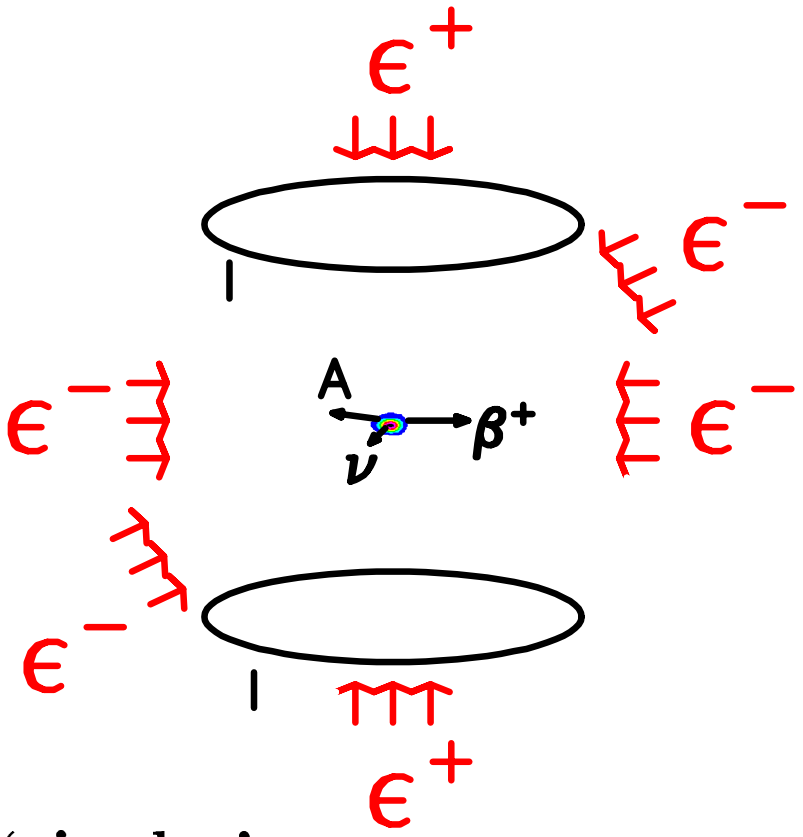
Searches for new interactions and exotic particles with neutral atom traps at TRIUMF



TRIUMF Neutral Atom Trap

- ^{38m}K β-ν: Best general limits on scalars coupling to 1st generation
Upgrade approved

Experiments with daughter ions in 'singles':

- Search for tensor interactions in ^{80}Rb:
- Search for wrong-handed interactions in ^{37}K

Planning two-body decays:

- Search for ∼20 keV sterile ν in ^{131}Cs e$^-$ capture decay
- Search for 'heavy' axions in ^{84m}Rb isomer decay

TRIUMF Neutral-Atom Trapping "TRINAT"

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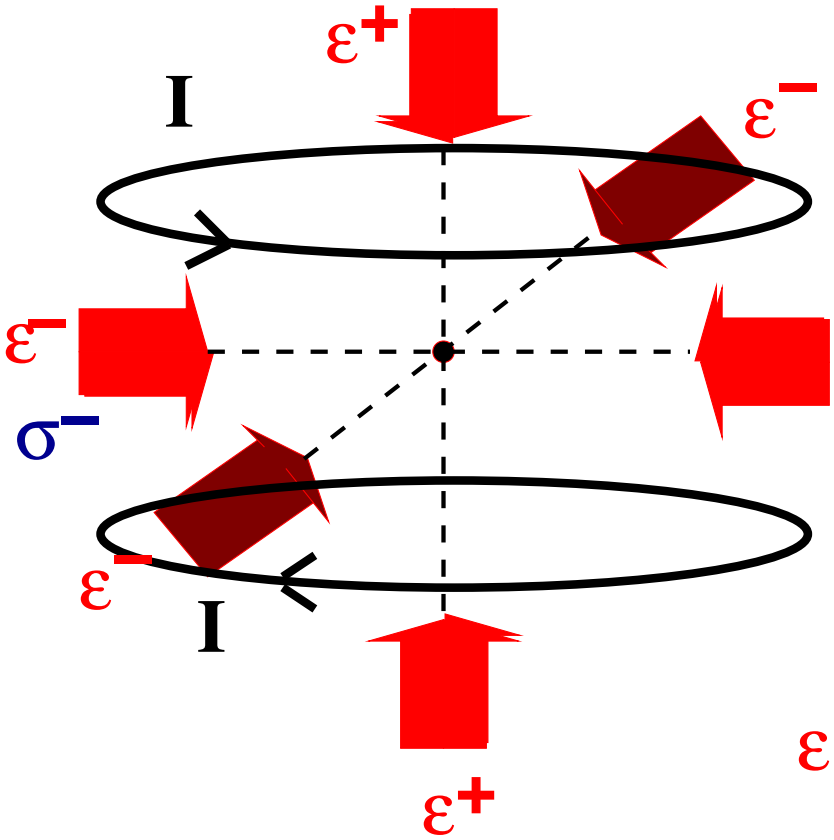
Supported by Canadian NSERC, Canadian NRC through TRIUMF, WestGrid, Israeli Science Foundation

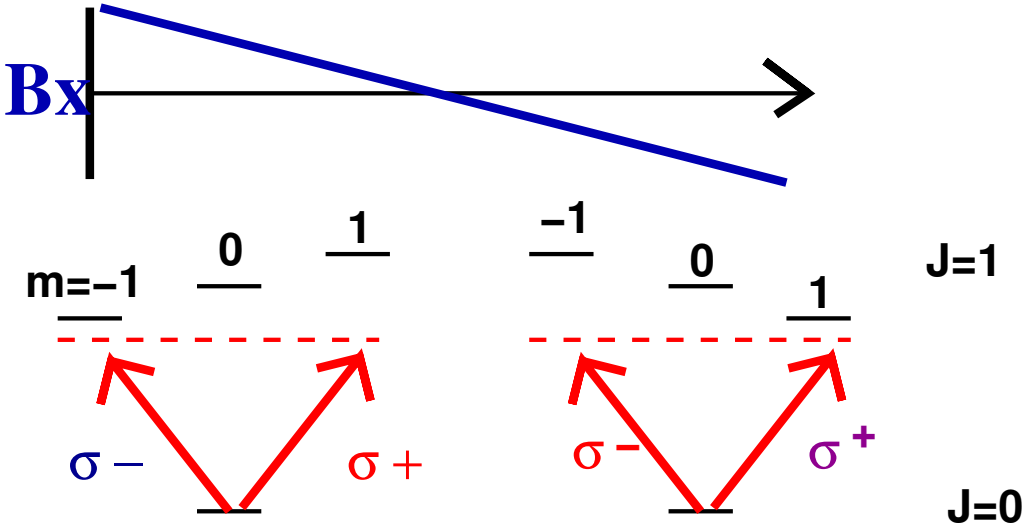
Zeeman Optical Trap (MOT)



Raab et al. PRL 59 2631 (1987)

