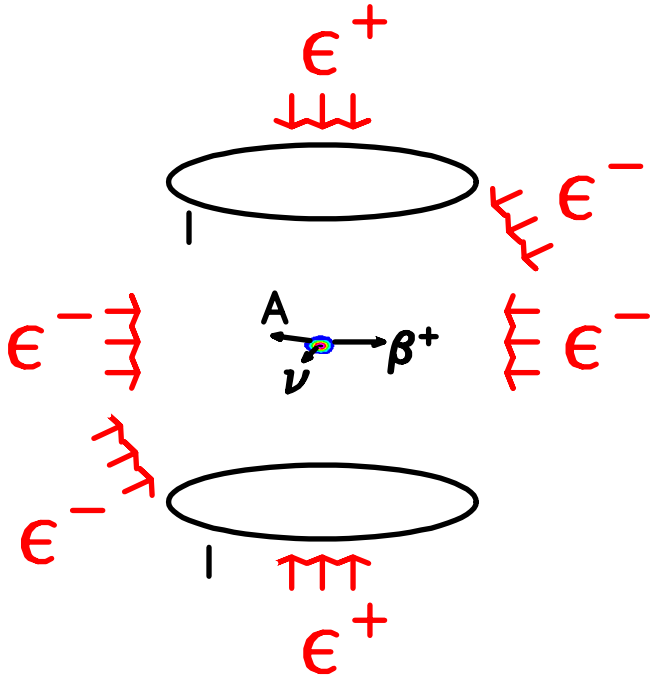
β-decay correlations with laser-trapped ^{37}K in the LHC era

- Precision measurement of angular correlations
  - Complementarity with particle phenomenology
- How our atom trap helps us
  - Spin-polarizing nucleus with laser
- Example: The most accurate A_β measurement
  - What we are learning from it
  - How much better we must do
- Plans for time-reversal violation in radiative β decay



TRIumf Neutral Atom Trap collaboration

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A_β is the Ph.D. thesis work of B. Fenker

Electroweak Interactions: what we "know"

- **E&M unified with Weak interactions**

$$\gamma \Longleftrightarrow Z^0, W^+, W^-$$

1) Only spin-1 "vector" exchange bosons
2) Only left-handed ν's: "parity is maximally violated"

- **Things we can test:**

1) Bosons with other spin?

2) Couplings to wrong-handed leptons?

2) A big 'Standard Model' success was predicting the Z^0.
Amount of atomic parity violation is sensitive to extra neutral bosons
(Francium PNC, Manitoba/Maryland/William & Mary/San Luis Potosi/TRIUMF)

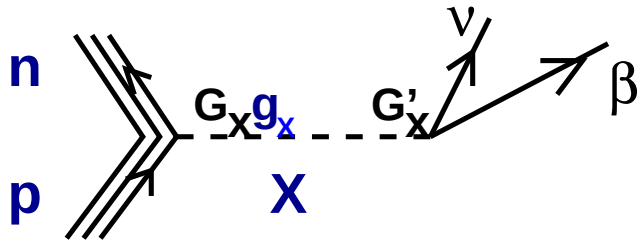
Why the weak interaction is 'weak' at low energy

'more massive virtual particles are created for shorter times/distances'

Propagator+vertices:

$$T \propto \frac{G_X(-g^{\mu\nu}+p^\mu p^\nu/M_X^2)G_X}{p^2-M_X^2} \xrightarrow{p<<M_X}$$

$$T \propto \frac{G_X^2}{M_X^2} \Rightarrow$$



Decay rates $\propto \frac{G_X^4}{M_X^4}$

Decay rate $\propto \frac{G^2}{M_W^2}\frac{G_X^2}{M_X^2}$ if process interferes with W (couples to left-handed ν)

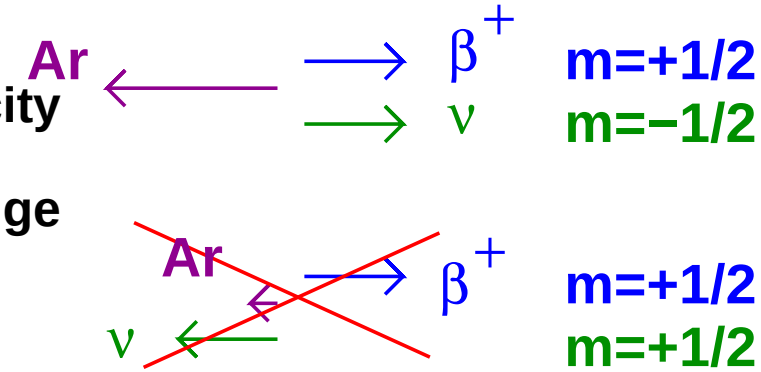
- IF $G_X \sim$ electroweak coupling, then absence of 0.1% changes in angular correlations $\Rightarrow M_X > 6$ or 30 M_W

- But if G_X small, then M_X can still be small. Popular in neutral boson models, motivated by particle astrophysics

Lepton helicity → angular distribution

For ^{38m}K, $0^+ \rightarrow 0^+$ decay:

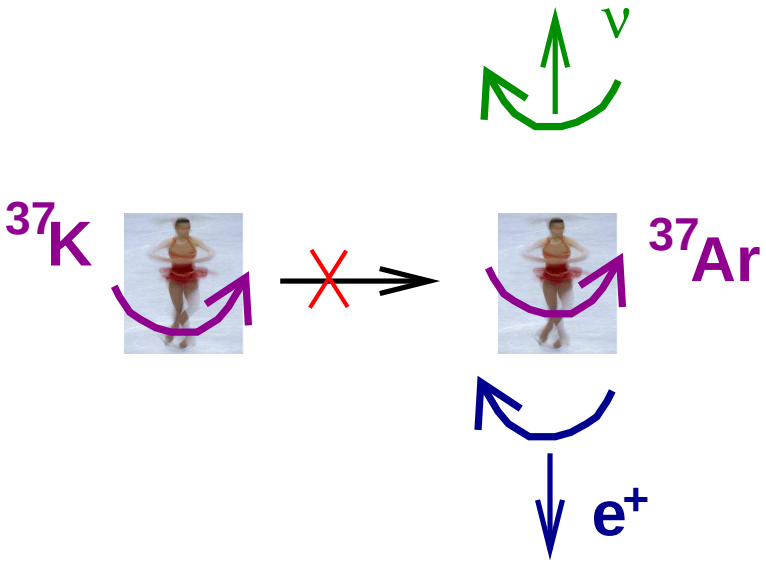
leptons have opposite helicity for W (vector) boson exchange



$$W[\theta_{\beta\nu}] = 1 + b\frac{m}{E} + a\frac{v_\beta}{c}\cos\theta_{\beta\nu}$$

$\Rightarrow$ **a** $= +1$, **b** $= 0$ $\quad a = -1$ for scalar

- **independent of isospin mixing and nuclear structure**
- **Radiative corrections 2x10^{-3}, recoil order term is 3x10^{-4}**

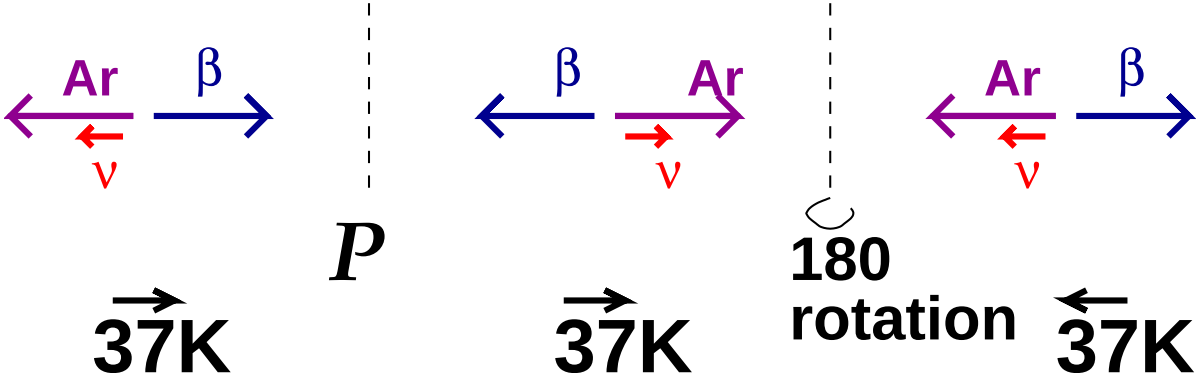


← This decay pattern needs non-S.M. chirality

Parity Operation can be simulated by Spin Flip

Under Parity operation *P*:

$\vec{r} \rightarrow -\vec{r}$ $\quad$ $\vec{p} \sim \frac{d\vec{r}}{dt} \rightarrow -\vec{p}$ $\quad$ $\vec{J} = \vec{r} \times \vec{p} \rightarrow +\vec{J}$



This is exact

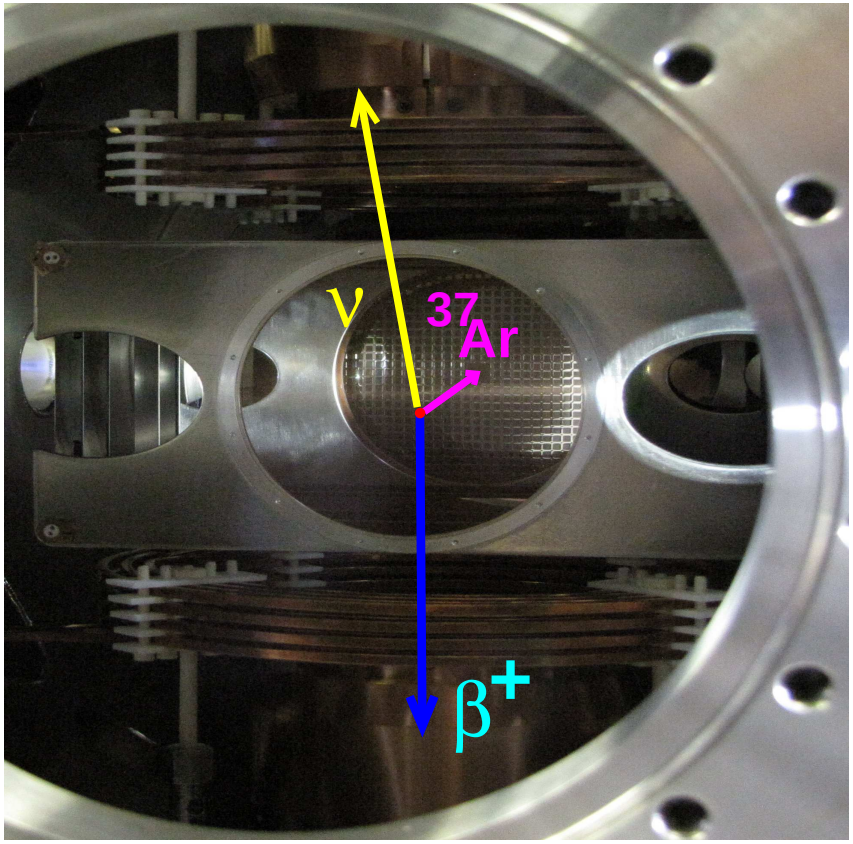
3-momentum $\not{T}$ correlation

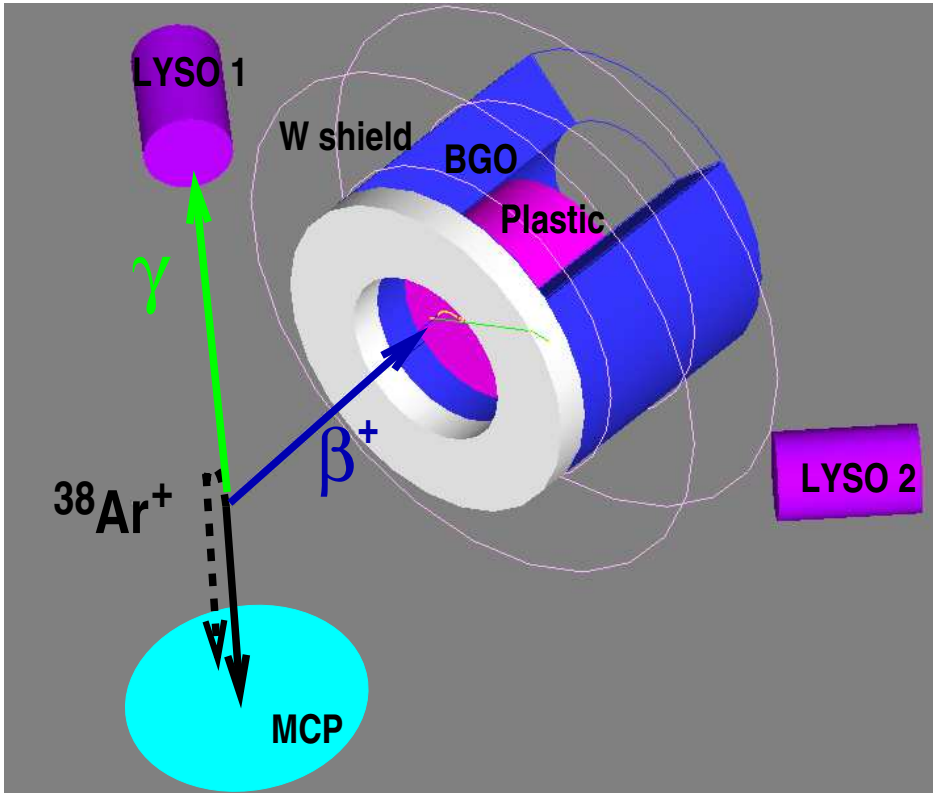
When t → -t :

$\vec{r} \rightarrow \vec{r} \qquad \vec{p} \sim \frac{d\vec{r}}{dt} \rightarrow -\vec{p}$

$$\vec{p_\nu} \cdot \vec{p_\beta} \times \vec{p_\gamma} = -\vec{p_{recoil}} \cdot \vec{p_\beta} \times \vec{p_\gamma}$$

$$\xrightarrow{t \rightarrow -t} \vec{p_{recoil}} \cdot \vec{p_\beta} \times \vec{p_\gamma}$$





BUT flipping t is not the same thing as running the decay backwards.

Particles interact on the way out, and you don't reverse that part.

One experimental discovery of parity violation

Wu, Ambler, Hayward, Hopper, Hobson, PR 105 (1957) 1413

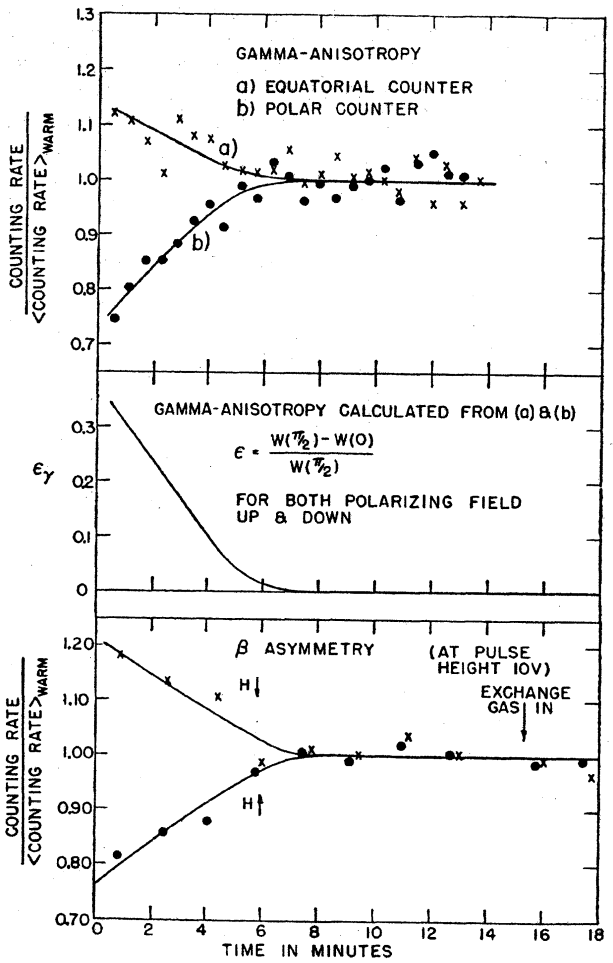
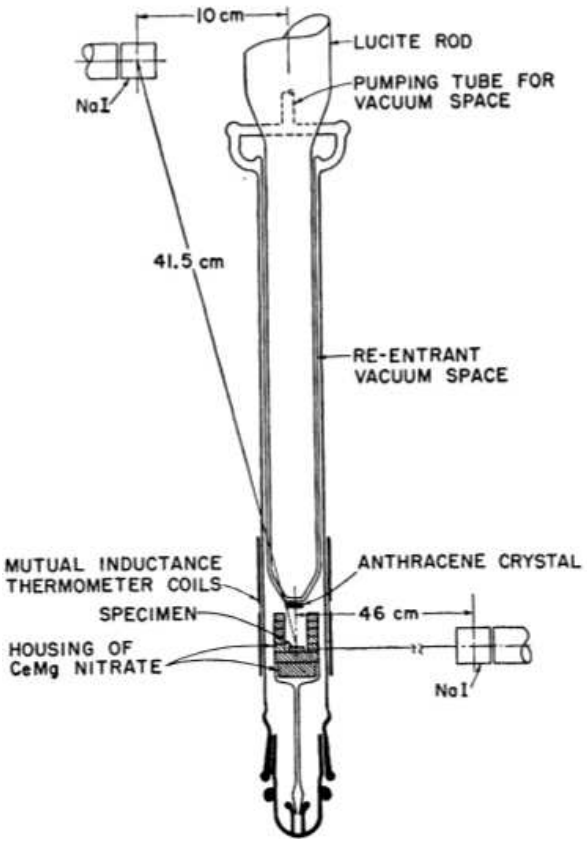


FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.

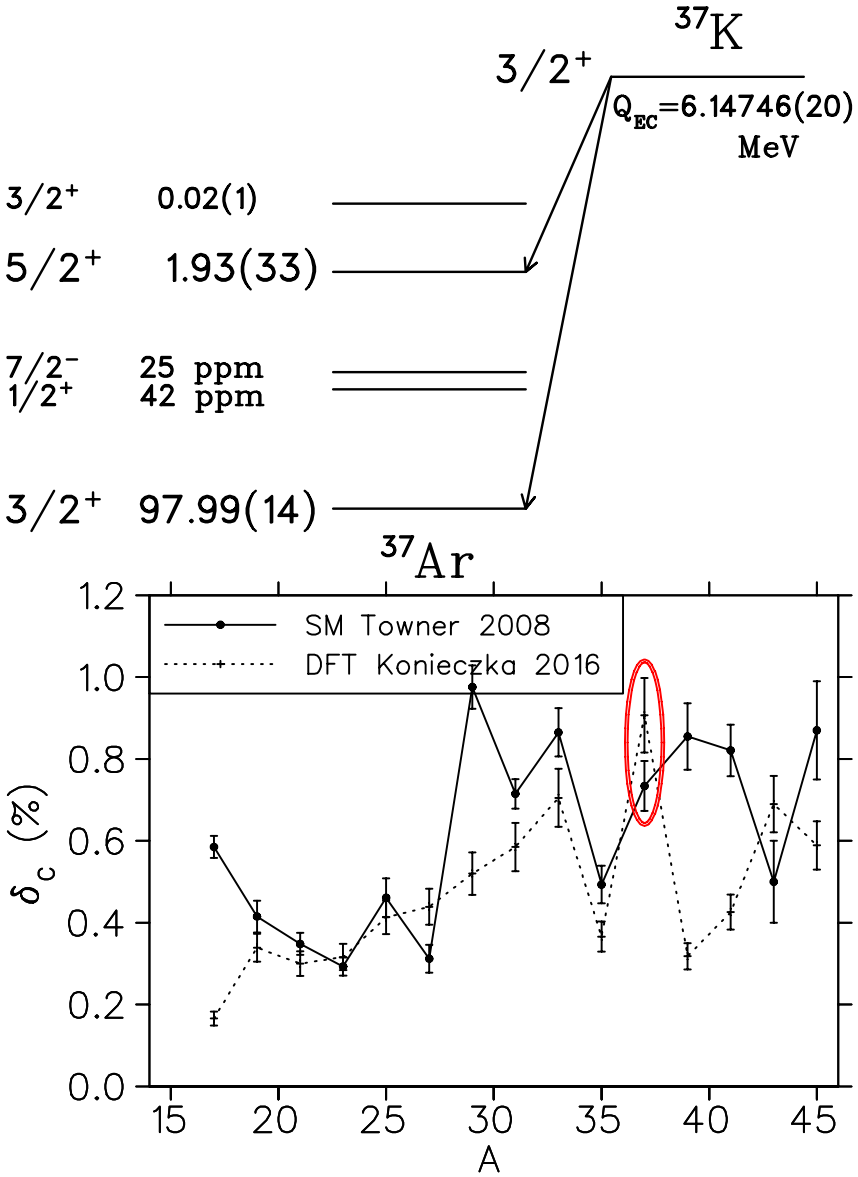


Dilution Refrigerator to spin-polarize

$^{60}\mathrm{Co} \rightarrow$
$^{60}\mathrm{Ni} + \beta^- + \bar{\nu}$

$$W[\theta] = 1 + A\hat{\mathbf{I}} \cdot \frac{\vec{p}_\beta}{E_\beta}$$
$$= 1 + A\frac{v}{c}\cos[\theta]$$
$$A = 1.0$$

^{37}K isobaric mirror decay: a 'heavy neutron' ?



