j_\chi(j_\chi+1)}{3}\left(c_{12}^\tau - \frac{\vec{q}^2}{m_N^2} c_{15}^\tau\right) c_{11}^{\tau'}$$

$$R_{\tilde{\Phi}'}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}) = \frac{j_\chi(j_\chi+1)}{12}\left[c_{12}^\tau c_{12}^{\tau'} + \frac{\vec{q}^2}{m_N^2} c_{13}^\tau c_{13}^{\tau'}\right]$$

$$R_{\Sigma''}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}) = \frac{\vec{q}^2}{4m_N^2} c_{10}^\tau c_{10}^{\tau'} + \frac{j_\chi(j_\chi+1)}{12}\left[c_4^\tau c_4^{\tau'} + \frac{\vec{q}^2}{m_N^2}(c_4^\tau c_6^{\tau'} + c_6^\tau c_4^{\tau'}) + \frac{\vec{q}^4}{m_N^4} c_6^\tau c_6^{\tau'} + \vec{v}_T^{\perp 2} c_{12}^\tau c_{12}^{\tau'} + \frac{\vec{q}^2}{m_N^2}\vec{v}_T^{\perp 2} c_{13}^\tau c_{13}^{\tau'}\right]$$

$$R_{\Sigma'}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}) = \frac{1}{8}\left[\frac{\vec{q}^2}{m_N^2}\vec{v}_T^{\perp 2} c_3^\tau c_3^{\tau'} + \vec{v}_T^{\perp 2} c_7^\tau c_7^{\tau'}\right] + \frac{j_\chi(j_\chi+1)}{12}\left[c_4^\tau c_4^{\tau'} + \frac{\vec{q}^2}{m_N^2} c_9^\tau c_9^{\tau'} + \frac{\vec{v}_T^{\perp 2}}{2}\left(c_{12}^\tau - \frac{\vec{q}^2}{m_N^2} c_{15}^\tau\right)\left(c_{12}^{\tau'} - \frac{\vec{q}^2}{m_N^2} c_{15}^{\tau'}\right) + \frac{\vec{q}^2}{2m_N^2}\vec{v}_T^{\perp 2} c_{14}^\tau c_{14}^{\tau'}\right]$$

$$R_{\Delta}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}) = \frac{j_\chi(j_\chi+1)}{3}\left[\frac{\vec{q}^2}{m_N^2} c_5^\tau c_5^{\tau'} + c_8^\tau c_8^{\tau'}\right]$$

$$R_{\Delta\Sigma'}^{\tau\tau'}(\vec{v}_T^{\perp 2}, \frac{\vec{q}^2}{m_N^2}) = \frac{j_\chi(j_\chi+1)}{3}\left[c_5^\tau c_4^{\tau'} - c_8^\tau c_9^{\tau'}\right].$$

Conclusion

If you like symmetries
nuclei are your friends!