Damped harmonic oscillator

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

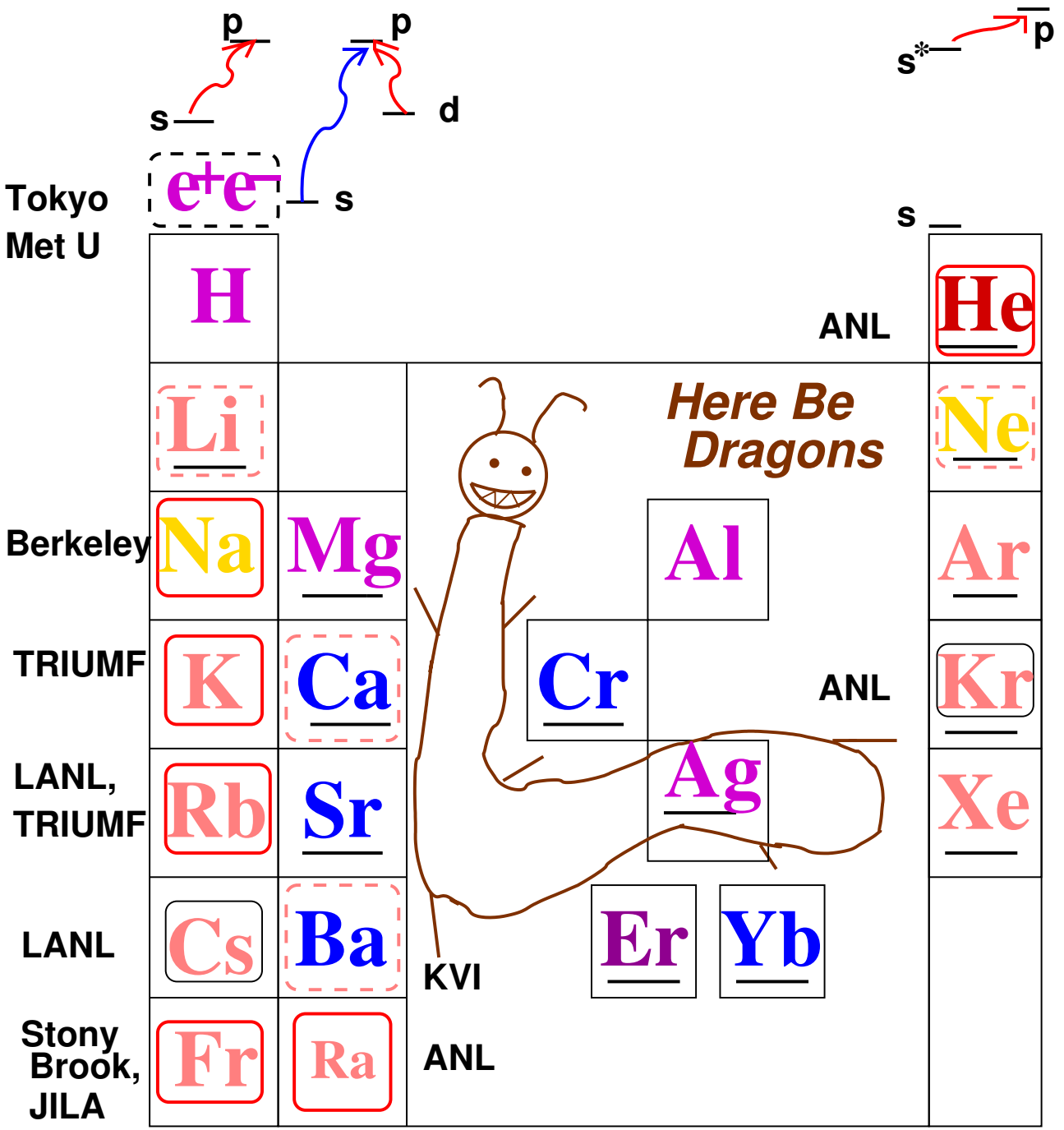


Bquad weak: recoils unperturbed

Velocities negligible

Vector polarization ~ 0
(Tensor alignment maybe)

Turn MOT off to polarize


p
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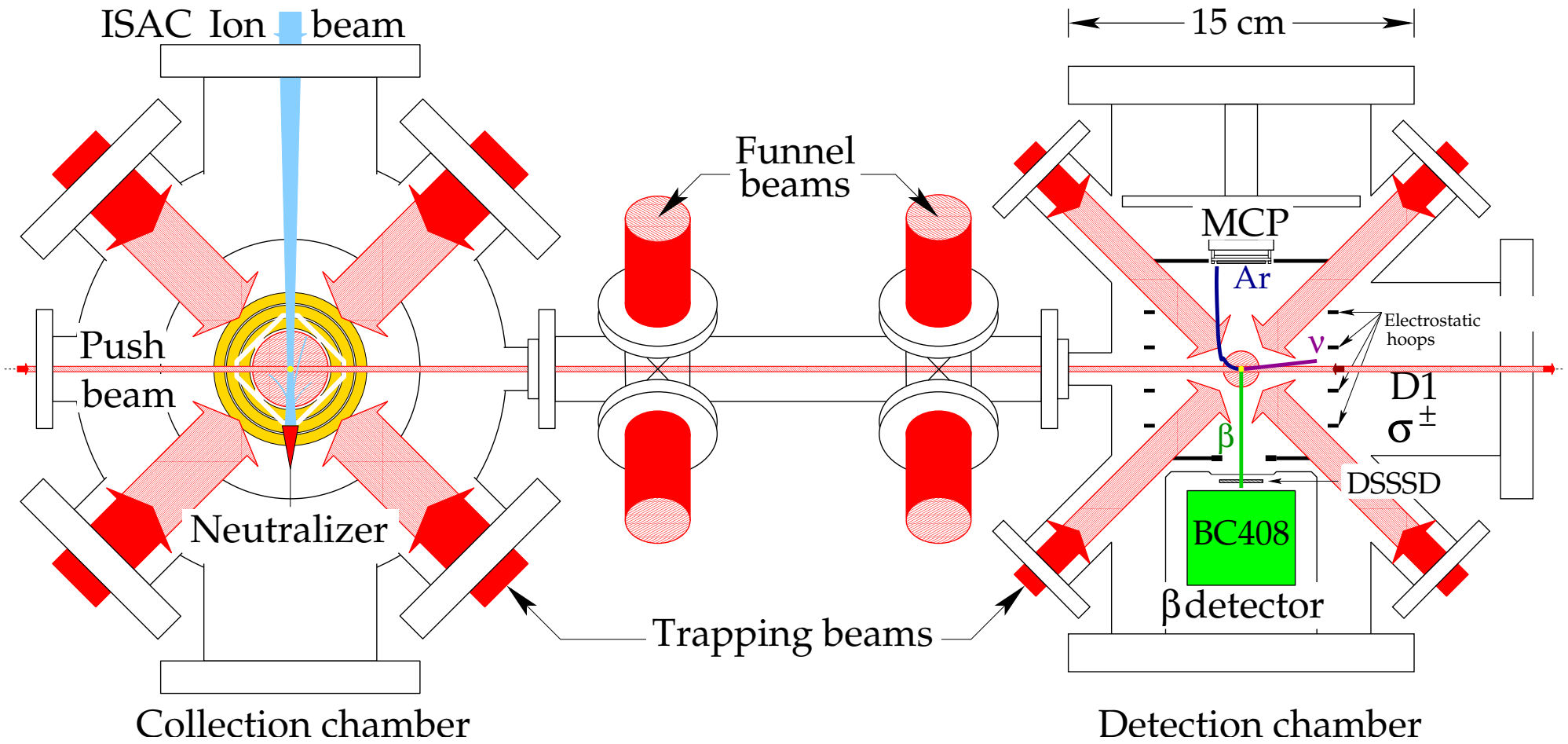
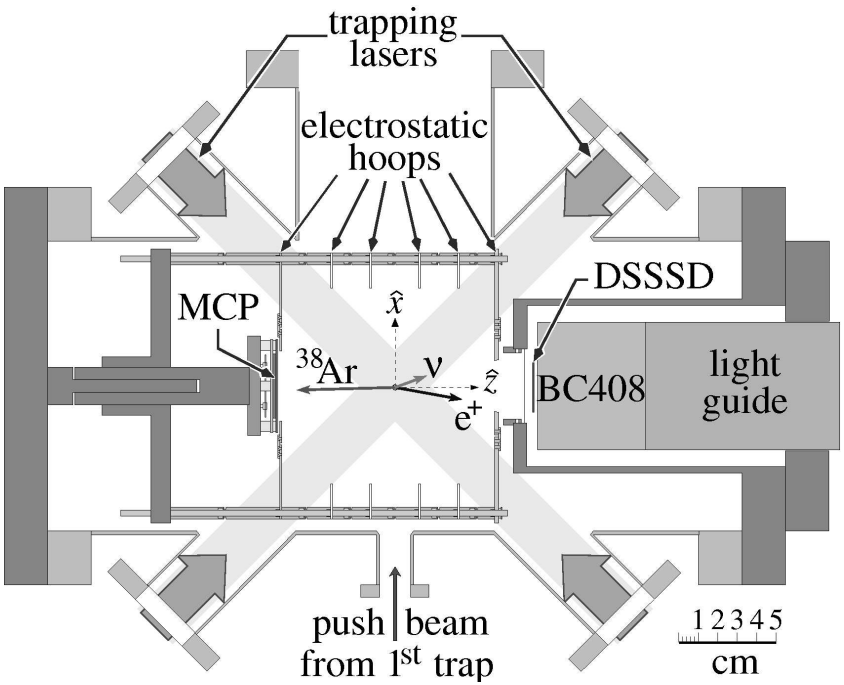
Dragons
Berkeley
Na
Mg
Al
Ar
TRIUMF
K
Ca
Cr
ANL
Kr
LANL,
TRIUMF
Rb
Sr
Ag
Xe
LANL
Cs
Ba
KVI
Er
Yb
Stony
Brook,
JILA
Fr
Ra
ANL
Trapped in MOT
Radioactives trapped
Long–lived Rad.
Plans