$\mathcal{F}t$ (Shidling PRC 2014) $\Rightarrow$
$\rho = C_A M_{GT} / C_V M_F =$
0.5768 ± 0.0021
$\Rightarrow A_\beta[SM] = -0.5706 \pm 0.0007$

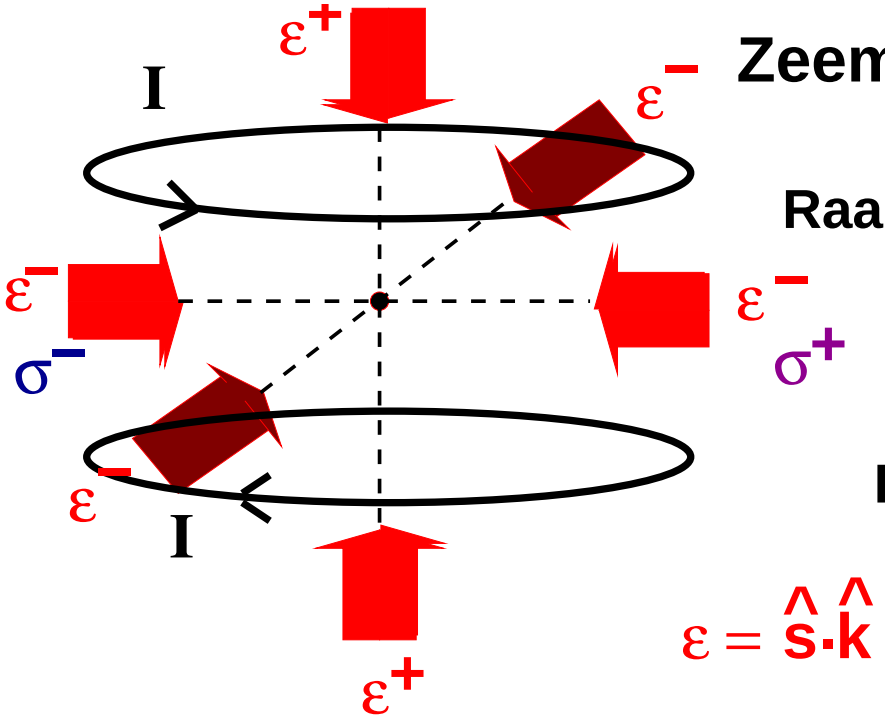
Recoil-order + Coulomb + finite-size corrections $\approx$ $-0.0028\ (E_\beta / E_0)$

1st-order recoil-order from E&M moments; small $\mu \Rightarrow$ small weak magnetism (Coulomb corrections $\sim$ weak mag) Holstein RMP 1975

DFT for isospin mixing has improved its functional

Using weighted average for δ_C would $\rightarrow \rho = 0.5774 \pm 0.0022$

Magneto-optical trap

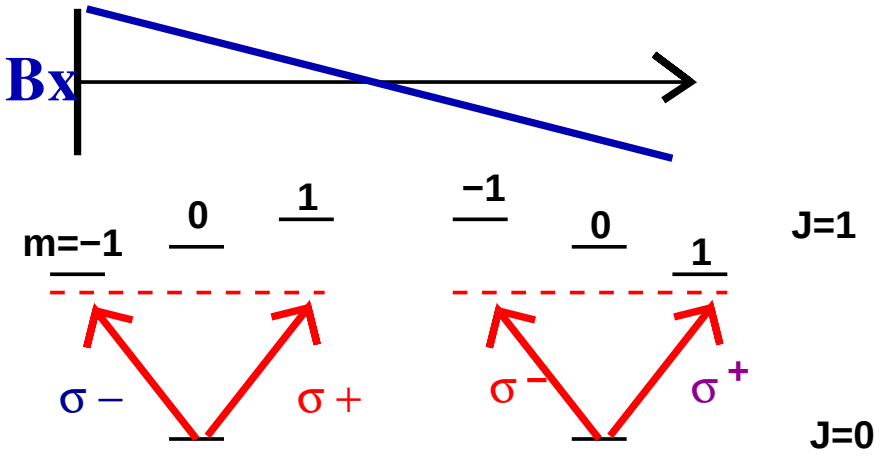


Zeeman Optical Trap (MOT)

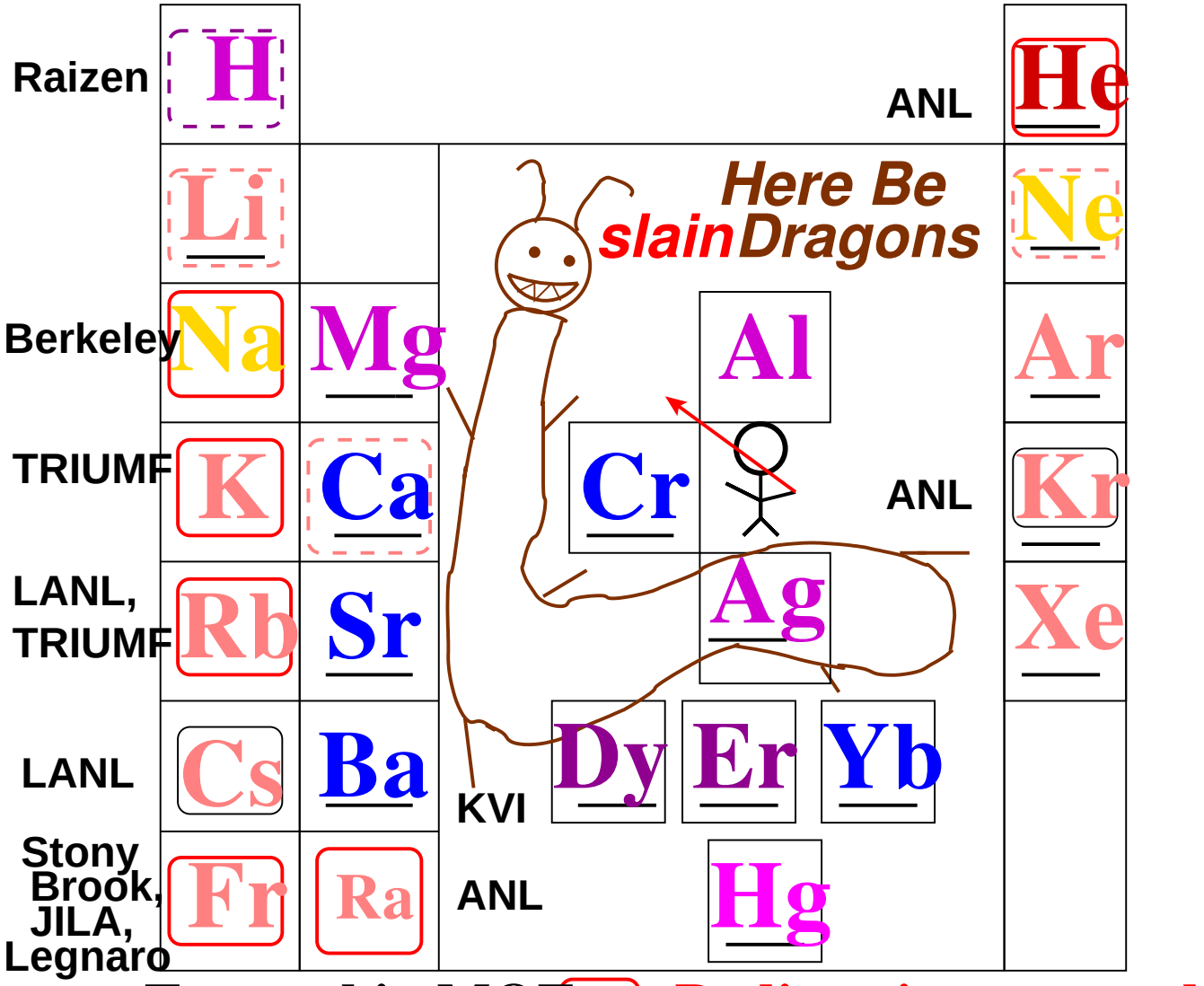
Raab et al. PRL 59 2631 (1987)

Damped harmonic oscillator

$$\varepsilon = \hat{s}\cdot\hat{k}$$



What elements can be laser cooled?



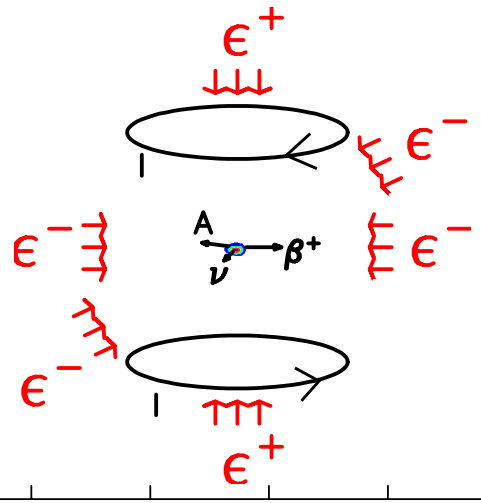
—— Trapped in MOT

Long−livedRad.

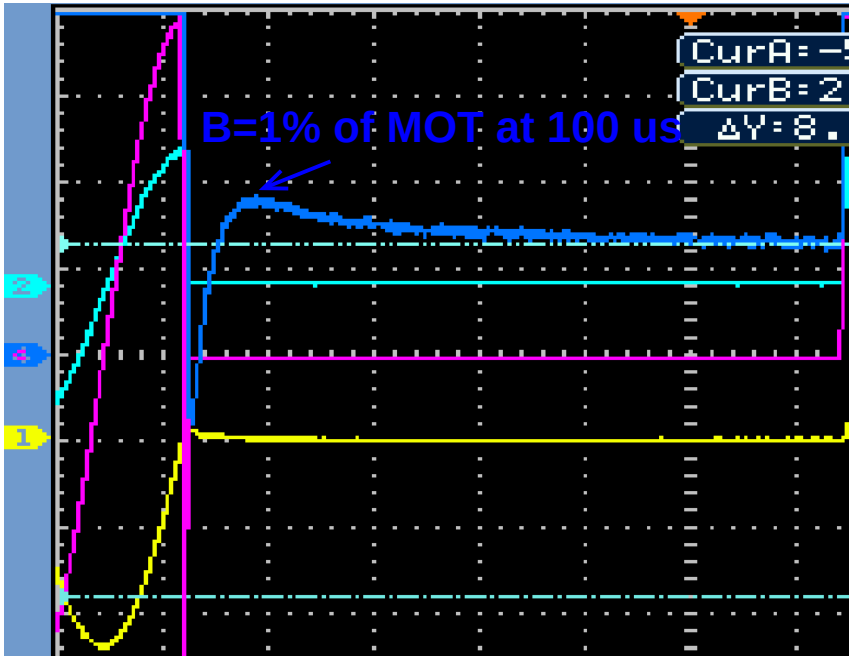
Radioactives trapped

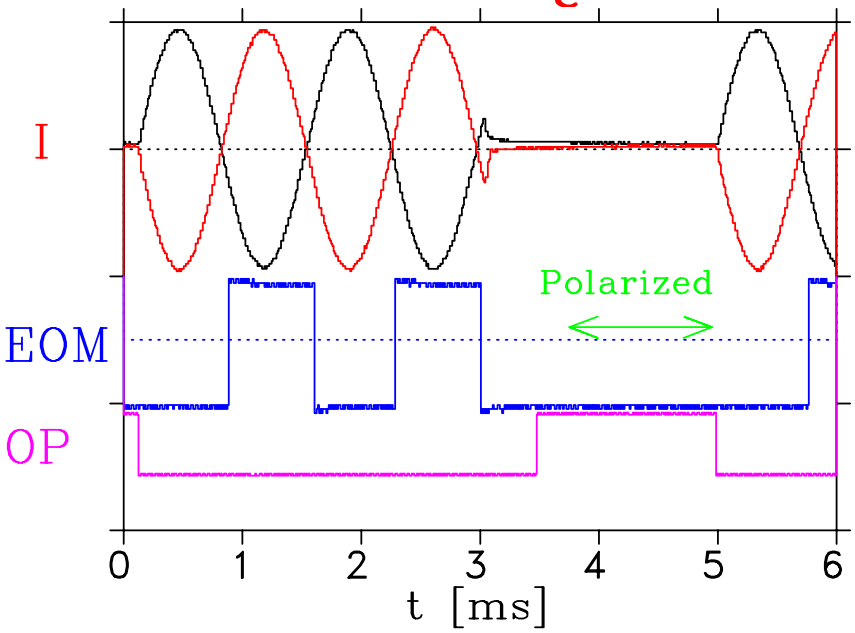
Plans

AC MOT to turn off trap



MOT's 7 G/cm Bquad off to 1% of its value in 100 μs:





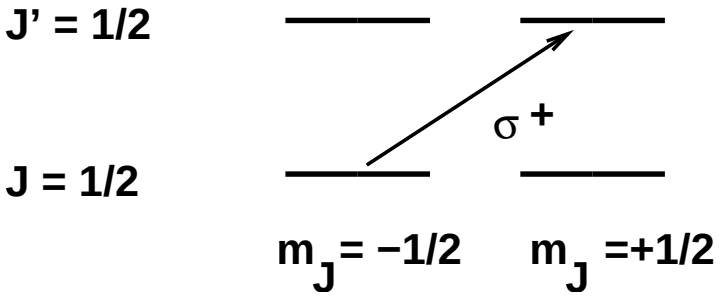
M. Anholm, M.Sc. thesis, UBC 2011

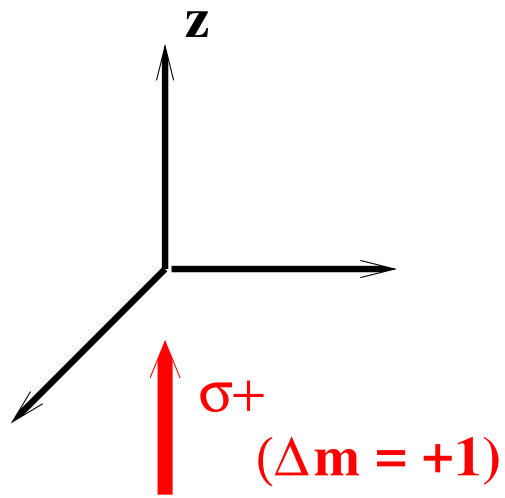
How to spin-polarize a nucleus with a laser: Part I

Polarize atom by Direct Optical Pumping

Biased random walk

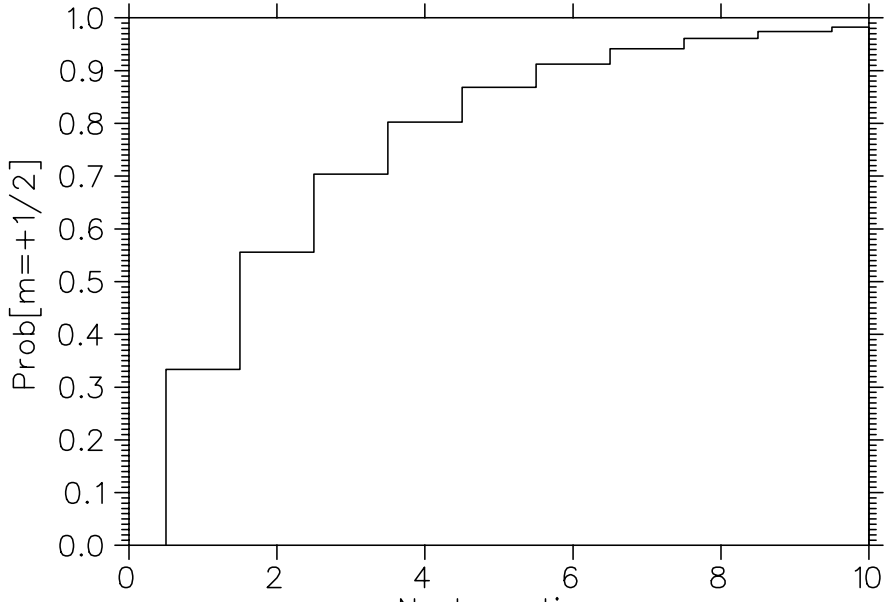
Simple example:



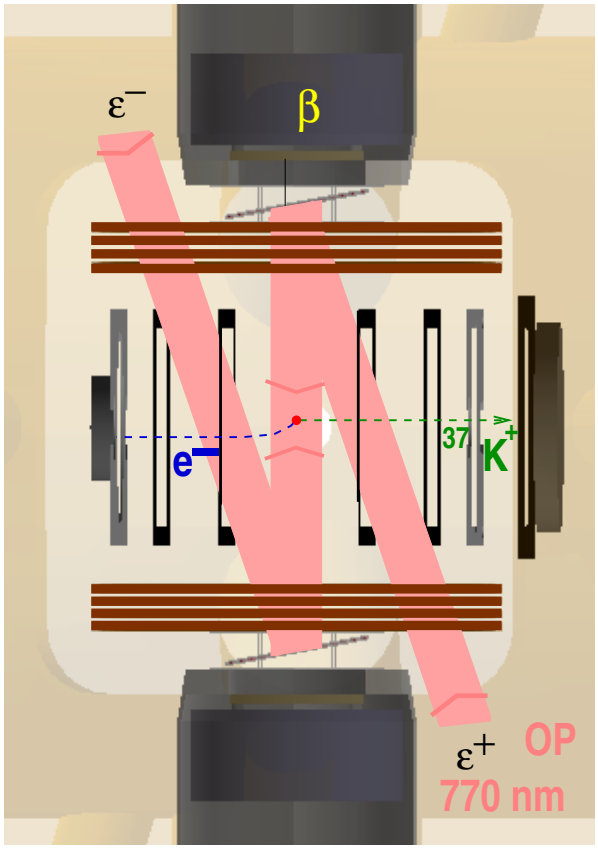


$P(m=1/2) = 1 - (2/3)^N$ after N steps

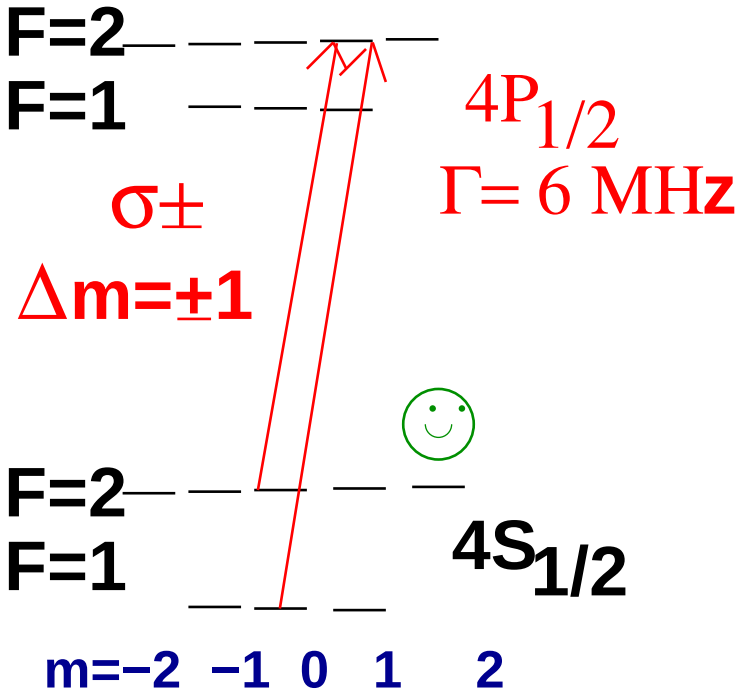
Need 12 photons absorbed to get to 99% of maximum.



Direct Optical Pumping, I=3/2



- Biased random walk
- $\sigma^{\pm}$ light $4S_{1/2} \rightarrow 4P_{1/2}$ transition



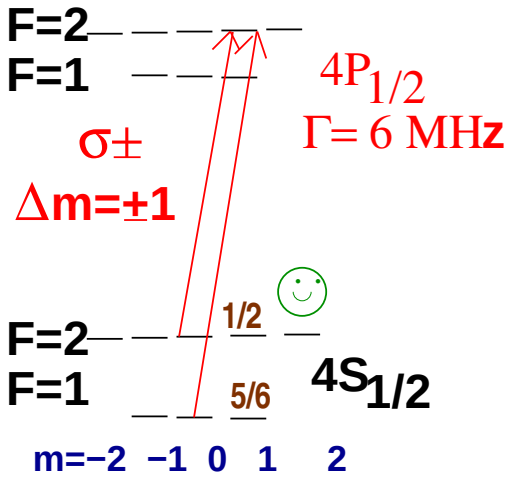
- optimize with ^{41}K, almost same hyperfine splitting as ^{37}K

$\vec{F} = \vec{J}_{\text{atom}} + \vec{I}_{\text{nucleus}}$ $\quad H_{\text{hyperfine}} = -\vec{\mu}_N \cdot \vec{B}_e = A\,\vec{I}\cdot\vec{J}$

Spin flips: $\sigma^+ \rightarrow \sigma^-$;

small frequency shift (-2 MHz) to compensate Zeeman shift

Quantifying Polarization from excited state population



Tail ∼ few % of peak ⇒ We need tail/peak to ∼ 10% accuracy to extract P to ∼ 0.1%

We can't quite extract P by inspection:
$\Delta F = 0$ for Larmor precession

Same centroid P from 2 approaches:

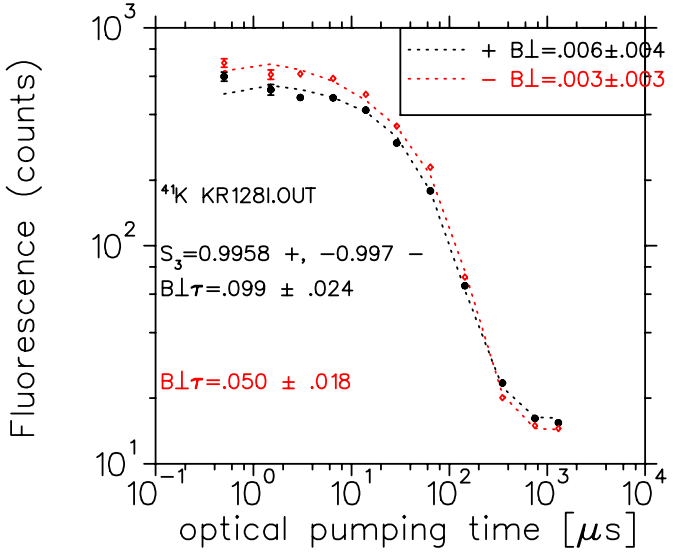
Rate eqs for classical populations

$$\frac{dN_i}{dt} = -R_{ji}N_i + R_{ij}N_j + \lambda N_j$$

Optical Bloch Eqs include $B_\perp$ rigorously

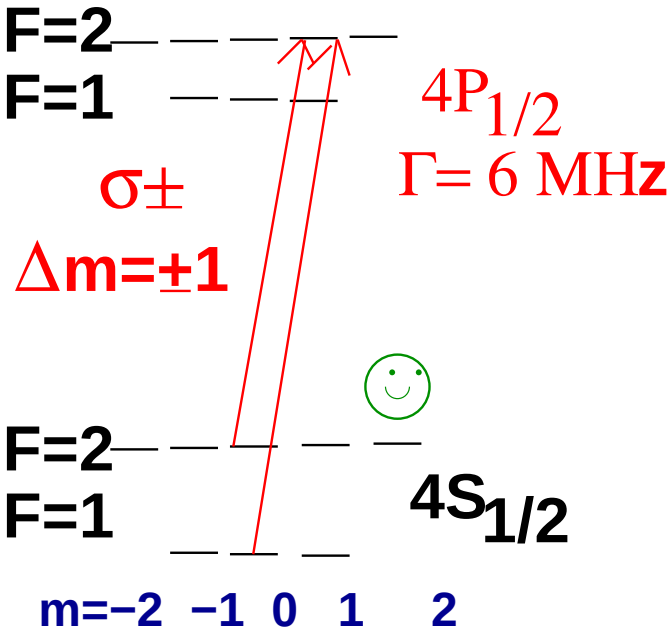
$$\frac{d\rho}{dt} = \frac{1}{i\hbar}[H,\rho] + \lambda$$

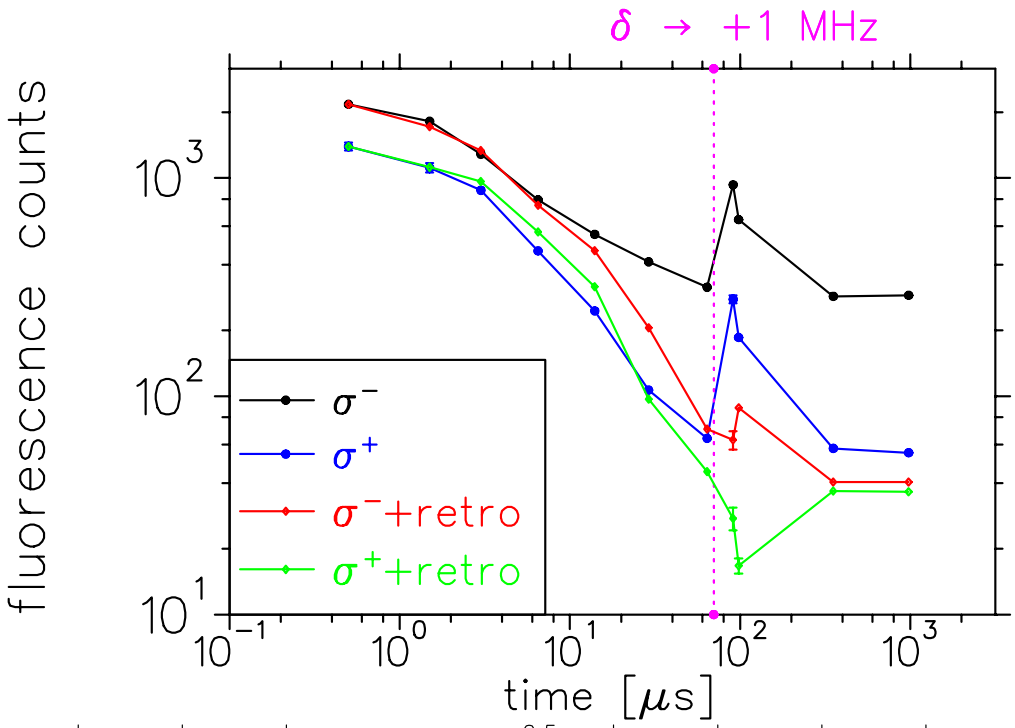
We measure S_3 and float $B_\perp$
(S_3=-0.9958(8), -0.9984(13), +0.9893(14), +0.9994(5))

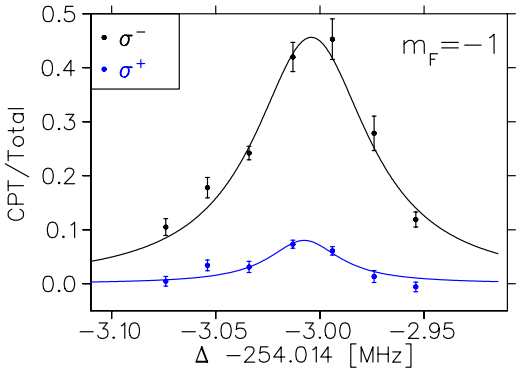


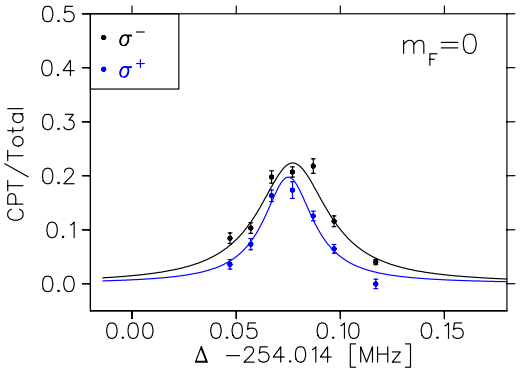
Coherent Population Trapping is bad

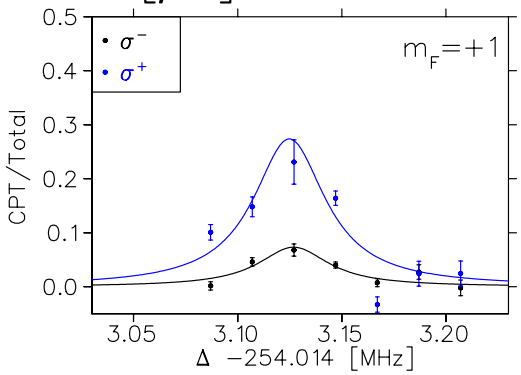
But easy to remove by counter-propagating beams and by RF detuning





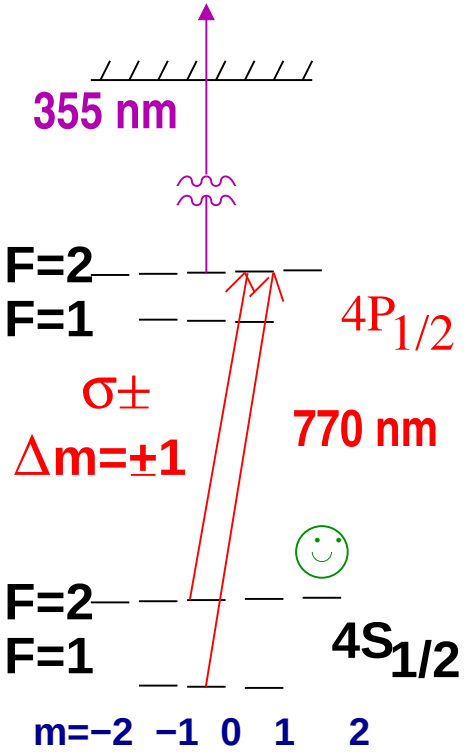


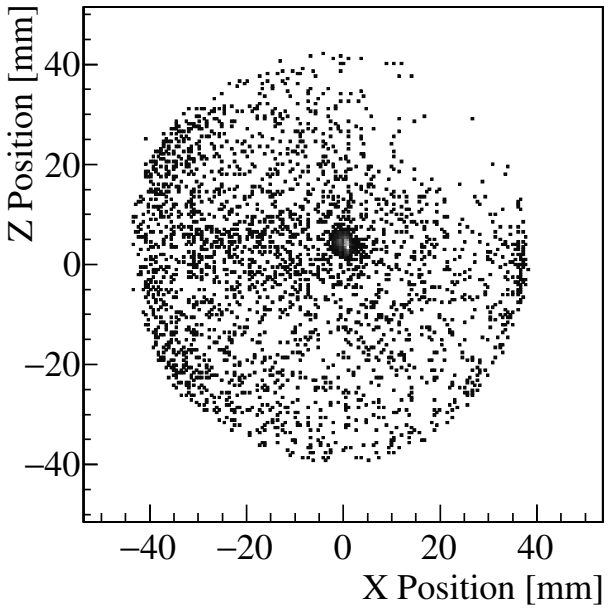


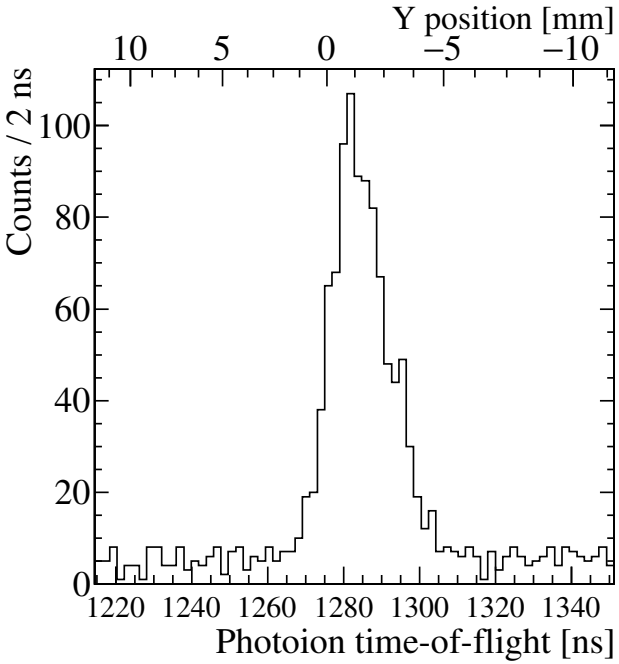


$\Rightarrow$ **B_z = 2.339(10) G**

Optical pumping and probing ^{37}K







Photoionize 1%

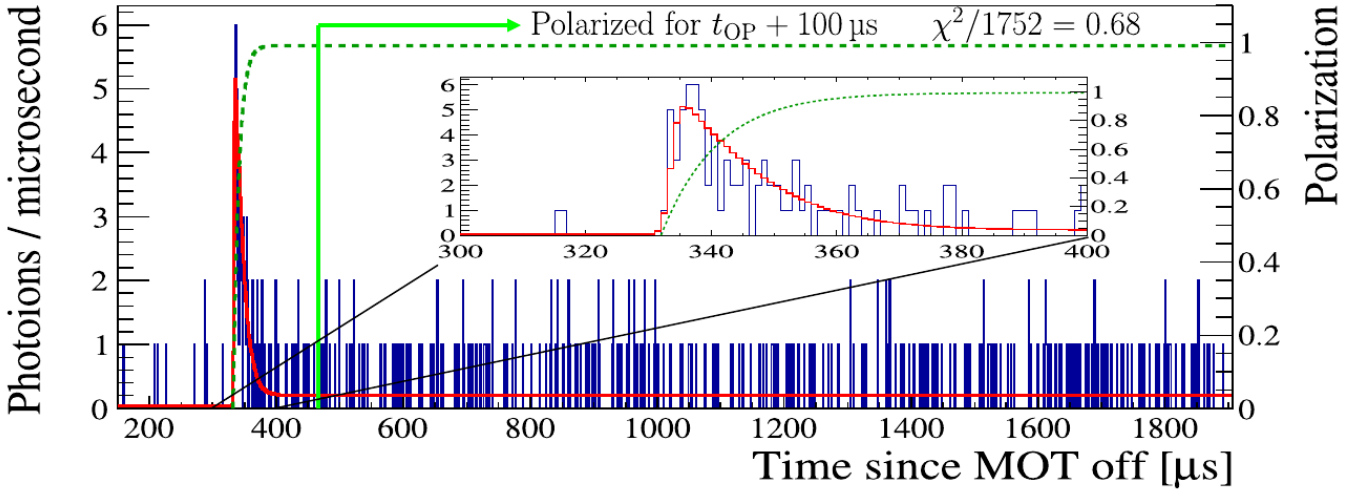
***in situ* probe**

P_+=+0.9913(8)

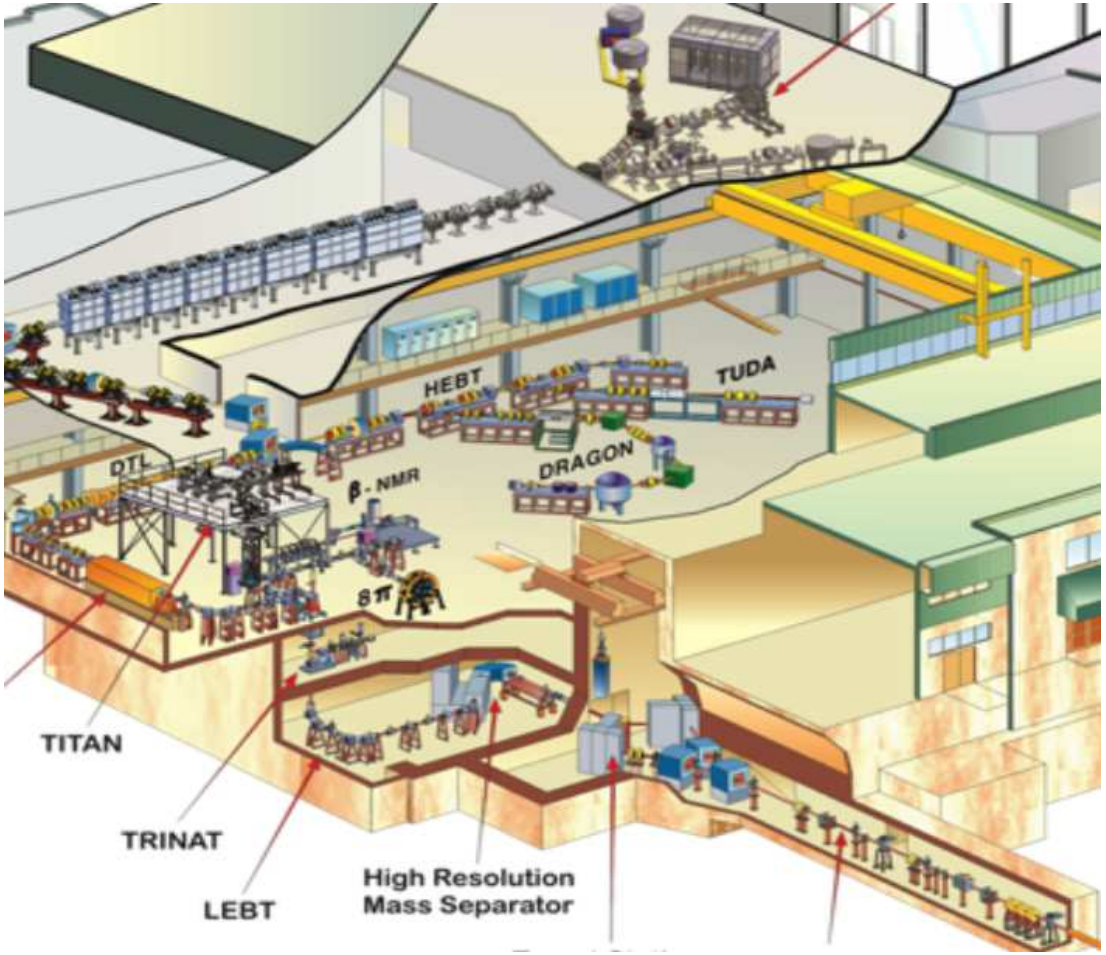
P_-=–0.9912(9)

$\sigma \propto$ (1-P)

Fenker NJP 2016



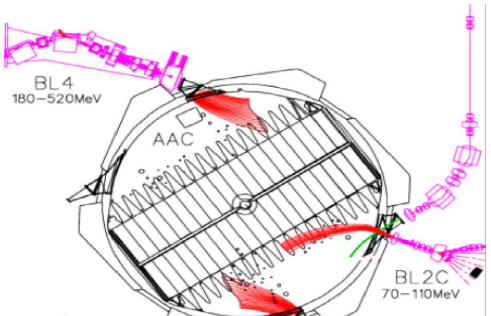
TRIumf Neutral Atom trap at ISAC



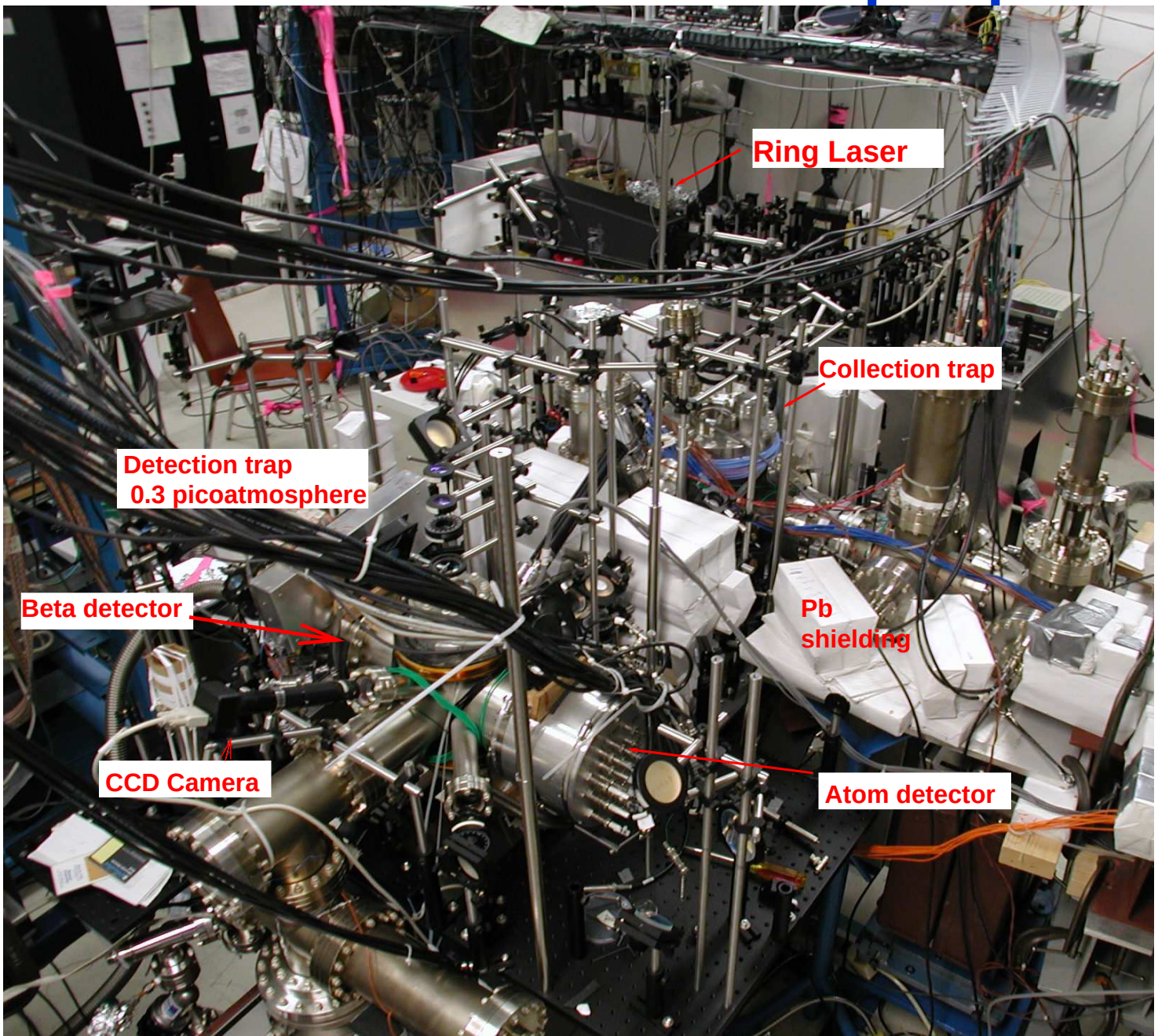
TiC target
1750°C

70 μA
protons

main TRIUMF cyclotron
'world's largest'
500 MeV H^- (0.5 Tesla)

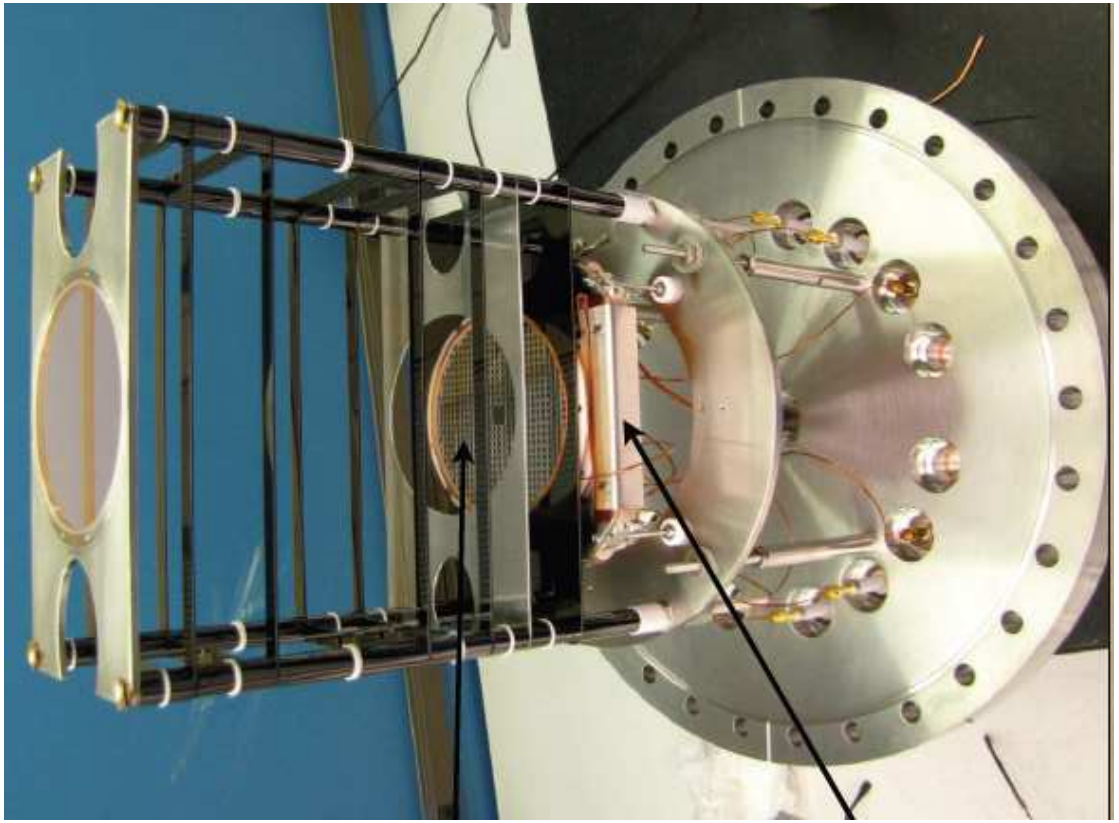


TRINAT lab: “tabletop experiment”