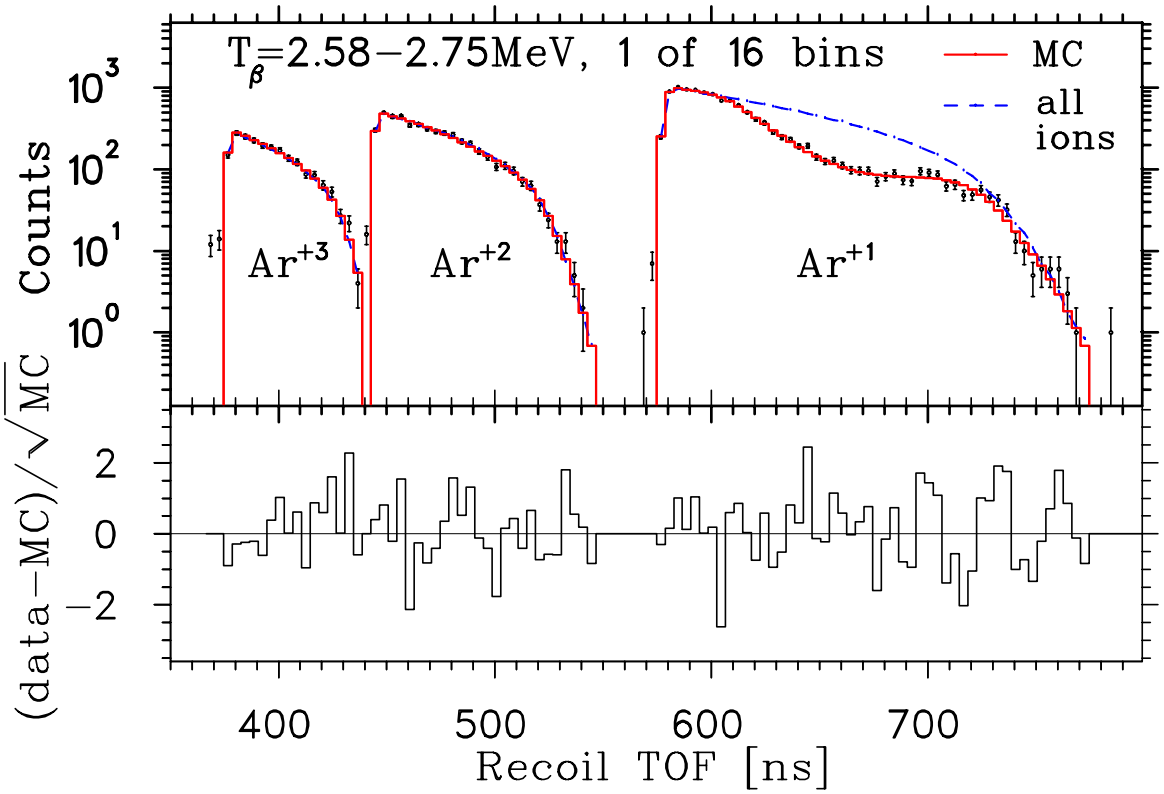
TRIUMF's Neutral Atom Trap

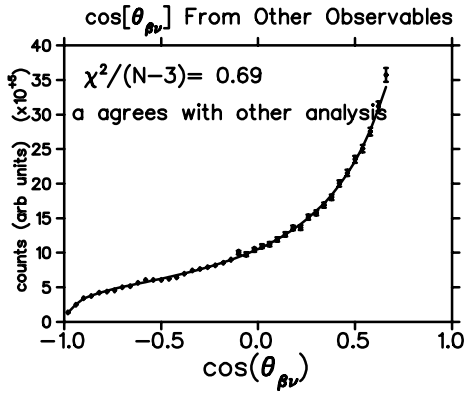
- Isotope/Isomer selective
- Evade 1000x untrapped atom background by $\rightarrow$ 2nd MOT
- 75% transfer (must avoid backgrounds!); 10^{-3} capture
- 0.7 mm cloud for β-Ar^{+} $\rightarrow$ ν momentum $\rightarrow$ β-ν correlation
- >97% polarized, known atomically

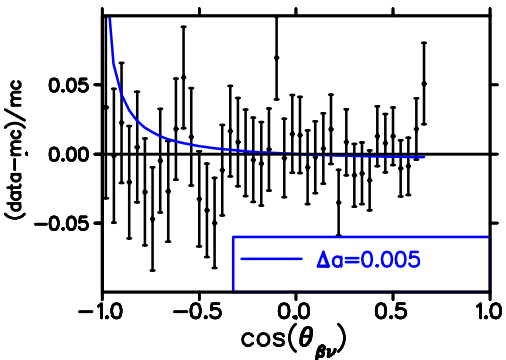


^{38m}K $0^+ \rightarrow 0^+$ β-ν correlation









Gorelov PRL Apr 2005

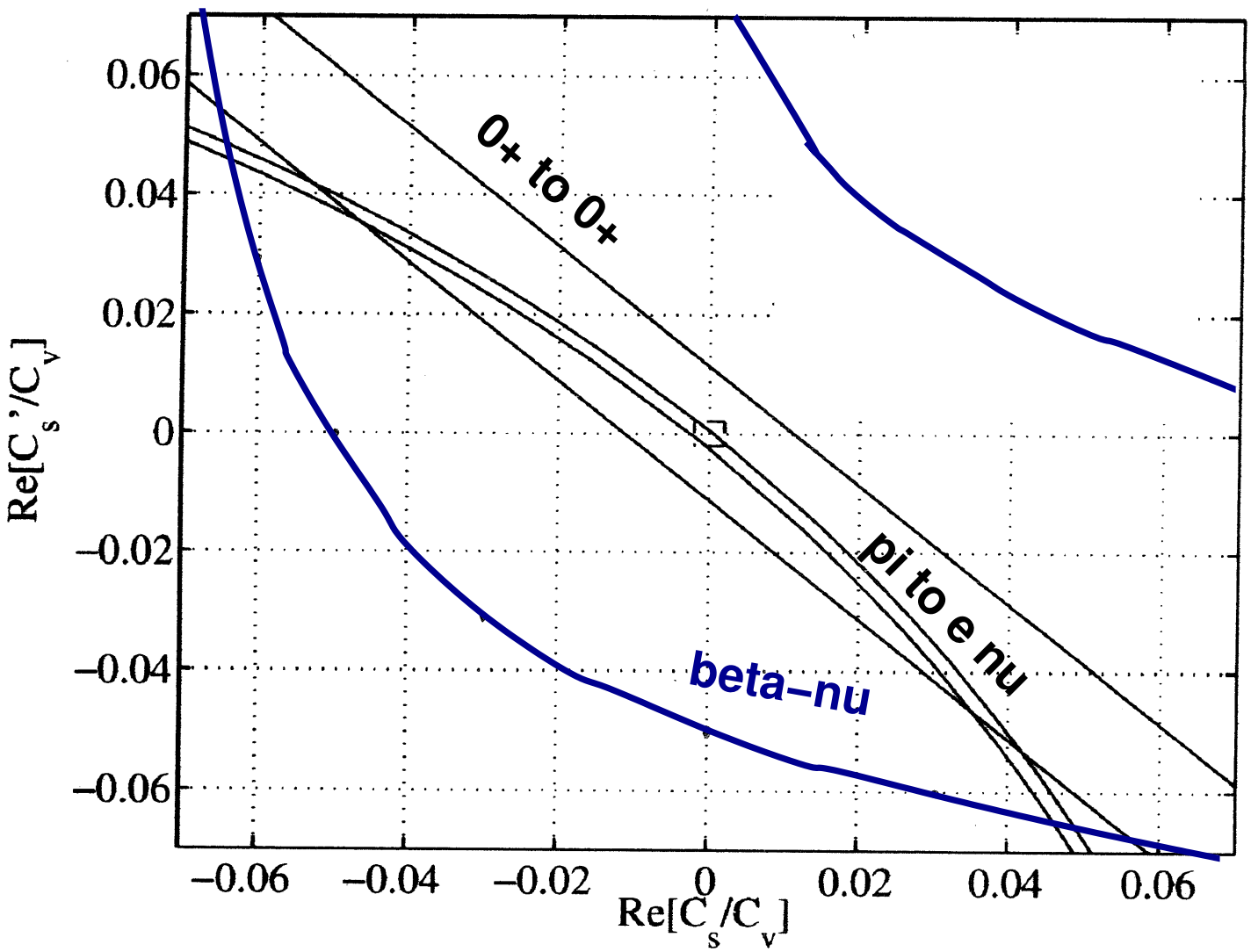
$$W(\theta) = 1 + b\frac{m_\beta}{E_\beta} + a\frac{v}{c}\cos\theta$$