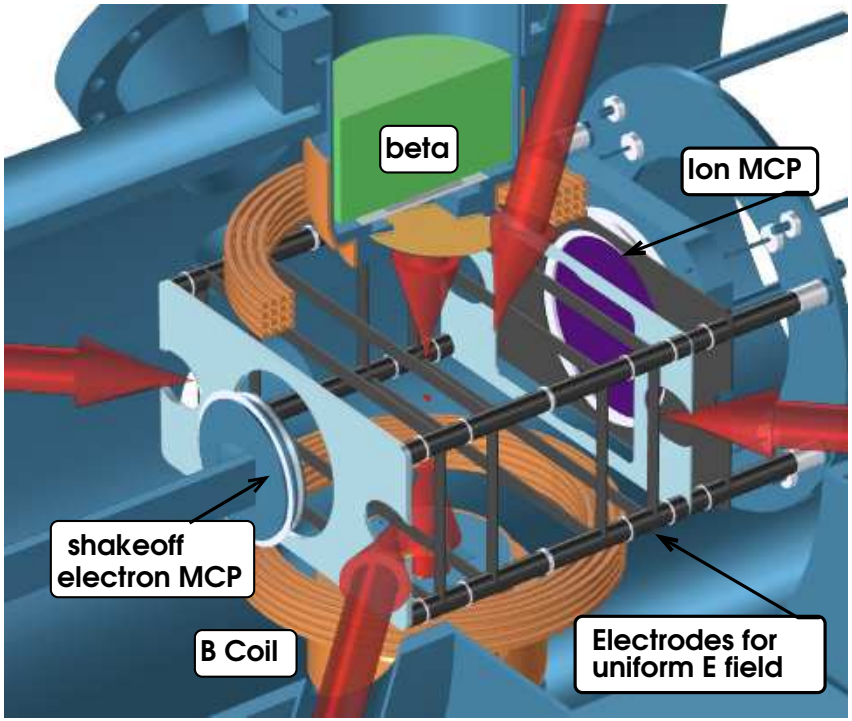
ISAC ion bea

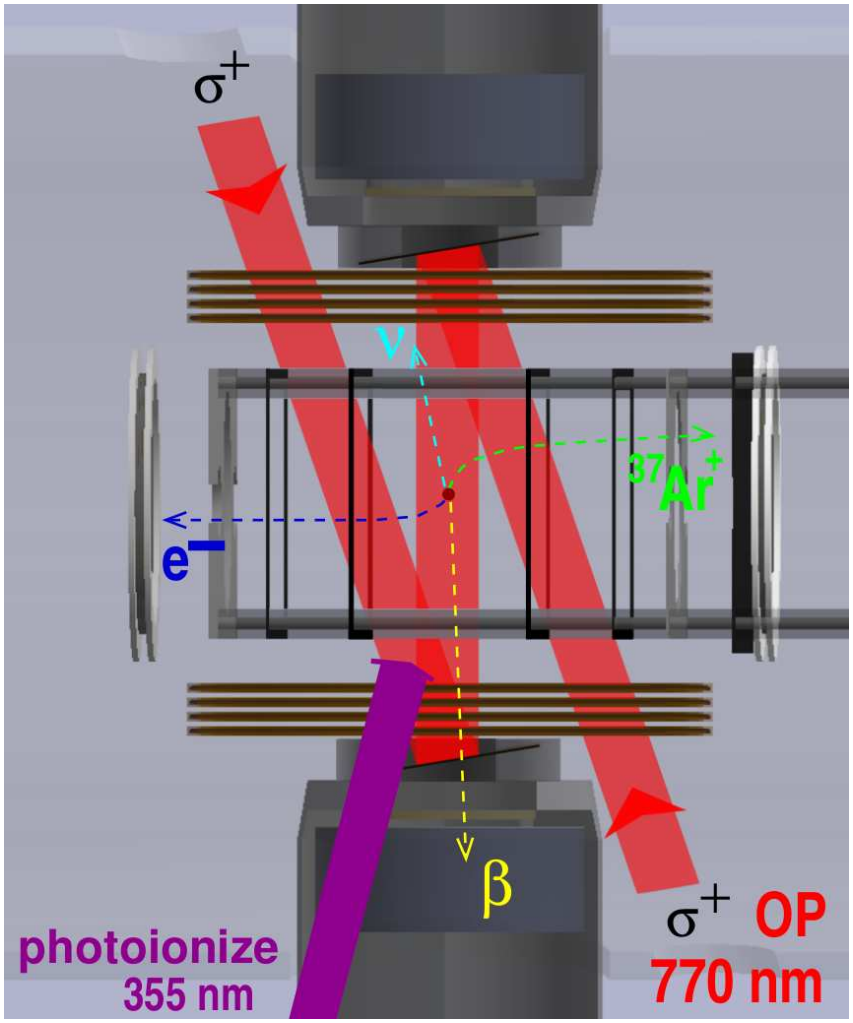
ion MCP assembly



electrostatic field, delay-line anode

^{37}K decay geometry

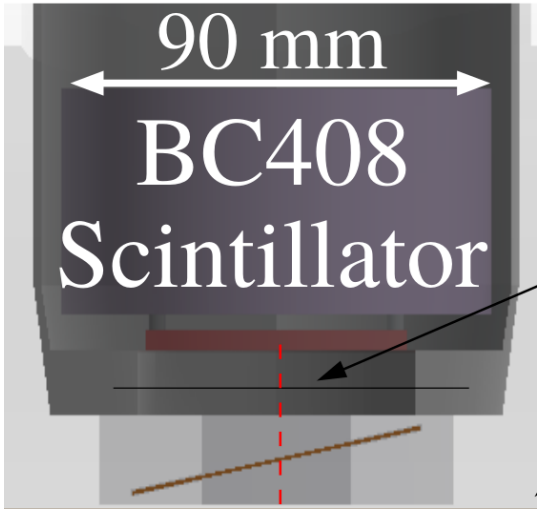


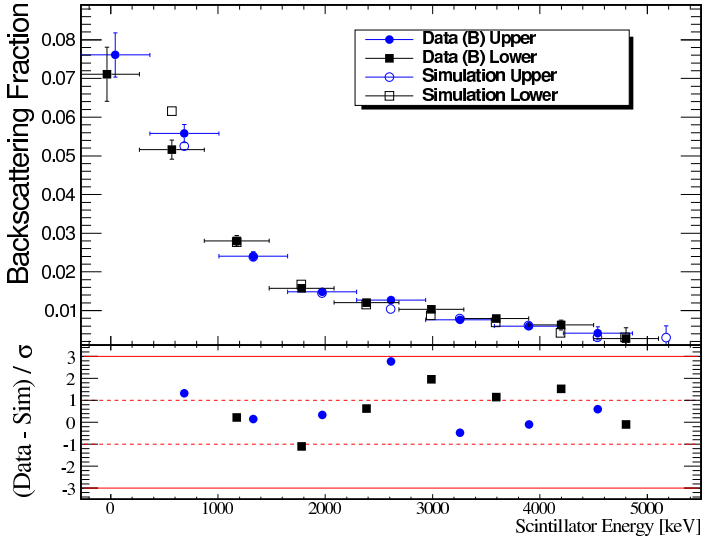


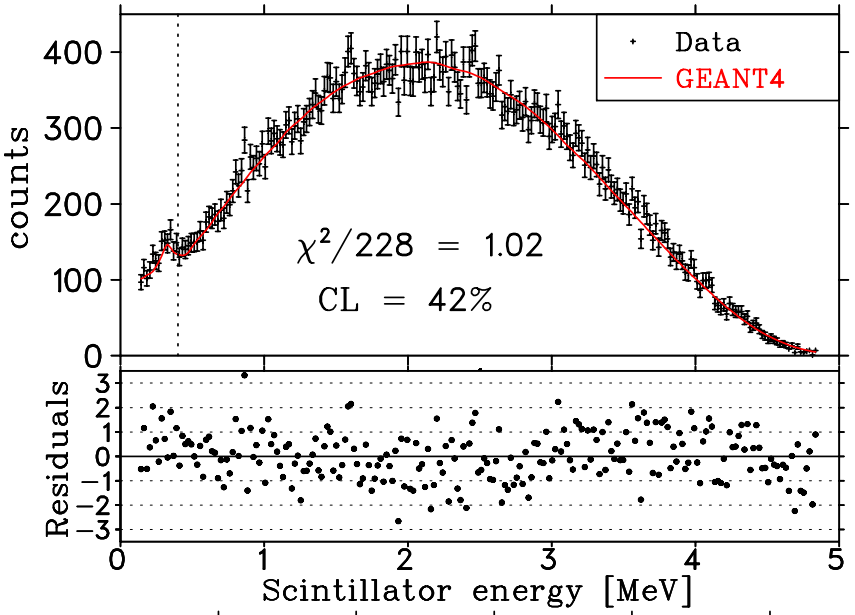
- β, recoil nucleus
- shakeoff $\boldsymbol{e}^-$ for TOF trigger

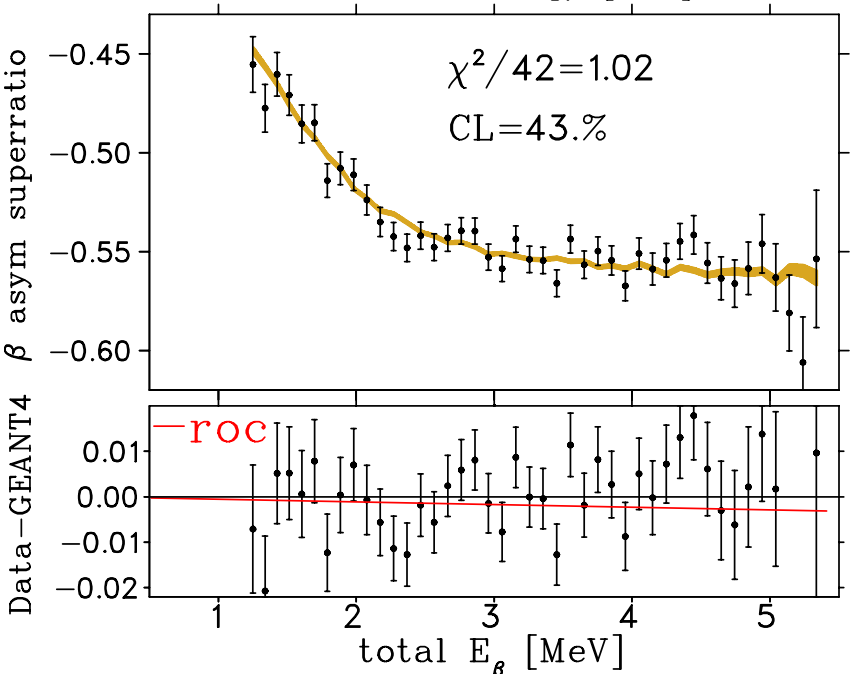
June 2014 data at reduced $\boldsymbol{E}$ field for $\boldsymbol{A}_\beta$
The decay pattern shown on the right is helicity-forbidden if the ν goes straight up, independent of Gamow-Teller/Fermi ratio.

β^+ asymmetry ^{37}K data



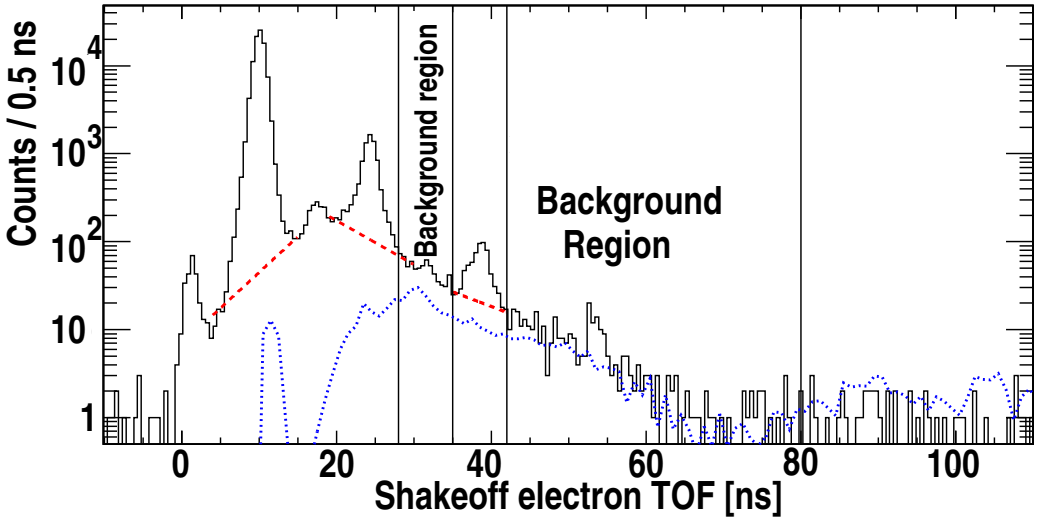


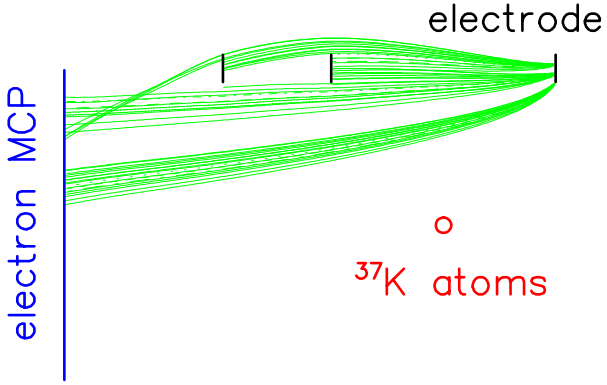




- **Backscatter from scint agrees ∼10%**

Background





- β telescope and shakeoff $\boldsymbol{e}^-$ coincidence remove most decays not from the trap cloud. Remainder is our largest uncertainty.
- Conservatively assume polarized between 0 and 100%.
- These will be removed by MCP position info when we increase to design $\boldsymbol{E}$ field

^{37}K $A_{\beta+}$ Uncertainties

Source $\times 10^{-4}$ [†: β scattering]	ΔA_β
Background (Correction 1.0014)	7
Trap Position	4
Trap Sail velocity	5
Trap Temperature & width	1
BB1 Radius†	4
BB1 Energy agreement	2
BB1 threshold	1
Scintillator threshold	0.3
GEANT4 physics list†	4
Shakeoff electon t.o.f. region	3
SiC mirror thickness†	1
Be window thickness†	0.9
Scintillator or summed†	1
Scintillator calibration	0.1
Total systematics	12
Statistics	13
Polarization	5
Total uncertainty	18

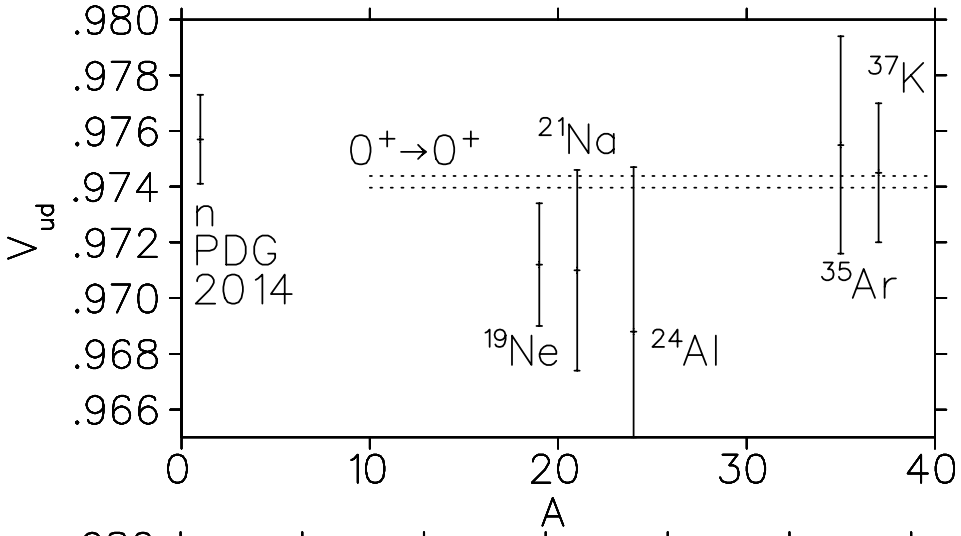
A_β = –0.5706 $\pm$ 0.0013 (stat) $\pm$ 0.0012 (syst) $\pm$ 0.0005 (pol) = -0.5706 $\pm$ 0.0018

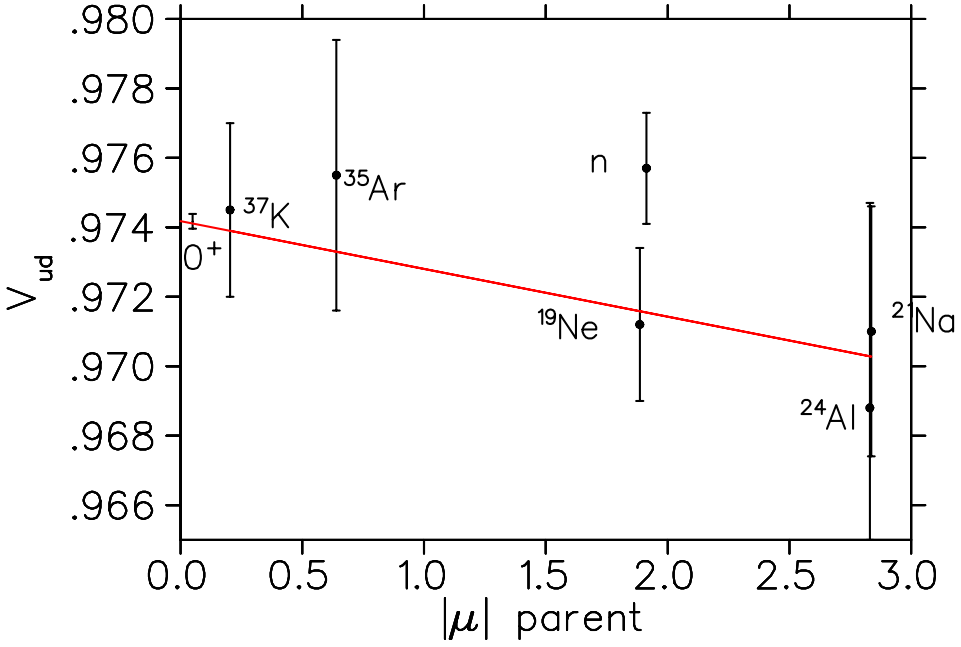
A_β[SM] = –0.5706 $\pm$ 0.0007

Better relative uncertainty than ^{19}Ne –0.0360$\pm$0.0008 [Calaprice 1975] and neutron 0.1197$\pm$0.0006 [PERKEO II PRL 2013, UCNA PRCr 2013]

We test physics $\rightarrow$

Conserved Vector Current ?



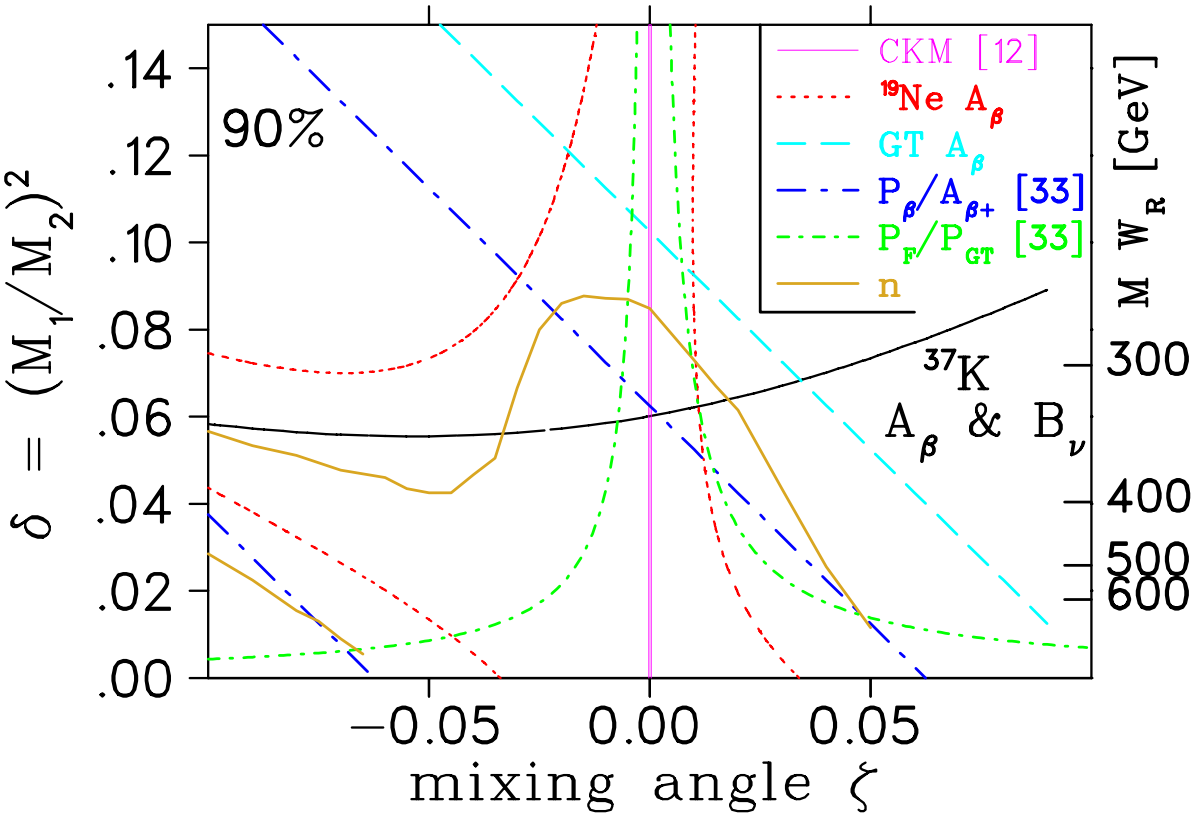


Together with $\mathcal{F}t$, A_β measures the vector current strength i.e. V_{ud}. Considered an isospin mixing test in different transitions than $0^+ \to 0^+$. It's also a CVC test in a different system.

E.g. Salam and Strathdee Nature 1974: phase transitions at very high B fields could drive $\theta_{\text{Cabibbo}} \to 0$

Hardy Towner PLB 1975 applied to the ^{35}Ar A_β controversy.

Right-handed vector currents



^{37}K constraint complementary

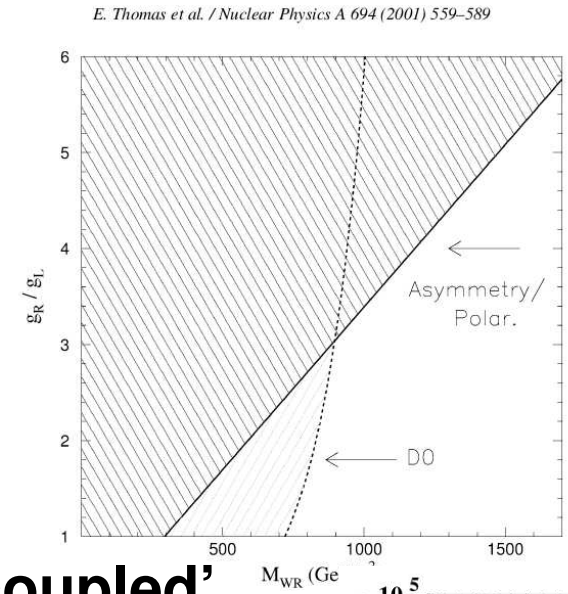
$\zeta = 0$:
$W_R\ M > 348$ GeV
(better than P_β/A_β ^{12}N Thomas 2001)

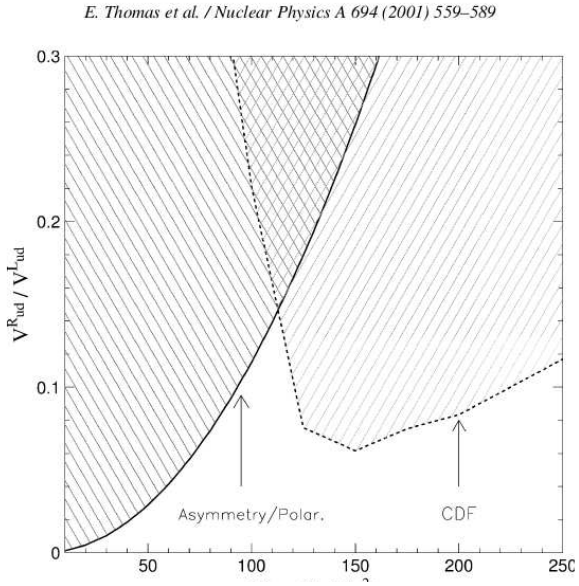
LHC $M'_W > 3.7$ TeV 90%

'Non-manifest' models:
^{37}K $\Rightarrow g_R \lesssim 7.7$ at 4 TeV
(or at 2 TeV $g_R < 4$, but LHC 2 TeV 'bump' had $g \sim 0.5$)
For $M'_W < 70$ GeV, nuclear β decay constrains $V_{\mathrm{ud\ R}}$
(Severijns Naviliat-Cuncic ARNPS 2011)

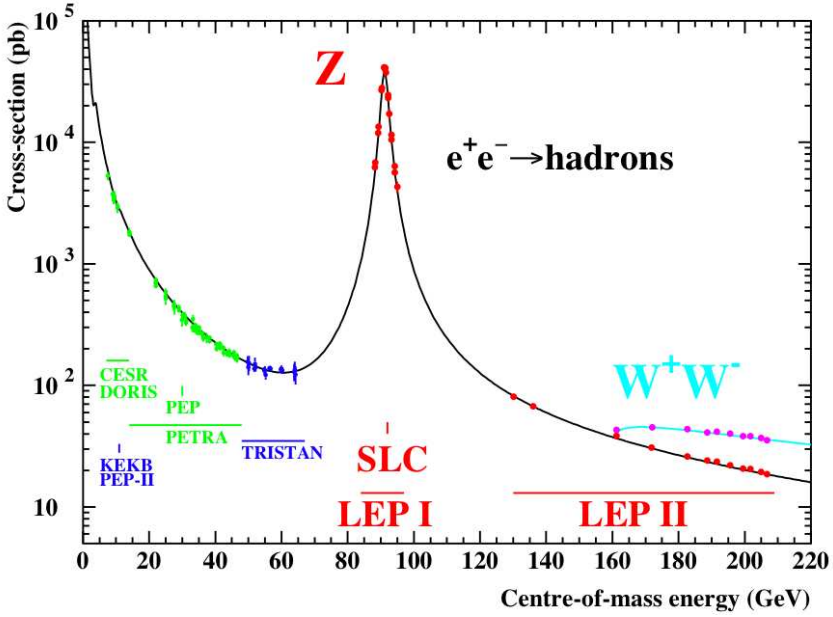
‘Non-manifest’ Left-Right models

$g_R > g_L$ or
$V^R_{ud} < V^L_{ud}$
E. Thomas NPA

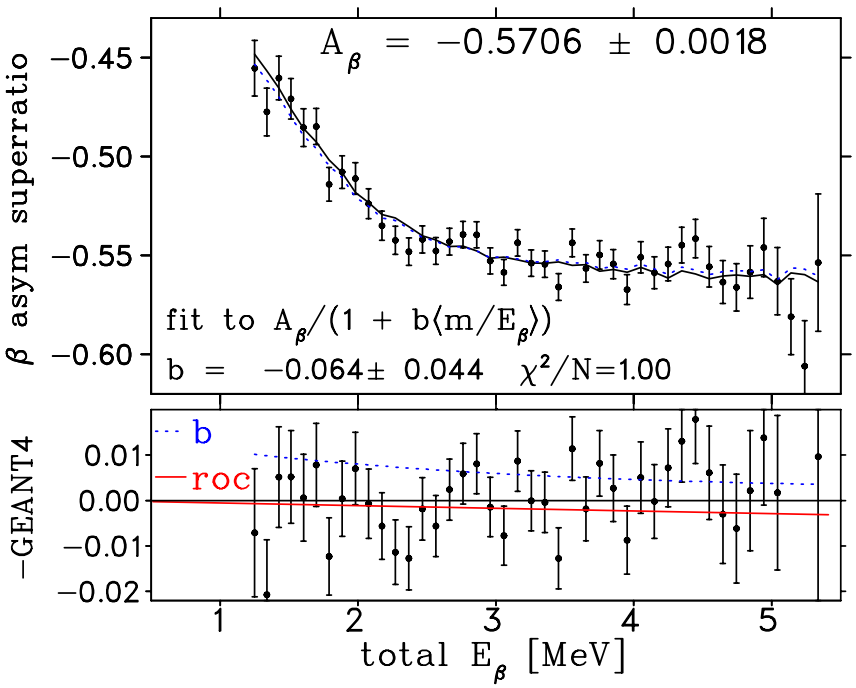




Hiding light ‘weakly coupled’ but electrically charged bosons from direct detection is tricky. But there is background at $M < M_W$; e.g. for measured $\sigma[e^+e^- \to W^+W^-]$ PDG lists tight cuts on final W mass



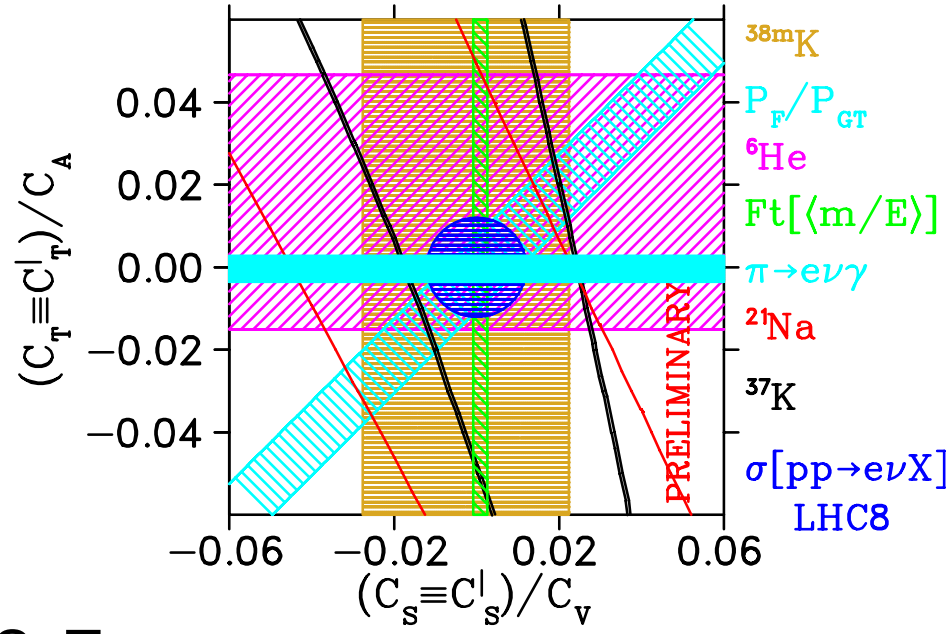
A_β [E_β] agrees with S.M.



Nucleon, Lepton Currents making up Lagrangian (a scalar) can separately transform like *S*, *T*, *V*, *A*

1957 version of EFT.

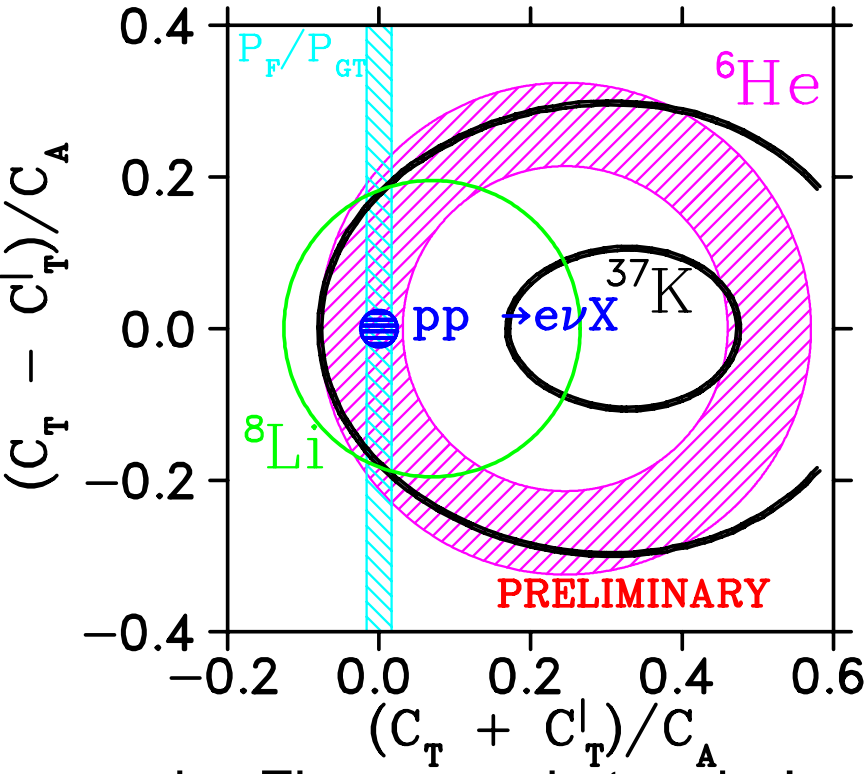
Fierz term $\propto \langle \frac{m_\beta}{E_\beta} \rangle$

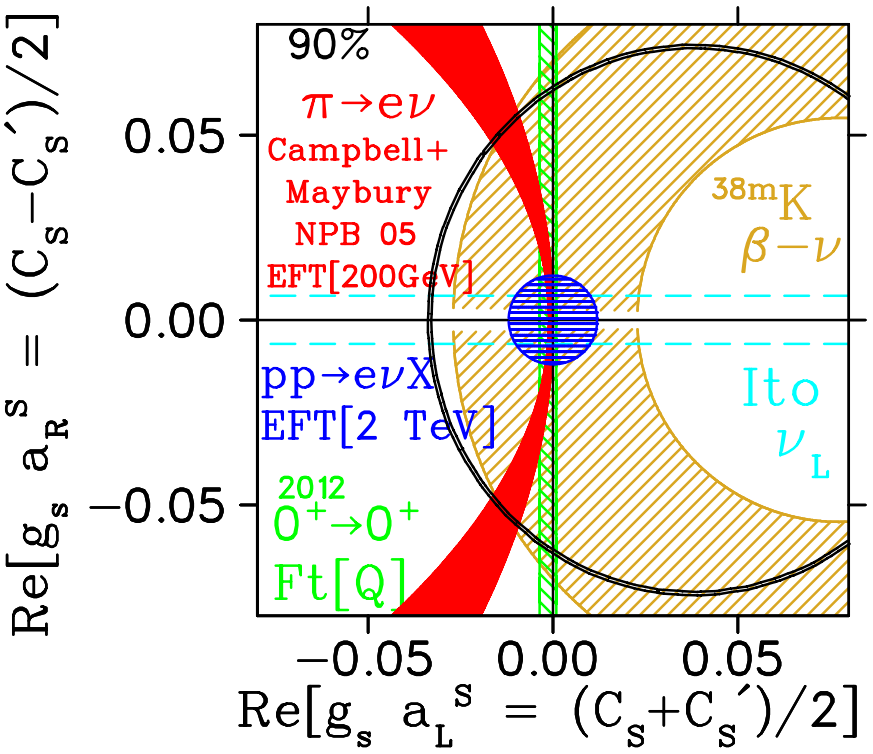


LHC8 $\sigma[p + p \to e\nu X]$
Naviliat-Cuncic
Gonzalez-Alonso AnDP 2013
(Cirigliano JHEP 2013)
1 event expected, 2 seen

Specific models: leptoquarks → S, T;
Profumo 2007 PRD: MSUSY sum over sparticles → S,T

Couplings to wrong-handed ν



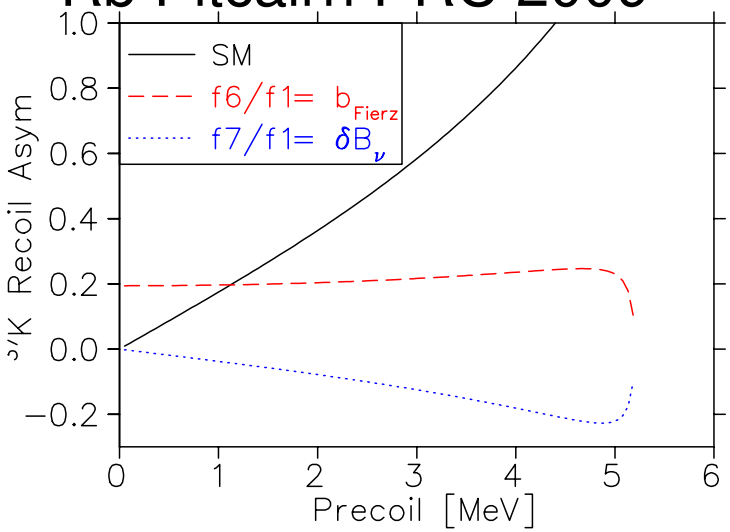


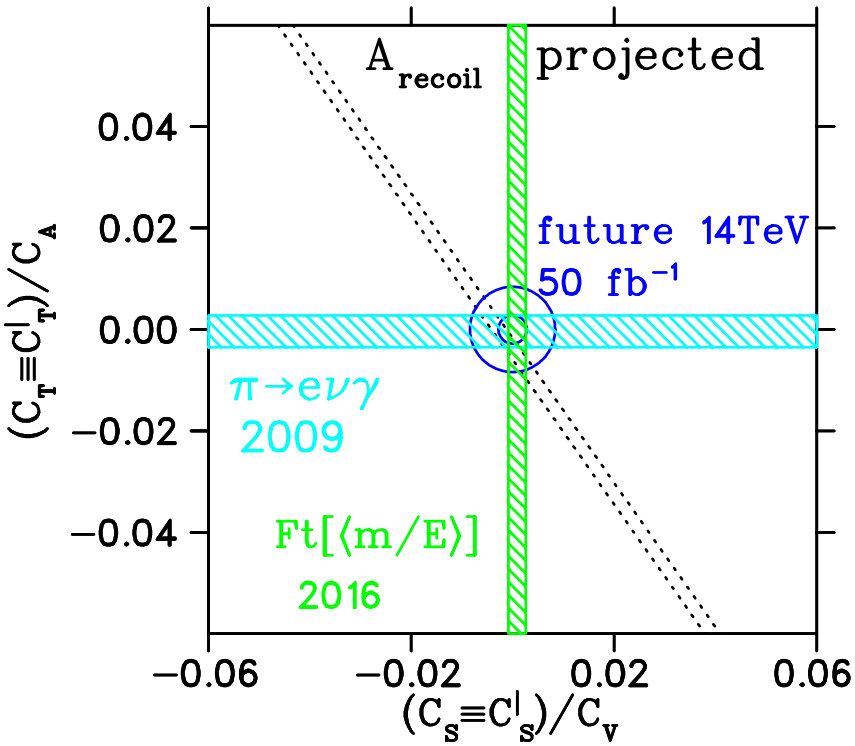
the Fierz term is 'easier' to constrain but has more competition

For scalars coupling to wrong-chirality ν, we compete with our own ^{38m}K β-ν Gorelov 2005

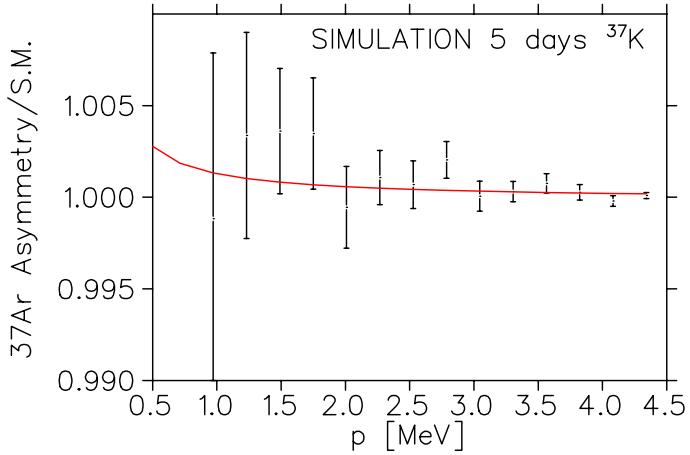
future $A_{recoil} \propto A_\beta + B_\nu$

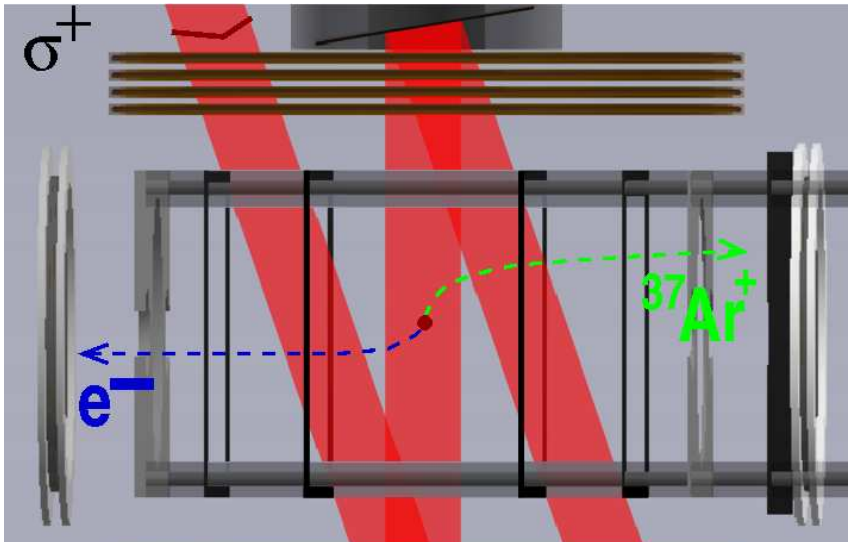
Technique demonstrated in ^{80}Rb Pitcairn PRC 2009





Ave A_{recoil} depends on ρ; p dependence doesn't





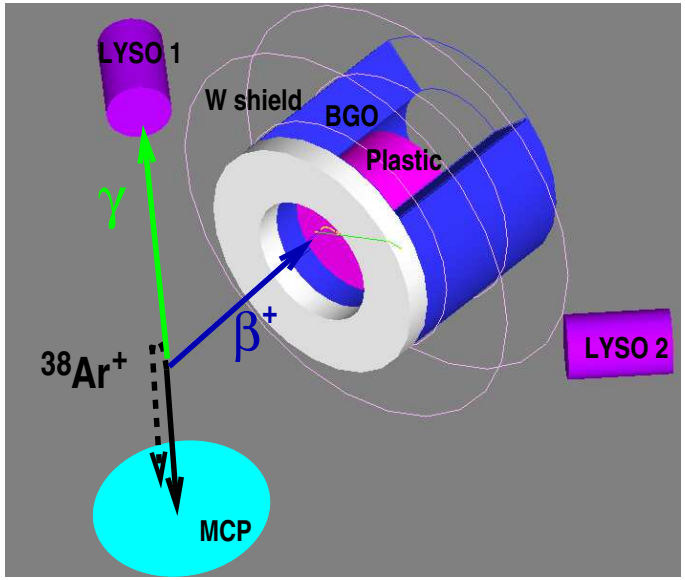
$\gamma\beta\nu\not{T}$ Experiment

Harvey Hill Hill PRL 99 261601 combine QCD+electroweak interaction in the nucleon's $\mathcal{L}$, and Gardner, He PRD 87 116012 (2013) reduce this to $\mathcal{L}$ =

$$-\frac{4c_5}{m_{\text{nucleon}}^2}\frac{eG_F V_{ud}}{\sqrt{2}}\epsilon^{\sigma\mu\nu\rho}\bar{p}\gamma_\sigma n\bar{\psi}_{eL}\gamma_\mu\psi_{\nu L}F_{\nu\rho}$$

which upon interference with S.M. gives $\not{T}$ decay contribution $\rightarrow$

$$|\mathcal{M}_{c5}|^2 \propto \frac{Im(c_5 g_V)}{M^2}\frac{E_e}{p_e k}(\vec{p_e}\times\vec{k_\gamma})\cdot\vec{p_\nu}$$

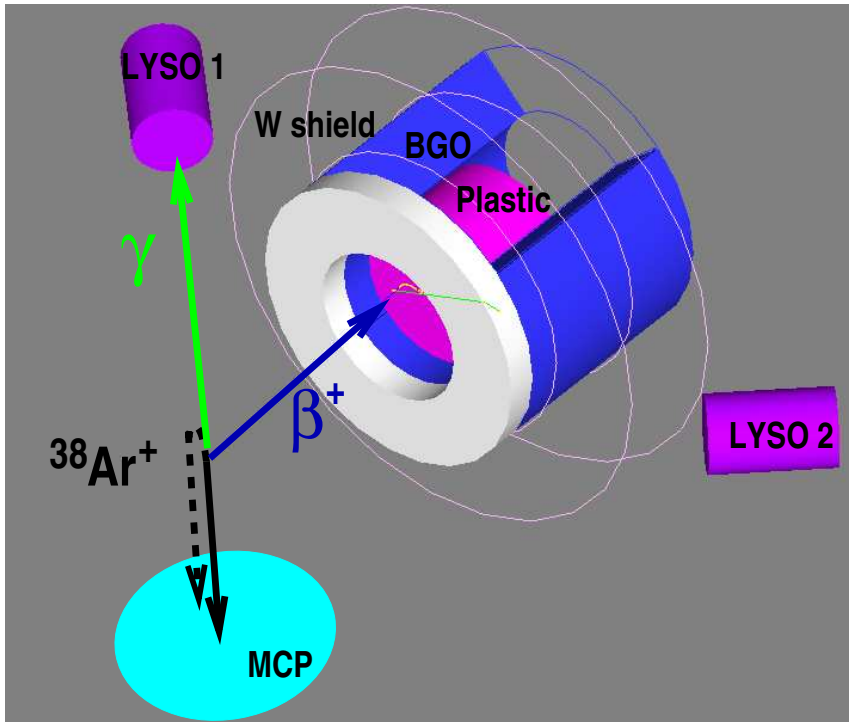


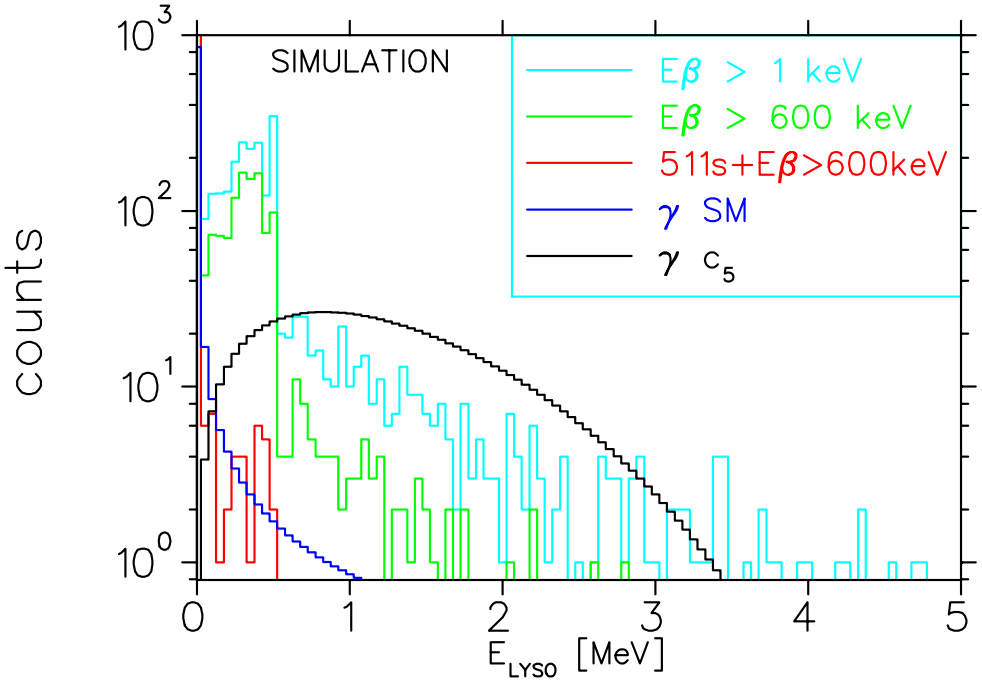
new physics $M \sim$ MeV

- $\not{T}$ 250x larger in ^{38m}K decay than n
- final state fake effect 8x10^{-4}
- ^{38m}K 40,000 atoms, 30000 events/week $\Rightarrow \sigma \sim 0.02$
- Test asymmetry of apparatus with coincidence pairs
- n $\rightarrow$ p $\beta\nu\gamma$ branch (Nico Nature 06, Bales PRL 16) $\Rightarrow$ $\frac{\text{Im}(c_5)}{M^2} \leq 8MeV^{-2} \Rightarrow$ Asym can be 100%

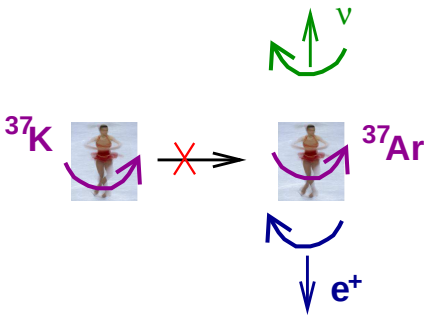
GEANT4 simulation of $\gamma\beta\nu\not{T}$

- the new 'c5' term needs Fermi or Fermi+GT transition $\Rightarrow$ β^+ emitters
- background from β 'external bremsstrahlung' suppressed by requiring β^+ to hit plastic
- Require two 511's in BGO, so we know they didn't go to γ detector, enables measurements at $E_\gamma < 0.2$ MeV.