$\tilde{a}$=0.9981 ± 0.0030(stat)
± 0.0037(syst)

$$a \approx 1 - (|C_S|^2 + |C'_S|^2)$$
$$b \approx -Re(C_S + C'_S)$$

$a = +1$ vector; $a = -1$ scalar

‘Best general constraints on scalars coupling to 1st generation’
Better constraints from other experiments for some scalars
SUSY can make $C_S+C'_S\sim$ 0.001 Ramsey-Musolf nucl-th/0608035



Campbell and Murray NPB 2005

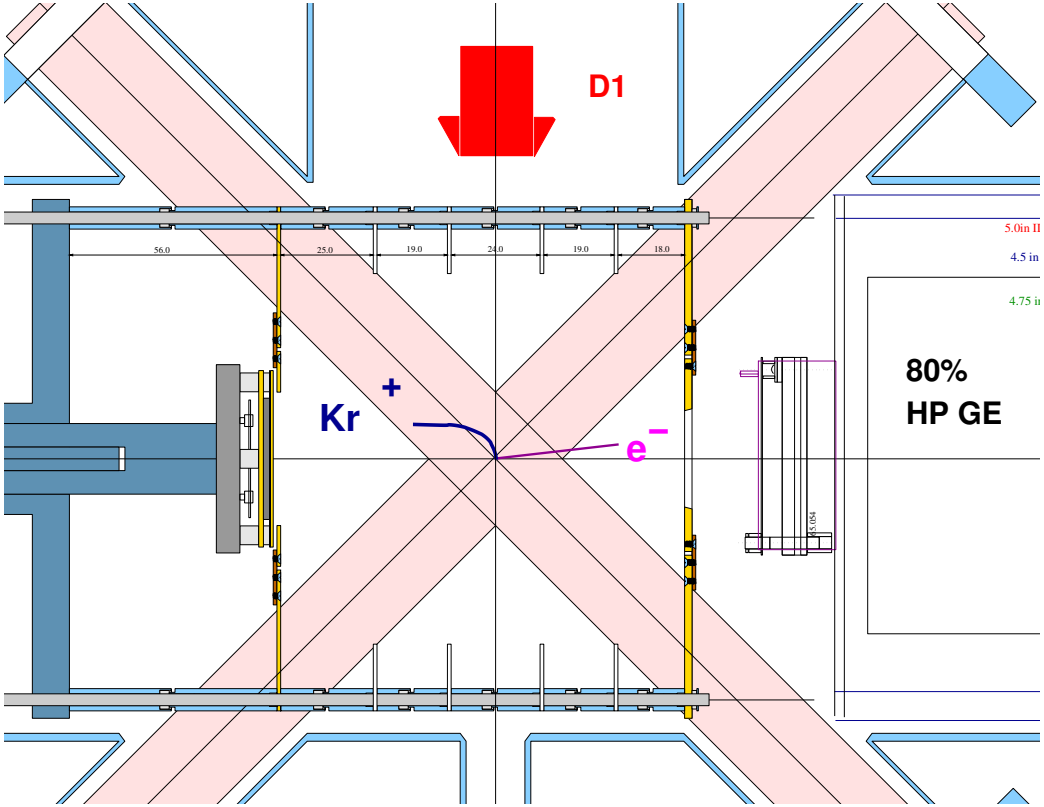
^{80}Rb decay: Search for Tensor Interactions

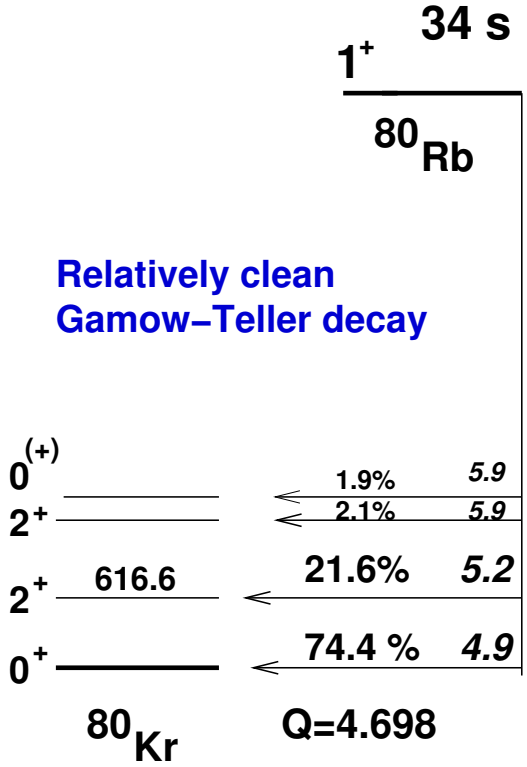
Spin asymmetry of recoils $A_{recoil} \propto A_\beta + B_\nu$ (Treiman PR 1958)

- **For pure Gamow-Teller ^{80}Rb, $A_{recoil} = 0$**
- **non-SM results $\pi \to \nu e \gamma$ Bolotov 1992, PiBETA PRL 2004:**
  resolved by further PiBETA: E. Frlez hep-ex/0606023
  Would need accuracy $\sim$0.002 to contribute
- **or 0.01 constrains $C_T C'_T$, complements ^{6}He $\beta - \nu$**

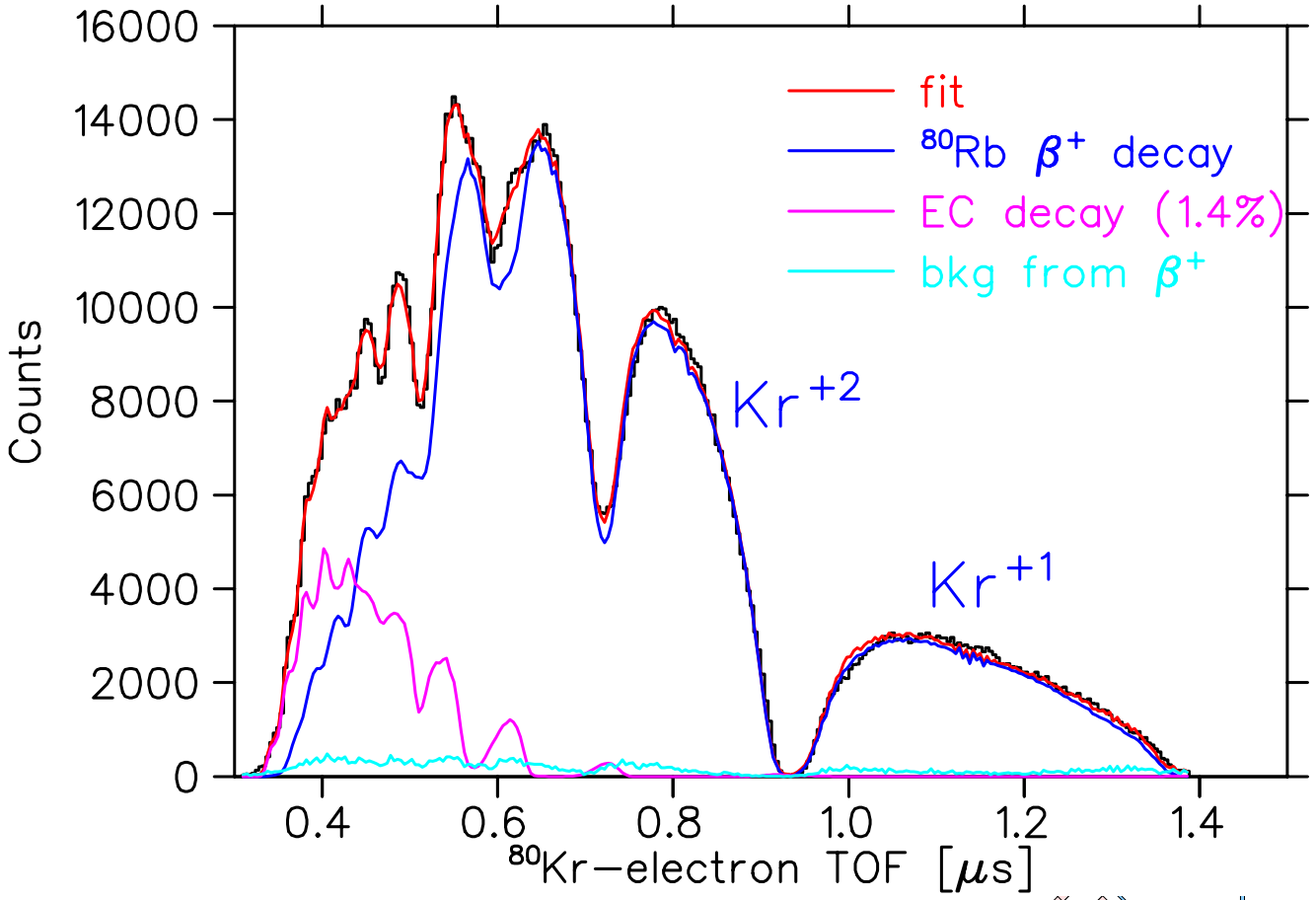
We have statistical error $\approx$ 0.007:

Need nuclear structure calculation of $\sim$ 0.02 correction



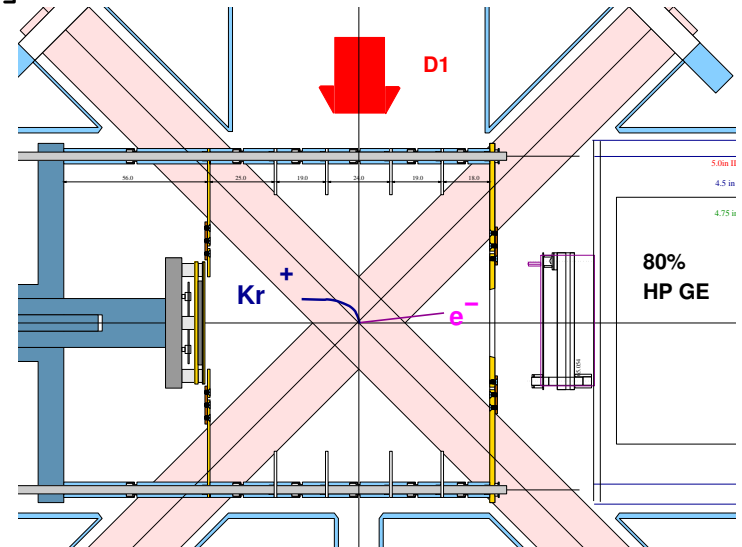


^{80}Rb Data: TOF contributions:

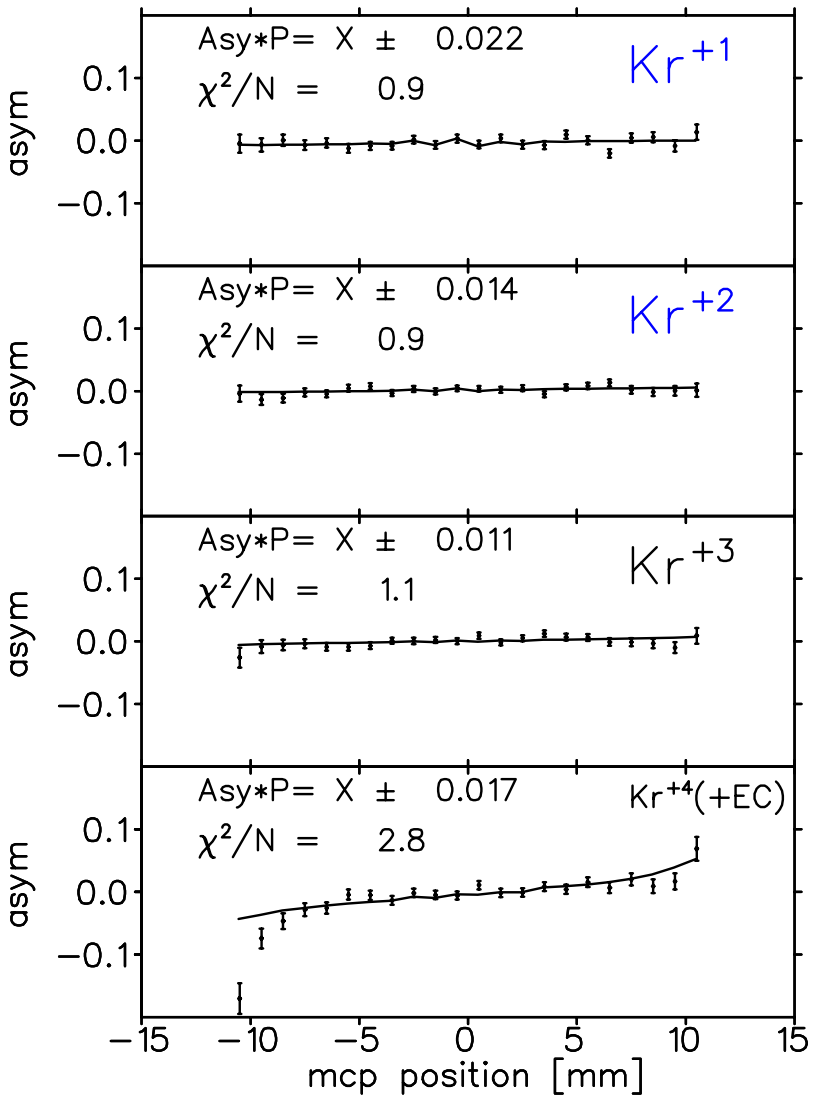


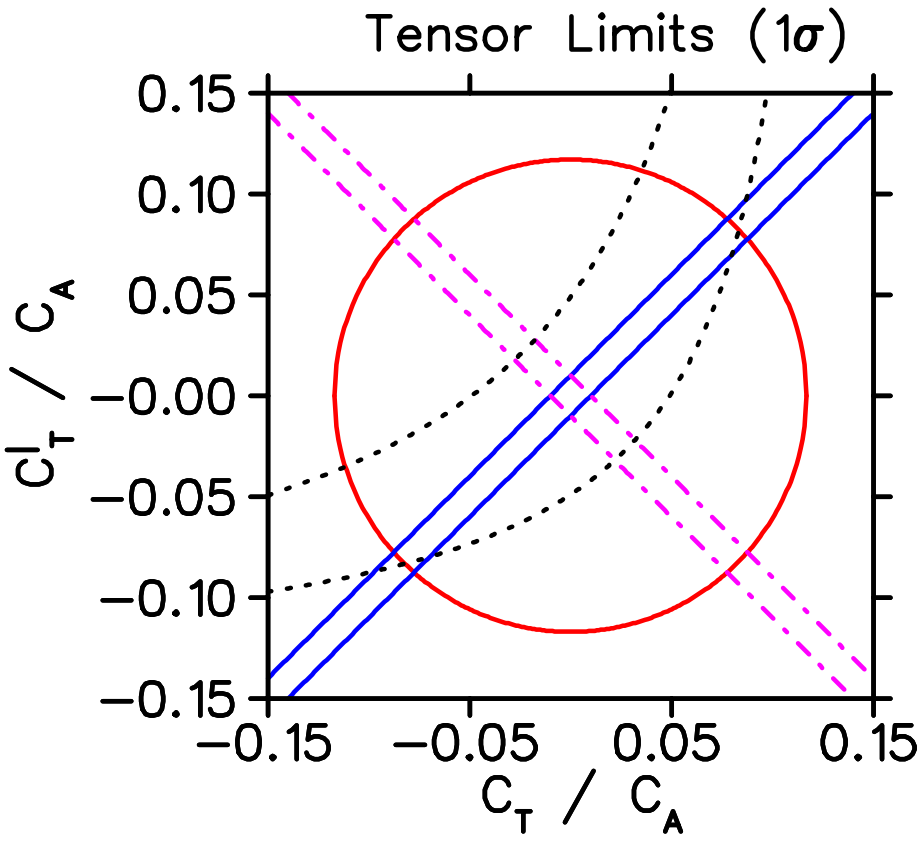
- **Kr^{+1}, Kr^{+2} clean**

- **recoil-shakeoff electron like Scielzo LBL NPA'04**



^{80}Rb Singles Recoil Asymmetry: statistics for ≈ 0.007





^{6}He $\beta-\nu$ PR 132 (1963) 1149 ORNL

PRC43 2825 (1991) P_F/P_{GT} Louvain

Ito+Prezeau PRL 94 161802 (05)

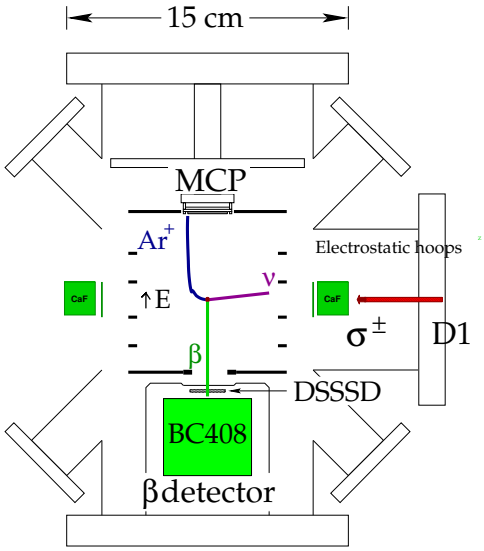
projected E956 0.007 err

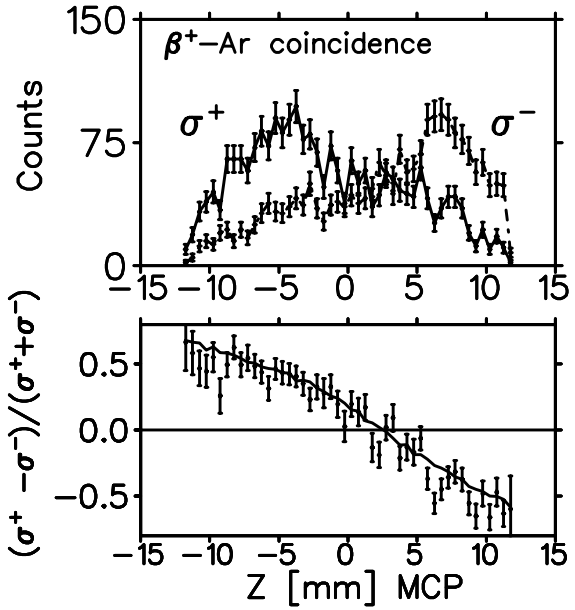
In Progress: Spin asymmetries in $^{37}\vec{K}$: a 'heavy neutron'

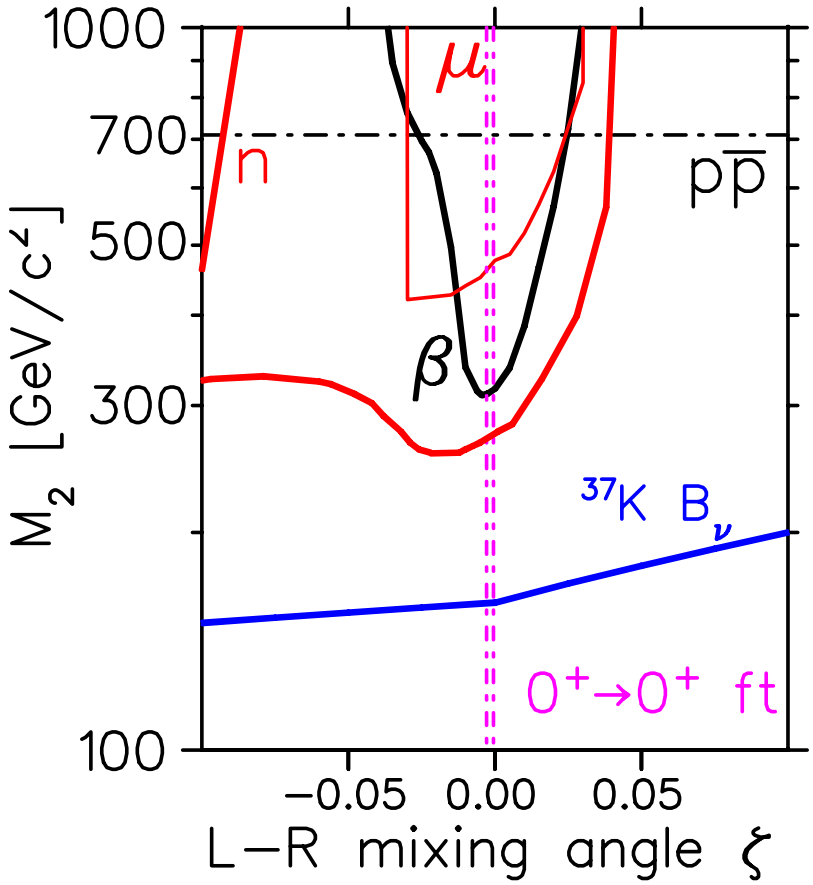
$^{37}\vec{K}$ D. Melconian preprint TRITRI-PP-06-13

^{37}K decays to its isobaric mirror ^{37}Ar → 0.2% corrections from CVC

We can search cleanly for $SU(2)_L \times U(1) \rightarrow SU(2)_L \times SU(2)_R \times U(1)$







$$P_z\, B_\nu\, \vec{I} \cdot \vec{p}_\nu$$

ν asymmetry

$P_z = 0.97 \pm 0.01$

$B_\nu = -0.755 \pm 0.020 \pm 0.013$

$(B_\nu^{SM} = -0.769)$

Planning: 20 KeV-mass sterile ν's $\quad |\nu_e\rangle = \cos\theta\ |\nu_{m\approx 0}\rangle + \sin\theta\ |\nu_x\rangle$

- **dark matter candidate... Dodelson PRL 1994**
- **$m_\nu \sim$10 keV, $\sin^2 2\theta \sim 10^{-8}$ Abazajian PRD 2006 Need ~0 background**

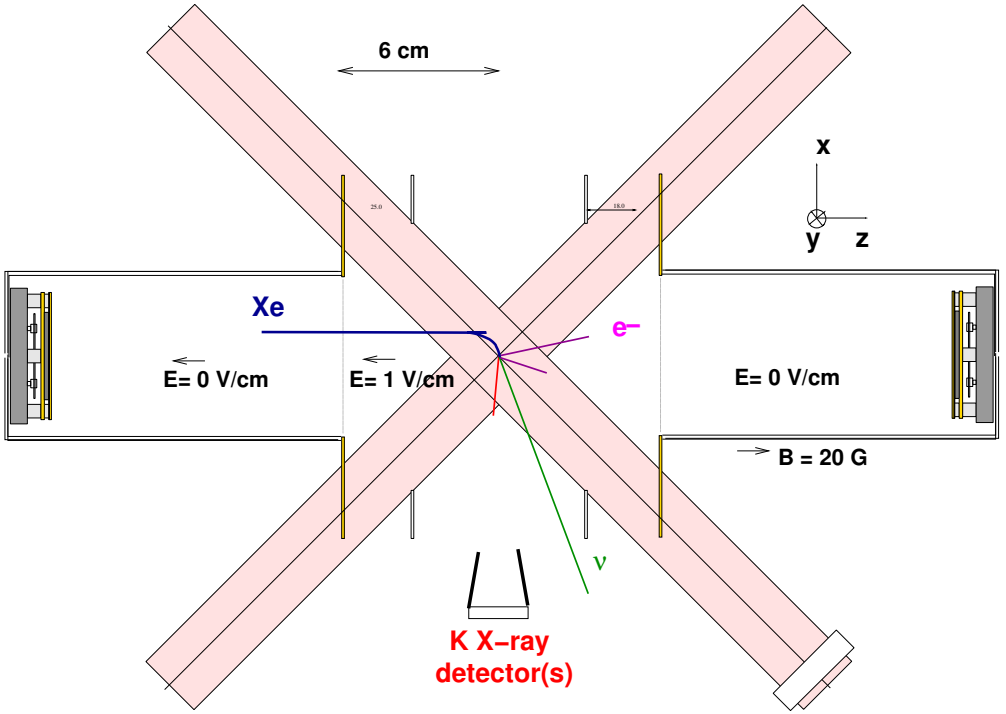
- **10^{-5} admixture possible at 40 keV: Useful for $T_{reheat} \approx$5 MeV**