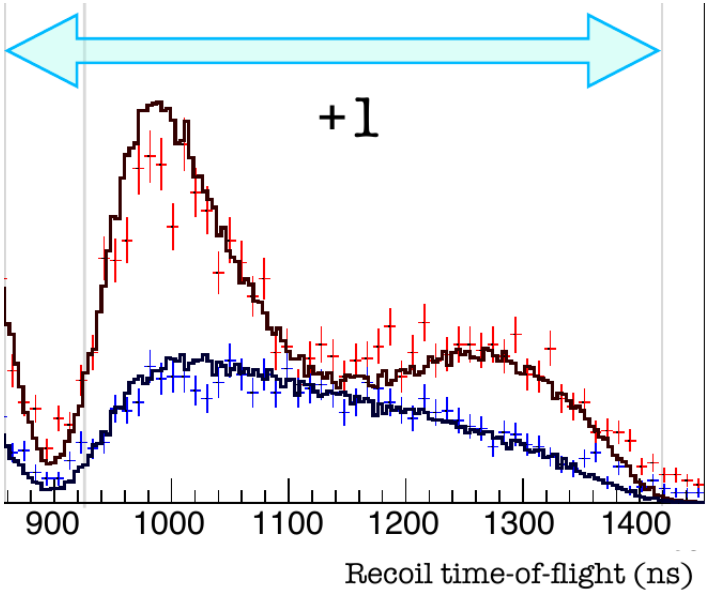
Helicity-driven null in mirror decay

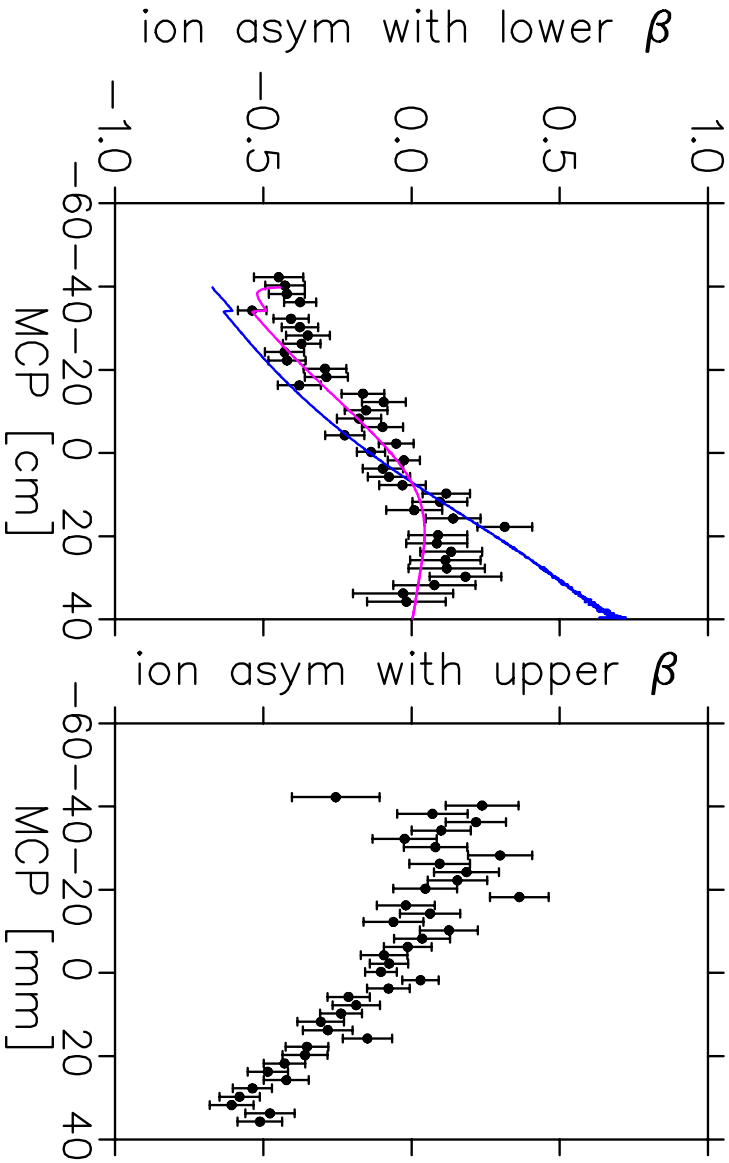


$$W(\theta_{\beta\nu i}) \approx 1 + \mathcal{A}_{\beta\nu i} \cos(\theta_{\beta\nu i})$$

$$\mathcal{A}_{\beta\nu i} = \frac{a + PB - 2cT/3}{1 + PA}$$

For P=-1, $\mathcal{A}_{\beta\nu i}$=1, independent of M_{GT}/M_F





2014 data under analysis

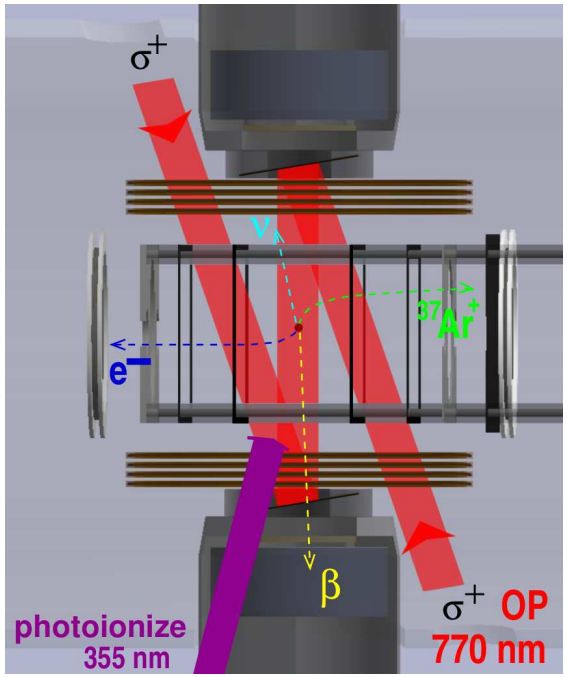
TRIUMF Neutral Atom Trap

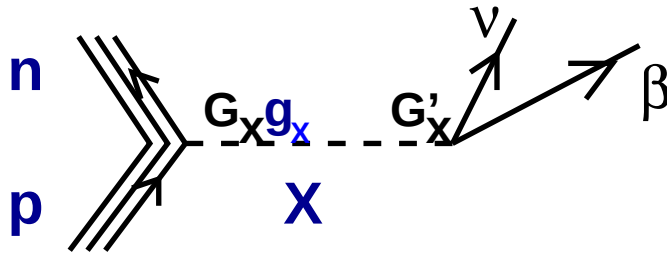
We have measured the β asymmetry of ^{37}K decay to be A_β=–0.5706 $\pm$ 0.0018

Agrees with theory, complements the best β decay measurements

We plan to measure A_β 3-5 x better, and A_{recoil} with sensitivity to '4-fermion contact' interactions complementary to $\pi \to e\nu\gamma$, $\pi \to e\nu$, and LHC $p + p \to e\nu X$

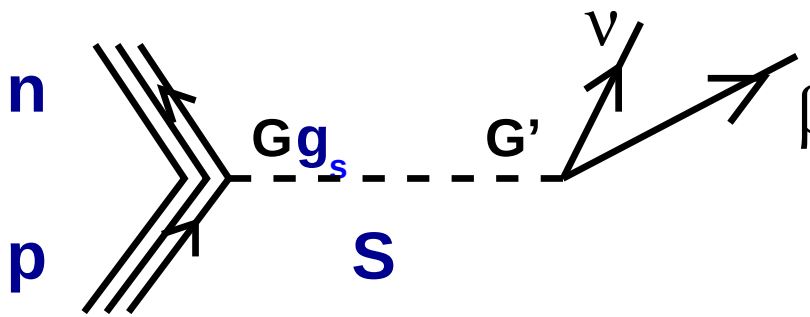
We also plan a TRV $\beta\nu\gamma$ 3-momentum correlation, first of its type in 1st-generation particles





nucleon form factors

Herczeg Prog Part Nucl Phys 46 (2001) 413 pointed out need for form factors



$$\langle p|\bar{u}d|n\rangle = g_s(q^2)\bar{u}_p u_n$$
$$\langle p|\bar{u}\sigma_{\lambda\mu}d|n\rangle = g_T(q^2)\bar{u}_p\sigma_{\lambda\mu}u_n$$

2001: "$0.25 < g_s < 1$" depressing to the experimentalist

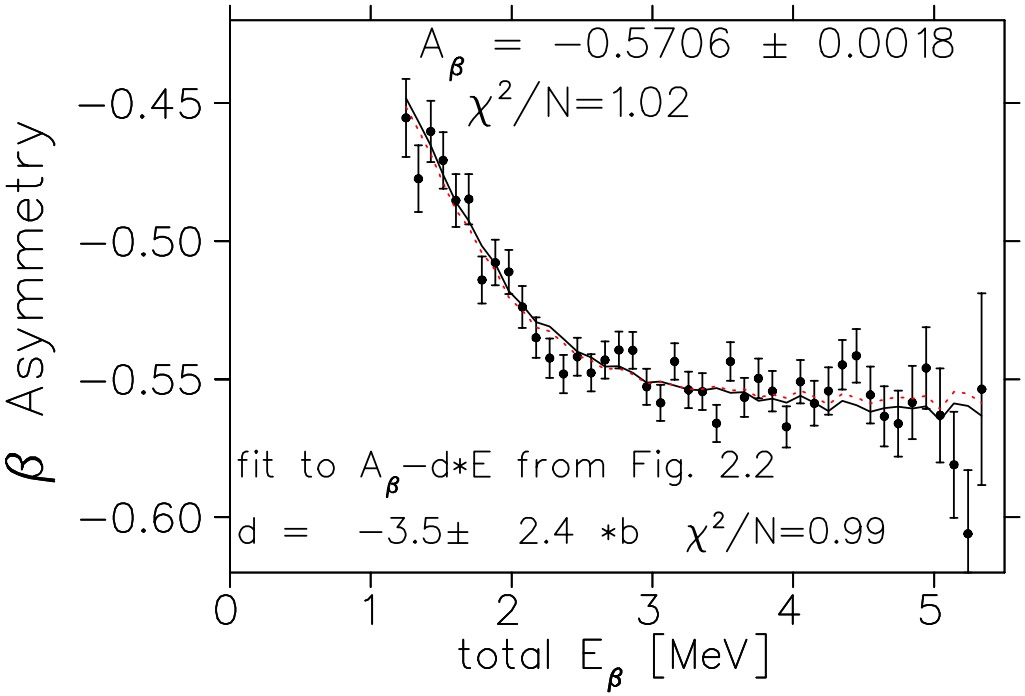
g_T related to transverse spin structure function

Bhattacharya, Cirigliano, ... Huey-Wen Lin... PRD 85 05412 (2012) first lattice gauge calculations, g_s = 0.8±0.4, g_T = 1.05±0.35

Green... Negele... PRD 86 114509 (2012) lattice QCD, g_s=1.08±0.28 (stat) ± 0.16 (syst); g_T = 1.038 ± 0.011(stat) ± 0.012(syst)

g_s=1.02±0.10 Gonzalez-Alonso, Camalich PRL 112 042501 (2014)

2nd-class currents



2nd-class currents violated isospin symmetry.
'induced tensor' ***d*** is predicted zero in isobaric mirror decay.
although the limit on ***d*** is not competitive yet, there are models where 2nd-class currents change with system where this result is complementary

4-Fermion interaction primer/jargon

Lee+Yang (Phys Rev 104 254 (1956)) 4-Fermion interaction

$$H_{\rm int} = \sum_X (\bar{\psi}_p O_X \psi_n)(C_X \bar{\psi}_e O_X \psi_\nu + C'_X \bar{\psi}_e O_X \gamma_5 \psi_\nu) \qquad (1)$$

$H_{\rm int}$ invariant under Lorentz transformations

X: the 5 possible Lorentz transformation properties:

vector (V) γ_μ axial vector (A) $\gamma_5\gamma_\mu$

tensor $\sigma_{\mu\nu}$ (T) scalar (S) pseudoscalar (P) γ_5

Combinations of C_X and C'_X produce projection operators $1 \pm \gamma_5$ which project out either L or R-handed ν's.

• Generalized in the SM to the quark-lepton interaction, C_V=C'_V and C_A=-C'_A, given by spin-1 W boson exchange. Only L-handed ν's are emitted.

'Tensor' and 'scalar' just mean these Lorentz transformation current properties: 'tensor' does not imply spin-2.

Spin-0 'leptoquarks' $\rightarrow \sigma_{\mu\nu}$ 'tensor' after 'Fierz' rearrangement.

MSSM and β decay correlations

Profumo, Ramsey-Musolf, Tulin
PRD 75 075017 2017
C_S+C'_S can be 0.001 in MSSM in 1-loop order including mixing

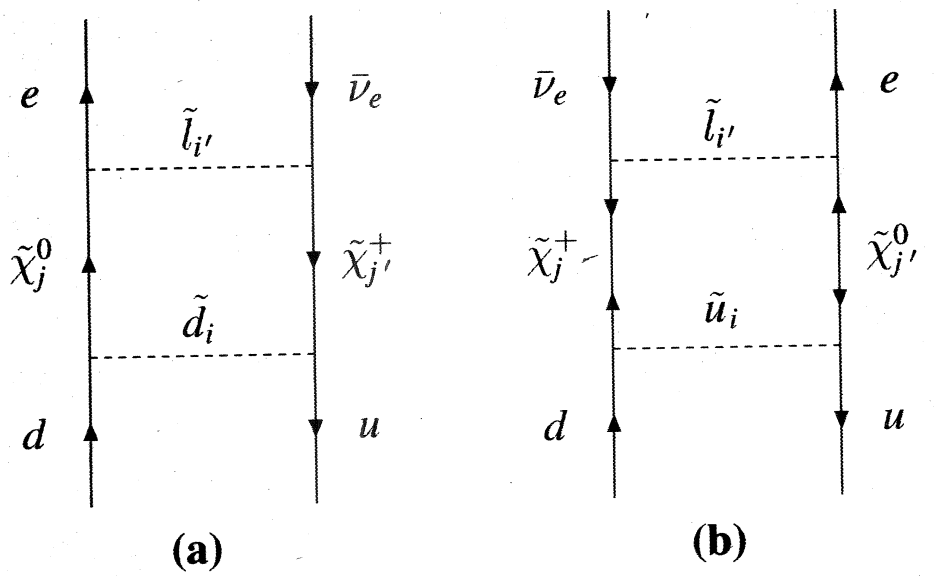


FIG. 2. Feynman diagrams relative to supersymmetric contributions giving rise to anomalous amplitudes in β decay processes.

Include mixing of:

- left and right sfermions (this is where β decay can help; constraints are said to be few)
- sfamily mixing (already tightly constrained, e.g. by $\mu \rightarrow$ e γ...)

Effective 4-fermi scalar and tensor couplings are generated that contribute to b_{Fierz} and spin correlation observables like B_ν as large as 0.001.

TRIUMF

$\not{T}$, $\not{CP}$, and 'Us'

CP and T symmetry are related by the 'CPT Theorem': All local Lorentz invariant QFT's are invariant under CPT.

Then $\not{CP} \Rightarrow \not{T}$

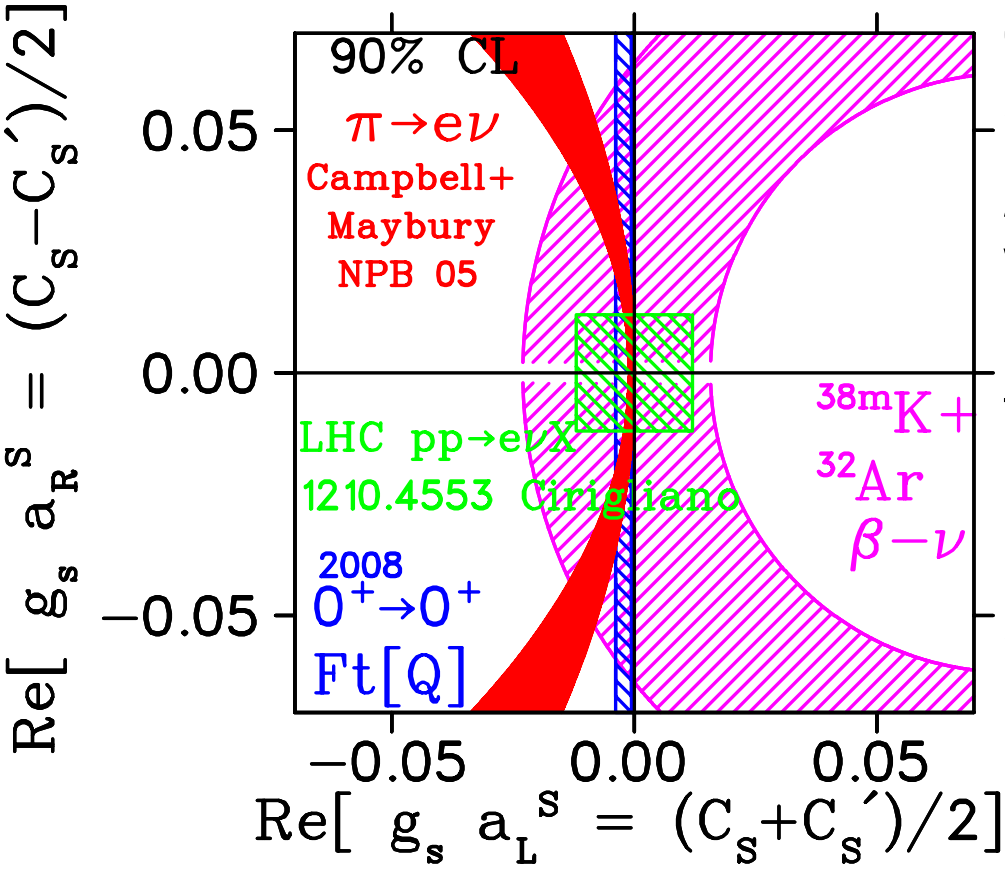
$\not{CP}$ discovered in $K\bar{K}$ meson decays in 1963

Sakharov JETP Lett 5 24 (1967) used $\not{CP}$ to generate the universe's excess of matter over antimatter:

- $\not{CP}$,
- baryon nonconservation, and
- nonequilibrium.