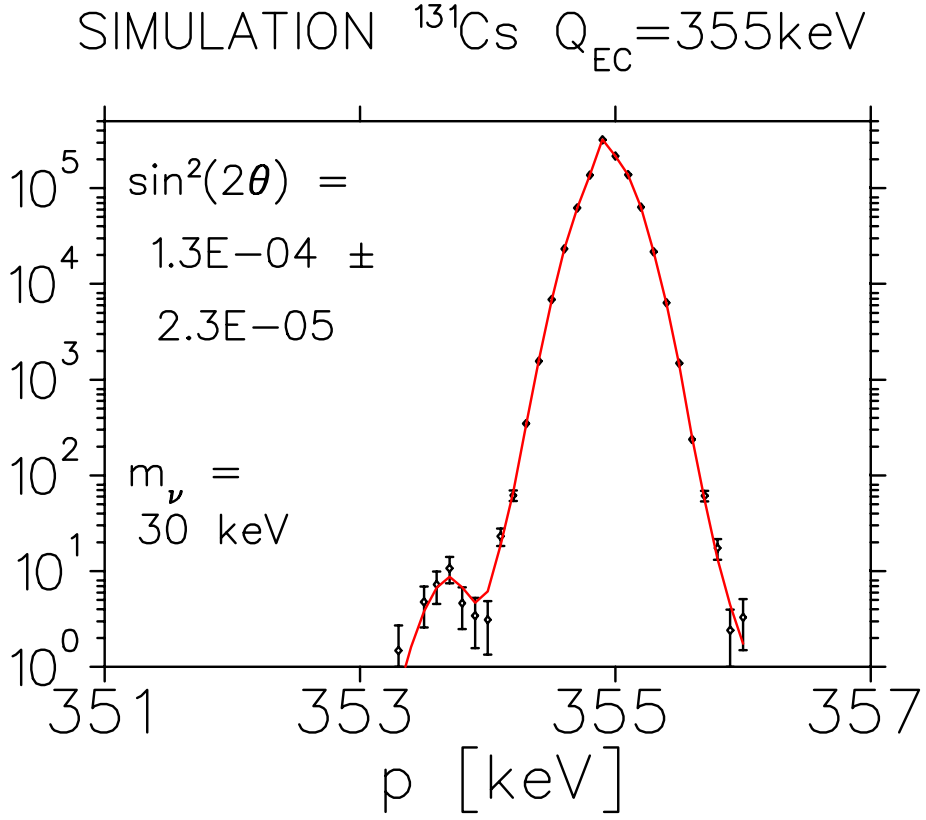
Electron Capture Decay: $^{131}Cs + e^- \rightarrow \nu + {}^{131}Xe$

$p' = \sqrt{Q^2 - m_{\nu x}^2} \Rightarrow \delta p/p \sim$0.001 ADDS EXTRA PEAK

Must measure momenta of all shakeoff e^-'s to 5% and K X-ray direction

Desired: 34 KeV X-ray with ΔE=0.3 keV and Δt<1 ns





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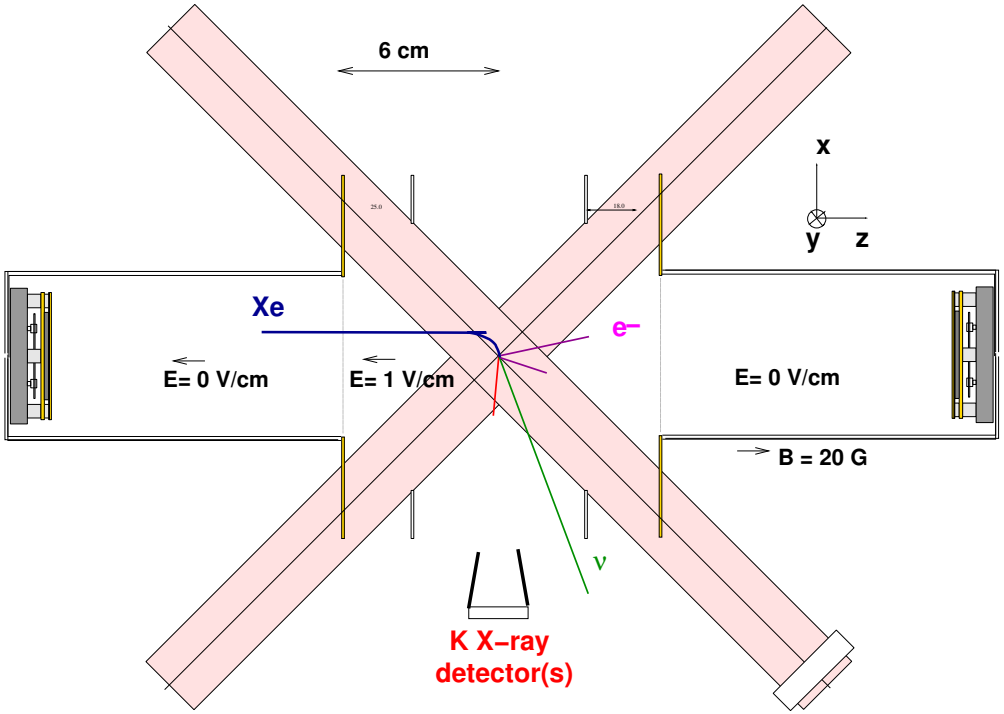