But known $\not{CP}$ is too small by 10^{10}, so 'we' need more to exist

E.g.: scalar interaction constraints



$0^+ \to 0^+$ ***fT*** values constrain scalars coupling to s.m. chirality

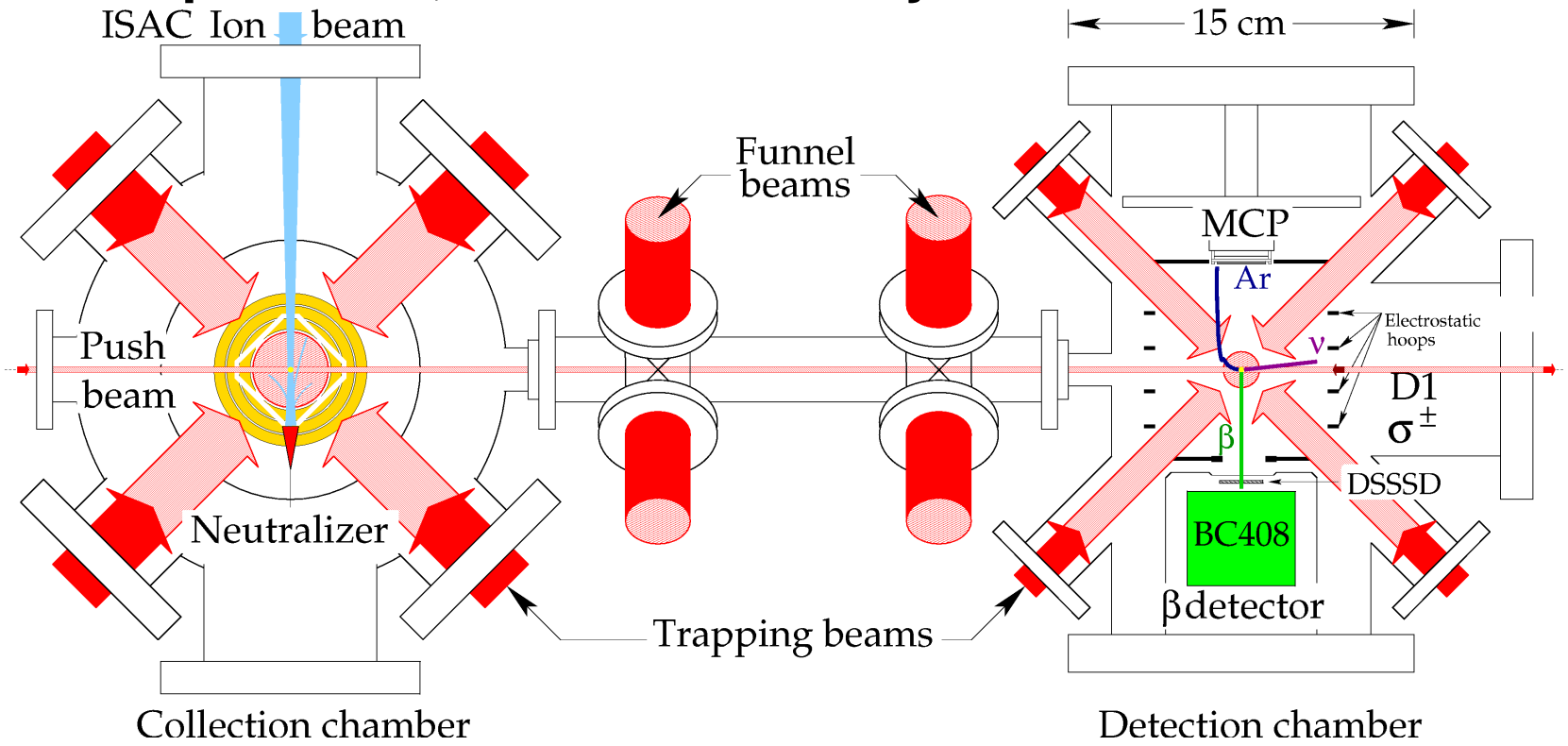
β-ν correlation constrains others as well

$\pi \to e\nu$ constrains both (even though it is pseudoscalar, higher order interaction)

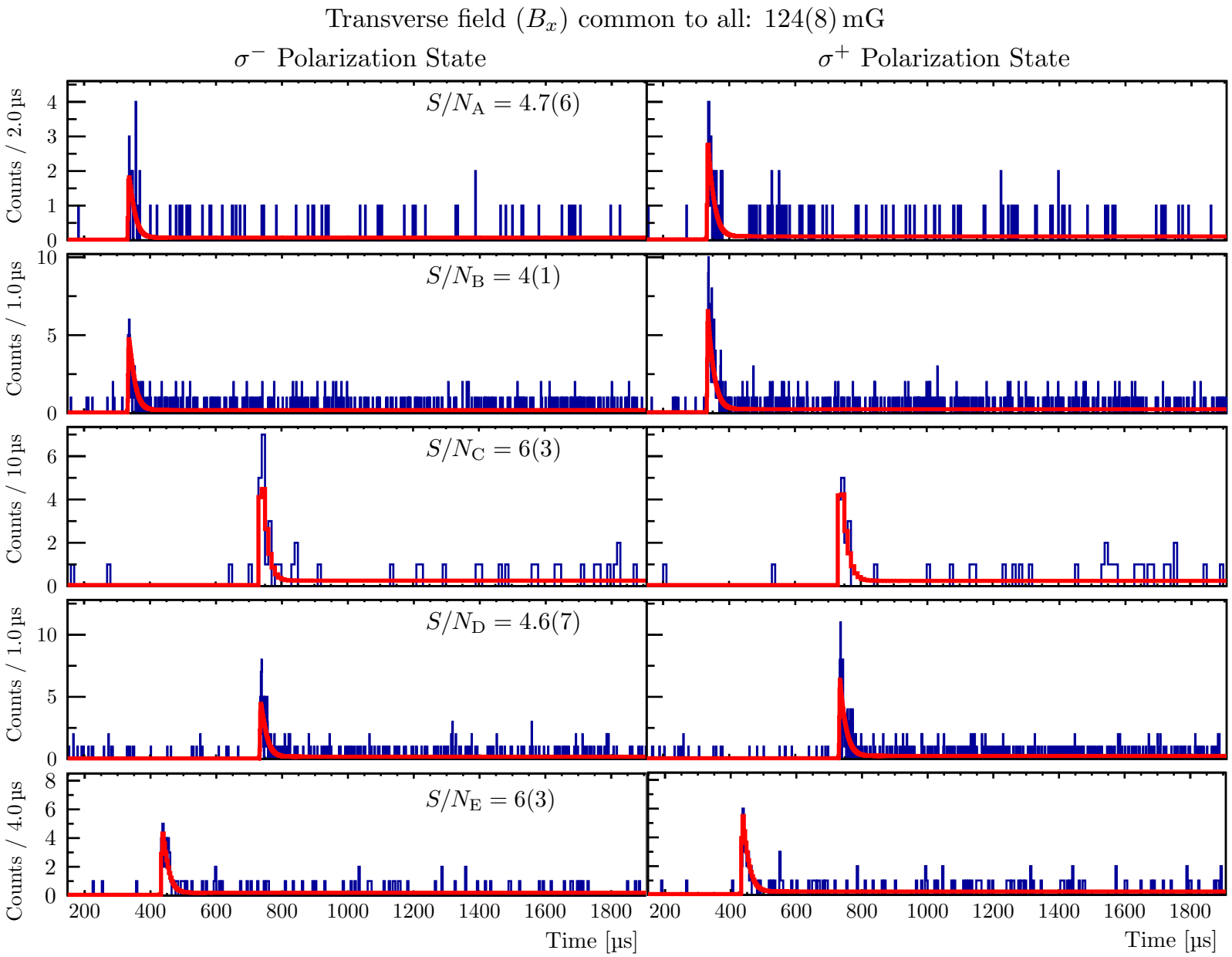
$\pi \to e\nu$ and pp→eνX are EFT constraints assuming scales (200 GeV and 1 TeV). Direct LHC searches for the bosons are a separate story.

TRIUMF's Neutral Atom Trap

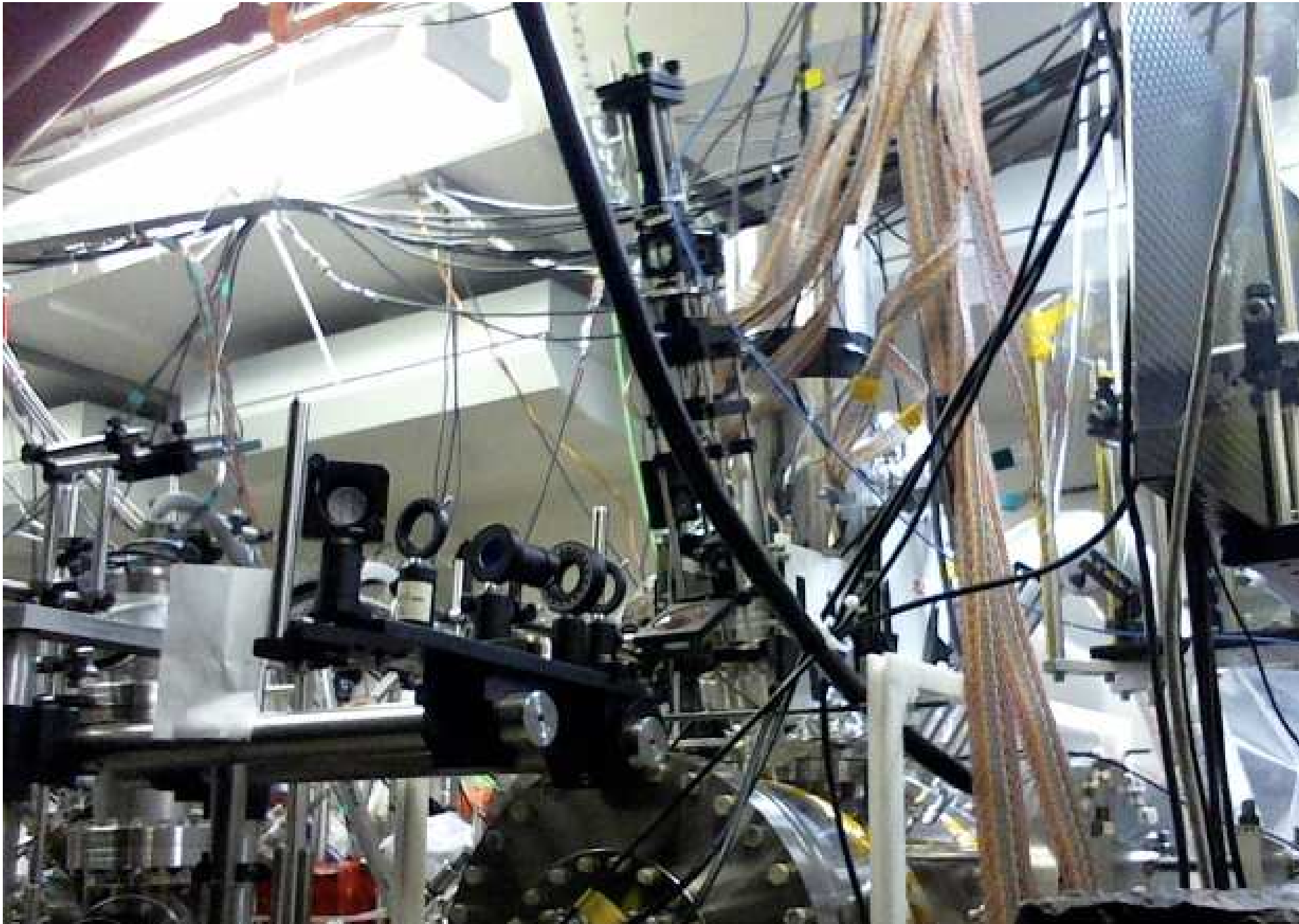
- **Isotope/Isomer selective**
- **Evade 1000x untrapped atom background by $\rightarrow$ 2nd MOT**
- **75% transfer (must avoid backgrounds!); 10^{-3} capture**
- **0.7 mm cloud for β-Ar$^+$ $\rightarrow$ ν momentum $\rightarrow$ β-ν correlation**
- **99% polarized, known atomically**



Polarization fit to all ^{37}K data

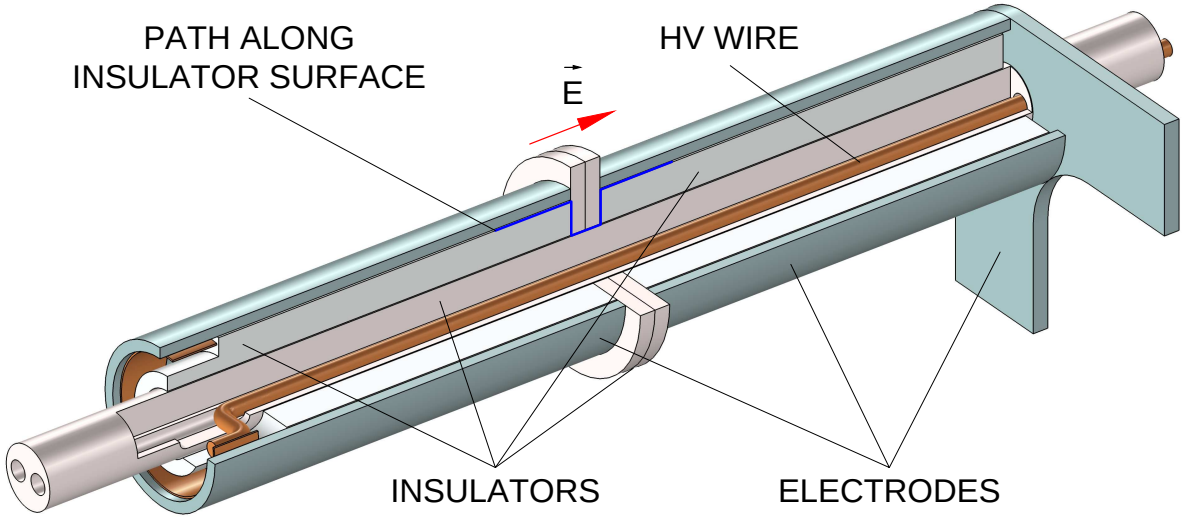


optics and detectors



E field status

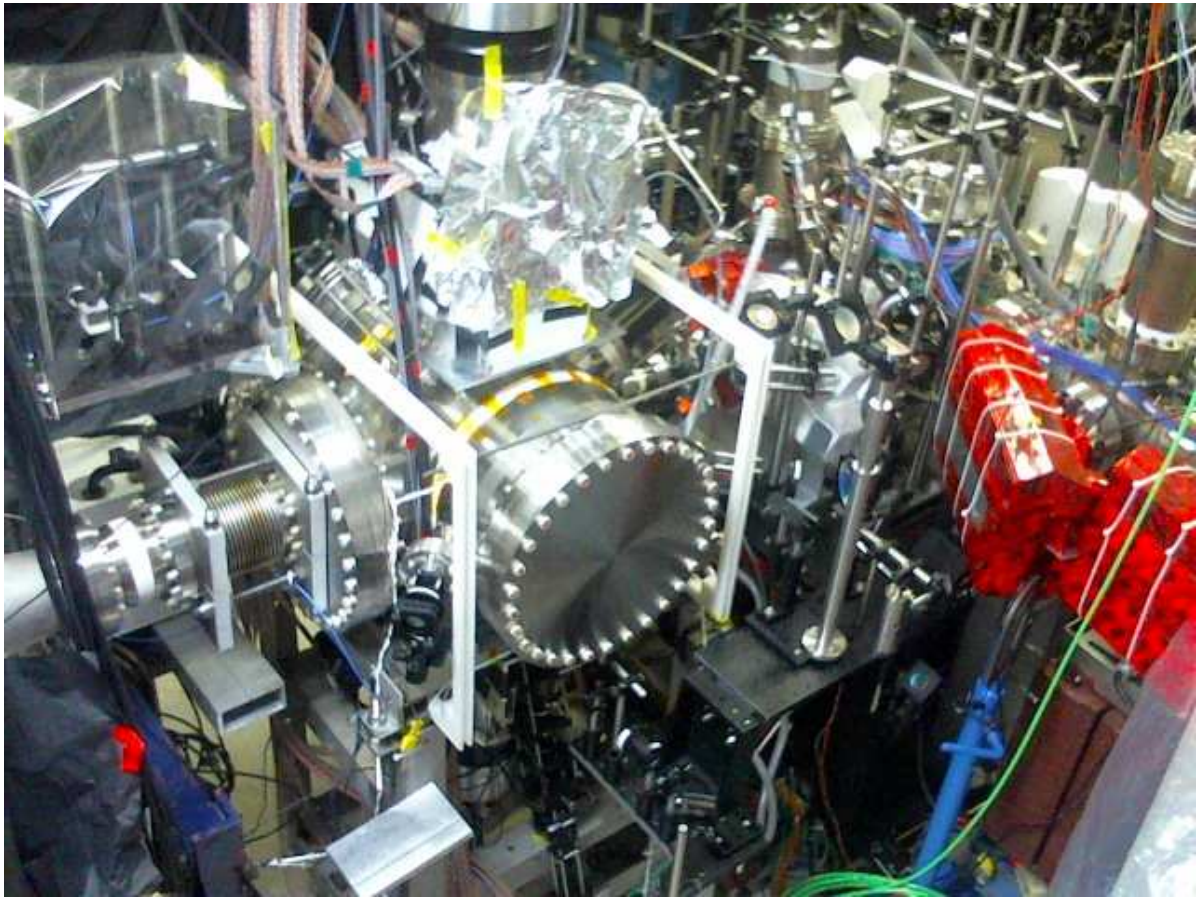
Nested insulators: E no longer falls across dielectric surfaces



- **Argon conditioning**
- **1.2 kV/cm reached**
- **Improved ion MCP mount (as in Hong et al. NIM Seattle-Argonne) in progress**
- **More compact shakeoff e^- MCP and wedge-and-strip readout to allow simulataneous ion and e^- detection.**

- **Remove A_β background**
- **Adds A_{recoil}**
- **All detectors together for trap diagnostics and for ρ-independent β-recoil observable**

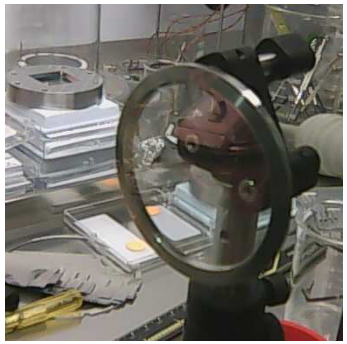
TRINAT lab: “tabletop experiment”



Polarization Improvements

SYST $\times 10^{-4}$	ΔP		ΔT	
	σ^-	σ^+	σ^-	σ^+
Initial T	3	3	10	8
Global fit v. ave	2	2	7	6
S_3^{out} Uncertainty	1	2	11	5
Cloud temp	2	0.5	3	2
Binning	1	1	4	3
B_z Uncertainty	0.5	3	2	7
Initial P	0.1	0.1	0.4	0.4
Require $\mathcal{I}_+ = \mathcal{I}_-$	0.1	0.1	0.1	0.2
Total SYSTEMATIC	5	5	17	14
STATISTICS	7	6	21	17

B. Fenker New J. Phys **18** 073028 2016



- **pellicle mirrors: less β^+ scattering**

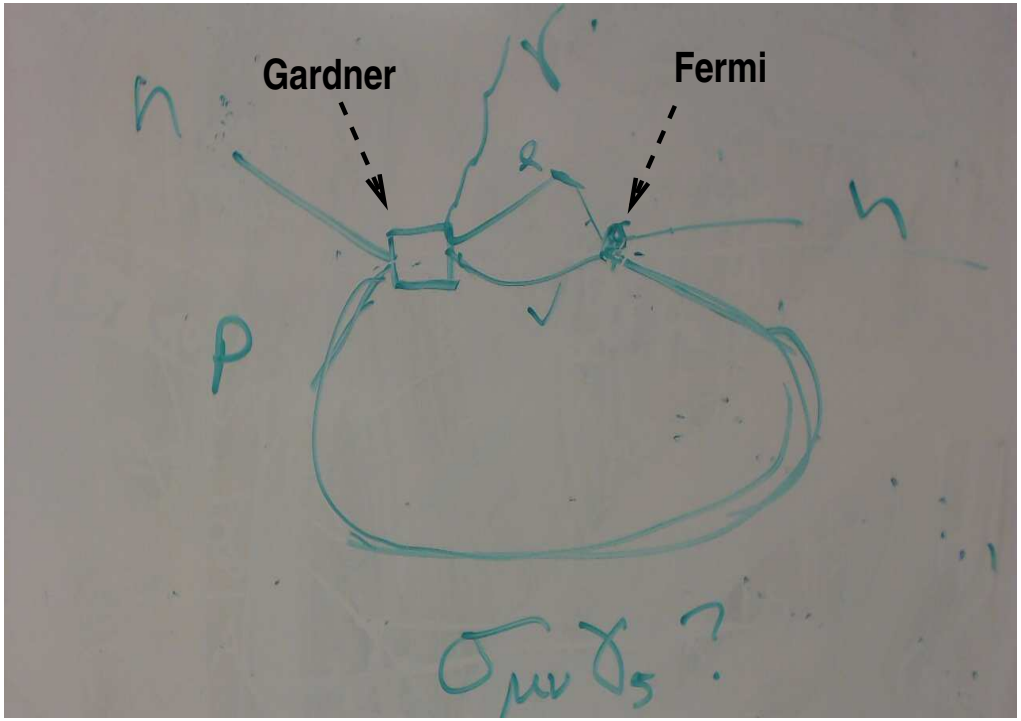
- **define T by OP**
- **trim B gradients**
- **improve S_3 flipping and gradients**
- **add flipping of B_z**
- **higher-power photoionizing laser**
- **gentler RAC-MOT**

$P(\sigma^+) = +0.9913(8)$ $T(\sigma^+) = -0.9770(22)$
$P(\sigma^-) = -0.9912(9)$ $T(\sigma^-) = -0.9761(27)$

- **Uncertainty $\propto$ (1-P)**

EDMs and $\not{T}$ radiative β decay

No spin involved, so different physics at lowest order, but



Ng, Vos on my office whiteboard:
'Im(c_5)' interaction
+ s.m. β decay
$\rightarrow$ n EDM at 2 loops

'Naive Dimensional Analysis':

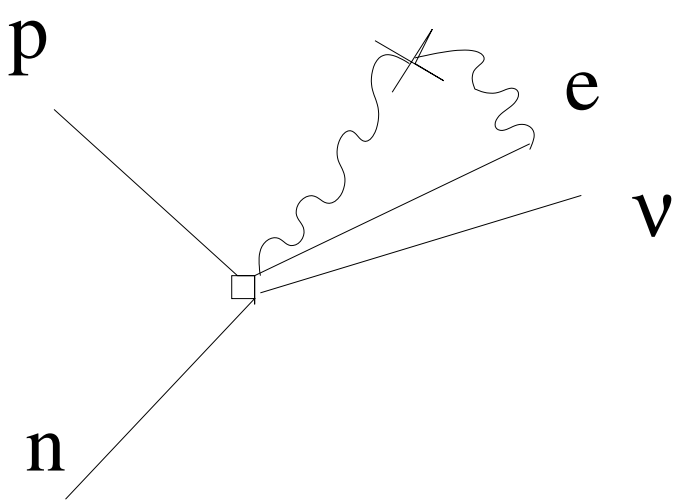
$$d_n \sim \frac{Im(c_5)G_F e}{M^2}\frac{G_F m_n^5}{(16\pi^2)^2} \sim \frac{10^{-22} e-cm}{M^2}[\mathrm{MeV}^{-2}]$$

$d_n[\mathrm{exp}] < 3 \times 10^{-26}$e-cm (Baker 2006 PRL)

null n EDM $\Rightarrow \frac{Im(c_5)}{M^2} < 3 \times 10^{-4}[\mathrm{MeV}^{-2}] \rightarrow 10^{-3}$ asym

We can still reach this sensitivity at higher $E\gamma$

D $\vec{I} \cdot \vec{v}_\beta \times \vec{v}_\nu$ and $\gamma\beta\nu$TRV



K. Vos, W. Dekens
(private communication)
One loop correction produces
large D observable

'Naive Dimensional Analysis'

$$D_{c5} \approx \mathcal{I} \frac{\alpha}{4\pi} 4 M_N^2 \frac{\mathrm{Im}(c_5)}{M^2} \Rightarrow$$

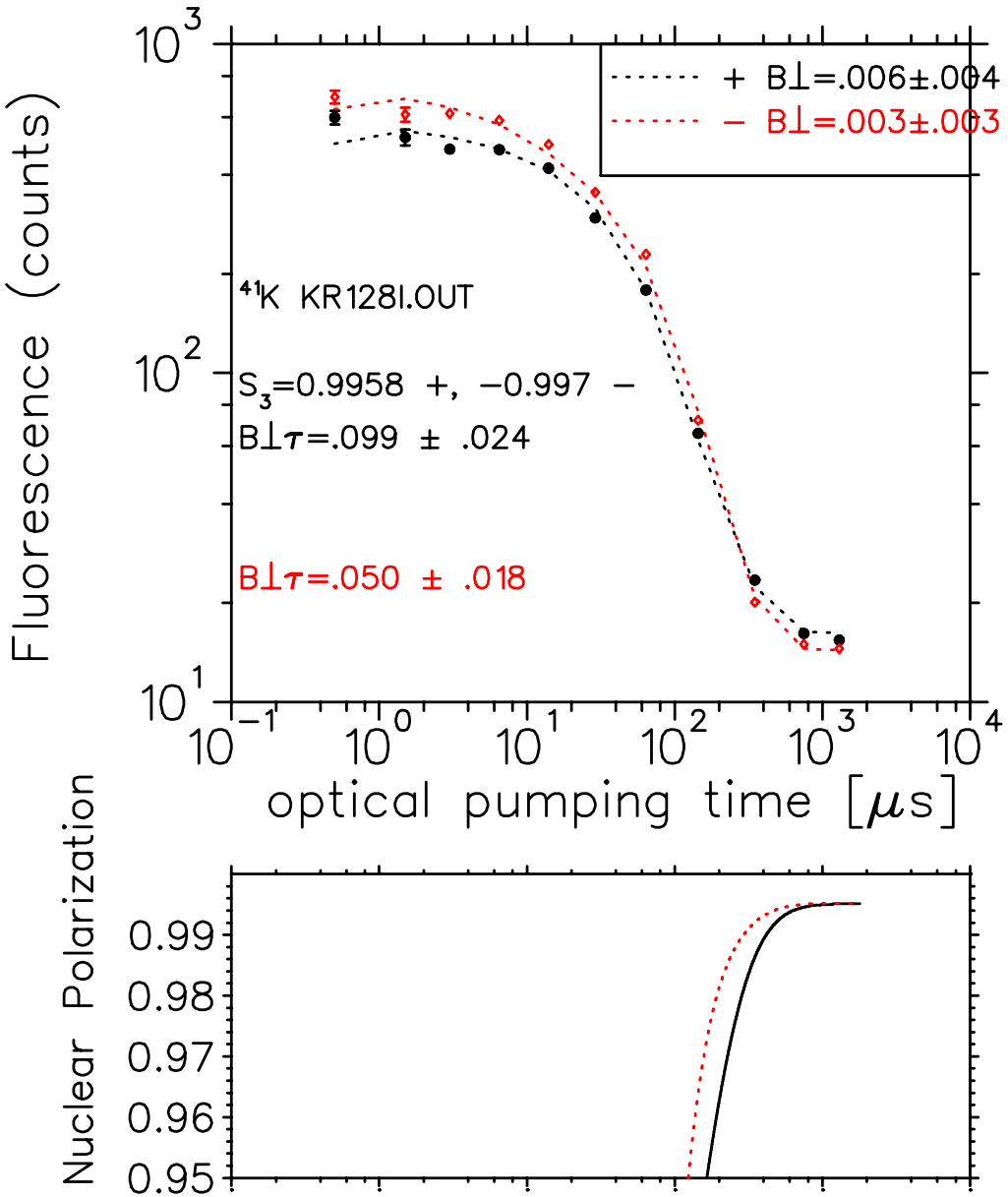
$$\frac{\mathrm{Im}(c_5)}{M^2} \leq 1/\mathcal{I} \;\; D_{c5} \times 10^{-3} [MeV^{-2}]$$

^{37}K wins by $p^2 \sim 25$ w.r.t neutron, and
if M^2 is tuned we could win by 25 more

But this is still a tight constraint,
depending on whether $\mathcal{I}$ is 0 or infinity

Fluorescence Diagnostic ^{41}K

- single-photon counting
- burst of fluorescence as atoms are optically pumped
- Modelled with rate equations including stray $B_\perp$ field and imperfect S_3
- Used to optimize parameters for use in ^{37}K

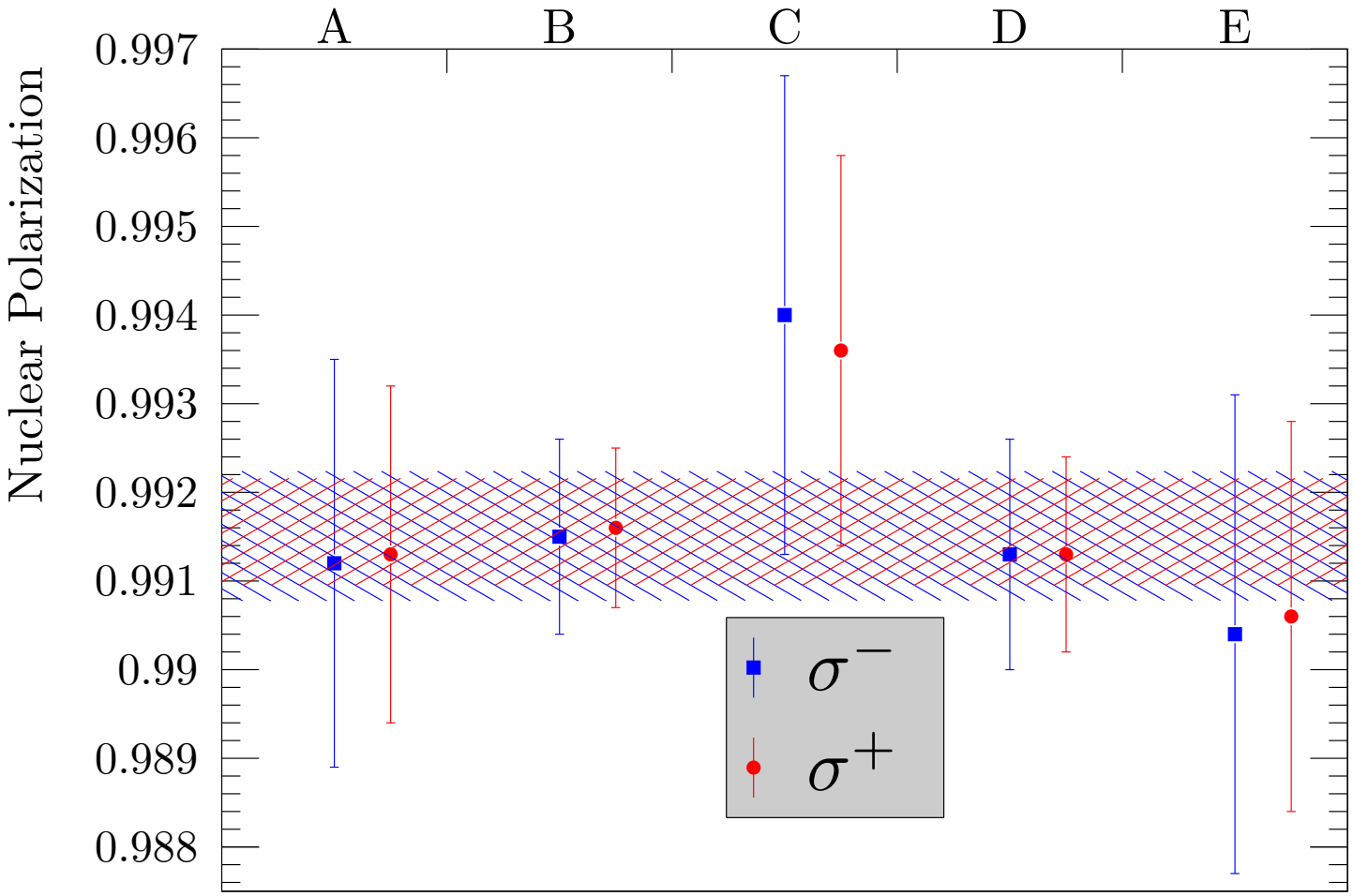


A_{β^+} Uncertainties and fixes

Source $\times 10^{-4}$ [†: β scattering]	ΔA_β
Background (Correction 1.0014)	7
Trap Position	4
Trap Sail velocity	5
Trap Temperature & width	1
BB1 Radius†	4
BB1 Energy agreement	2
BB1 threshold	1
Scintillator threshold	0.3
GEANT4 physics list†	4
Shakeoff electon t.o.f. region	3
SiC mirror thickness†	1
Be window thickness†	0.9
Scintillator or summed†	1
Scintillator calibration	0.1
Total systematics	12
Statistics	13
Polarization	5
Total uncertainty	18

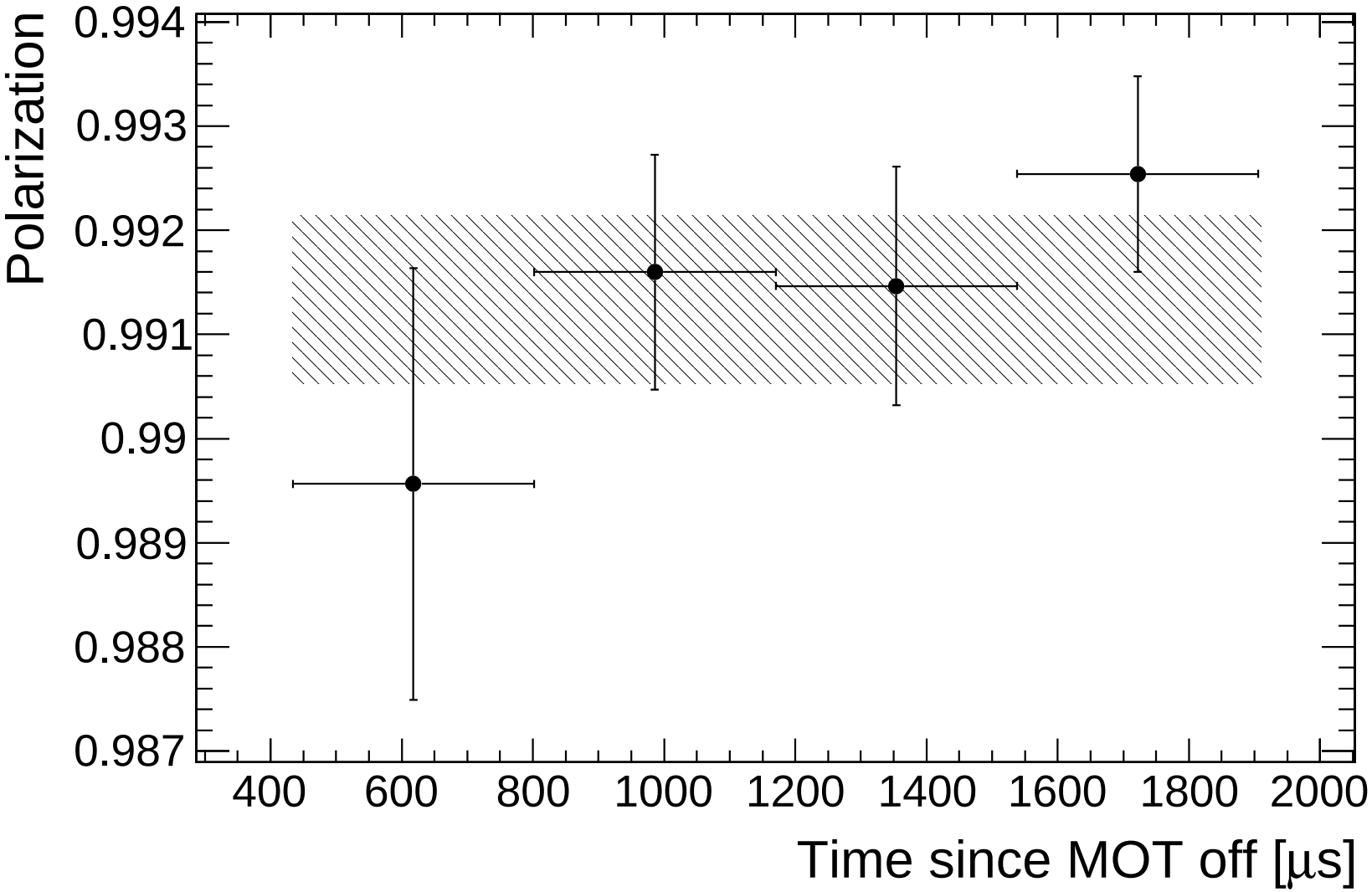
- **New trap control system and faster CMOS camera → smaller cloud temp. and size. Will try 405nm cooling.**
- **Pellicles → less β^+ scattering.**
- **Properly tapered collimators**
- **better ion MCP: better-known photoions**

Polarization by data set



Field [V cm^{-1}]	⟵ 395 ⟶	⟵ 535 ⟶	⟵ 415 ⟶
t_{OP} [µs]	⟵ 332 ⟶	⟵ 732 ⟶	⟵ 432 ⟶

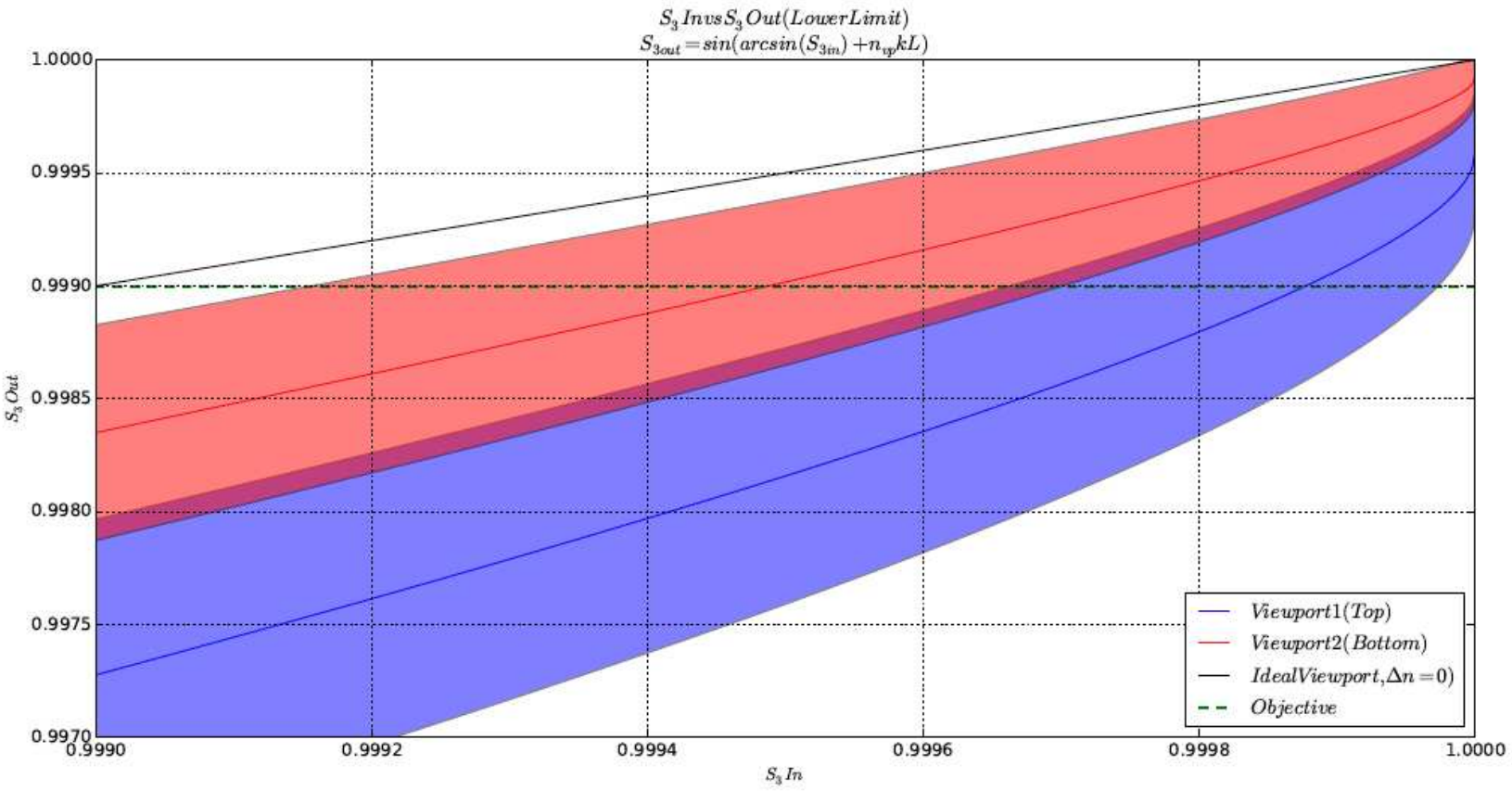
Polarization time dependence



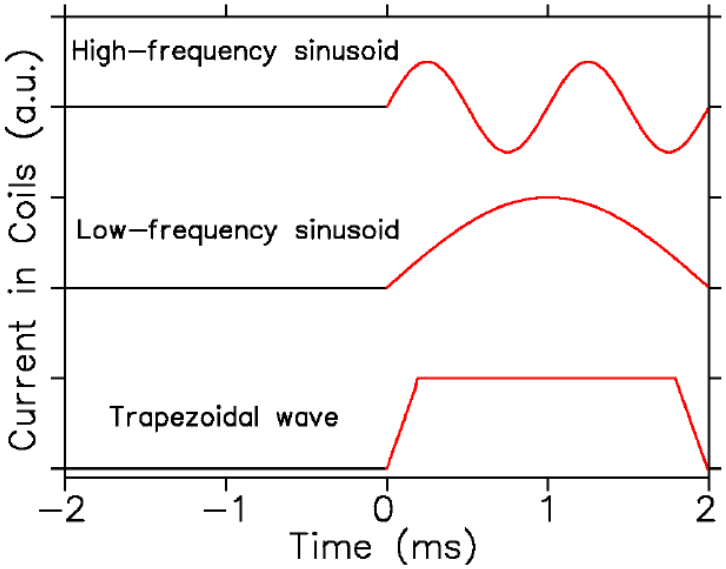
^{41}K data also suggest a 1 millisec B_{quad} component
materials: 316L, 316LN, Ti, glassy carbon electrodes

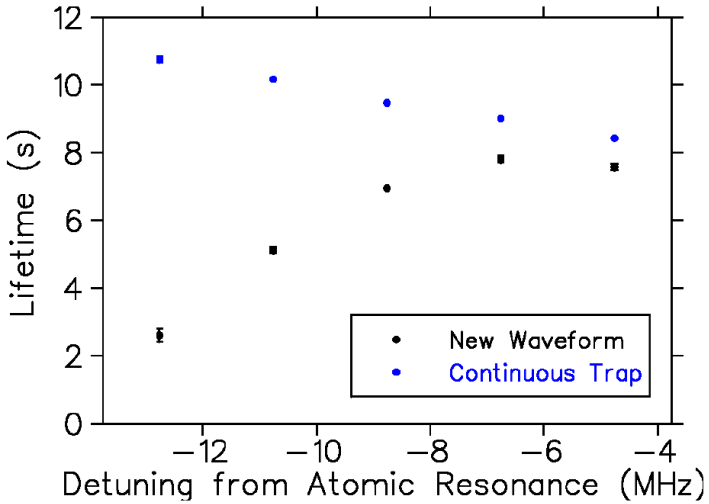
Viewport birefringence

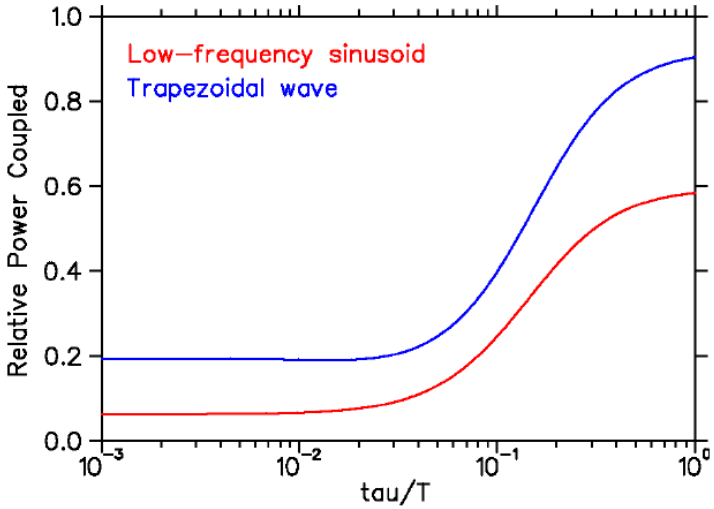
Characterizing viewport birefringence allows prediction of S_3 in center given S_3 in and out.

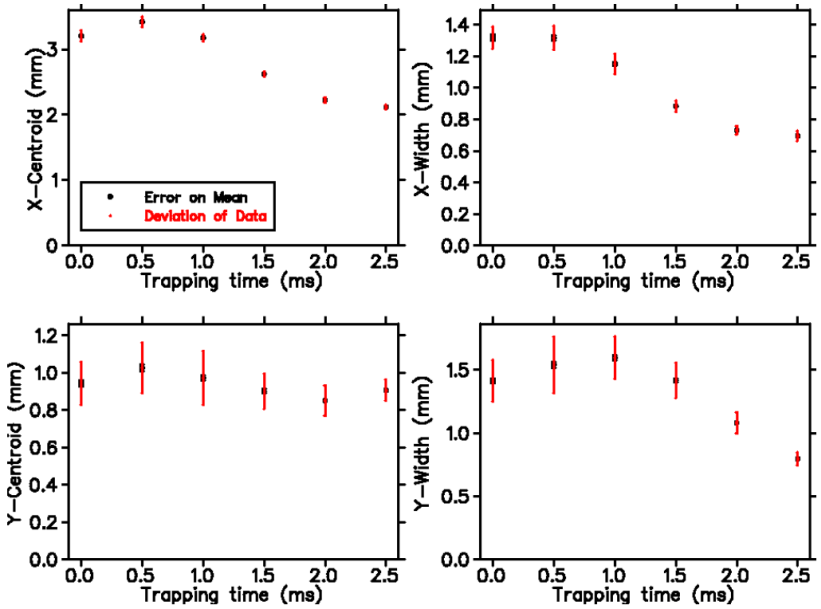


gentler RAC MOT





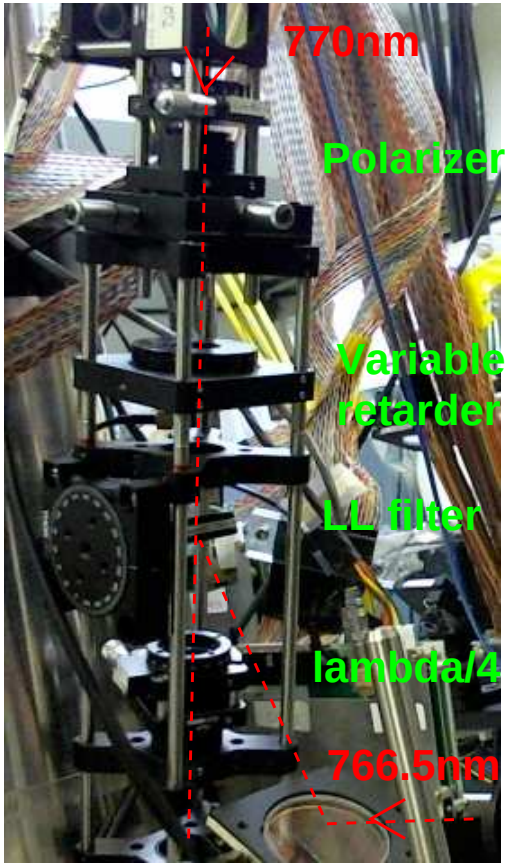




1/2-sinusoid dissipates less power and keeps confinement.

Liam Lawrence, McMaster U., poster CEU at DNP, Oct 14 downtown

Optics Techniques



- Combine 769.9nm D1 and 766.49 D2 with angle-tuned 780 nm laser-line filter
- Flip spin state with liquid crystal variable retarder
- Relieve stress-induced birefringence with PCTFE (Neoflon) viewport seals (S_3=-0.9958(8), -0.9984(13), +0.9893(14), +0.9994(5))