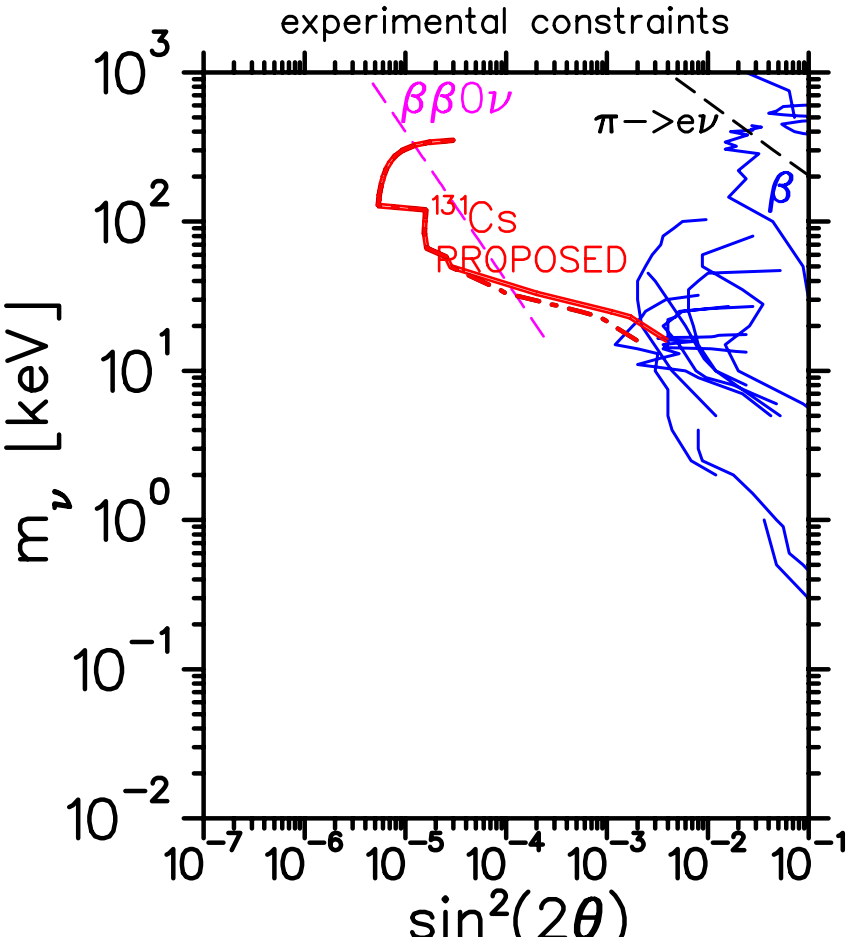

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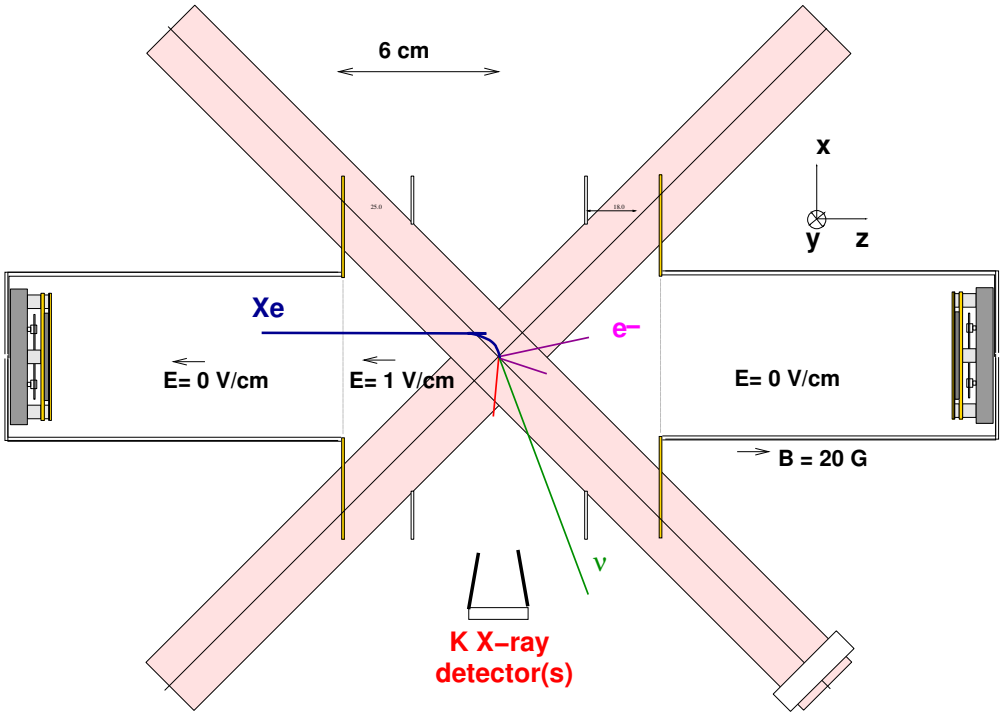

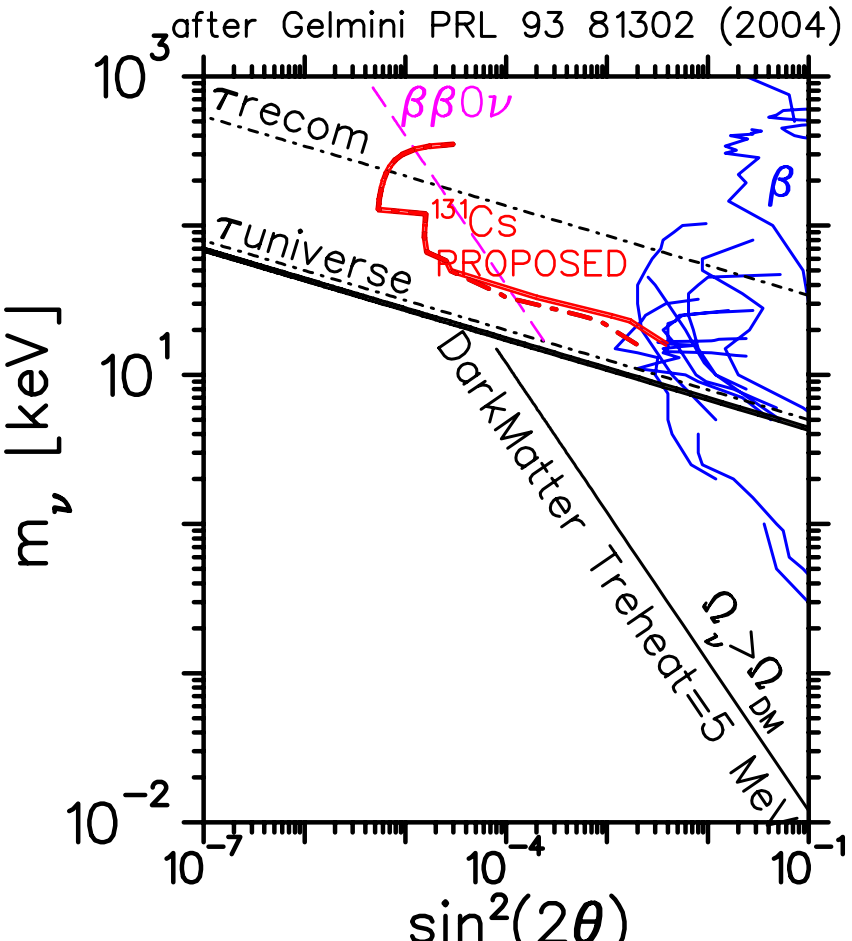

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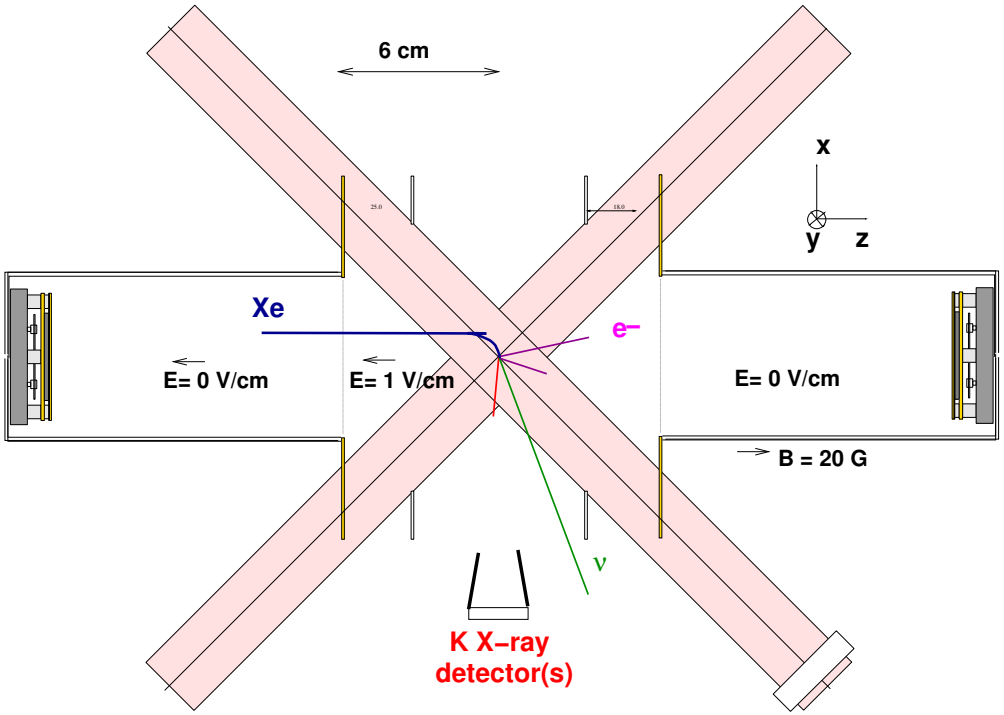
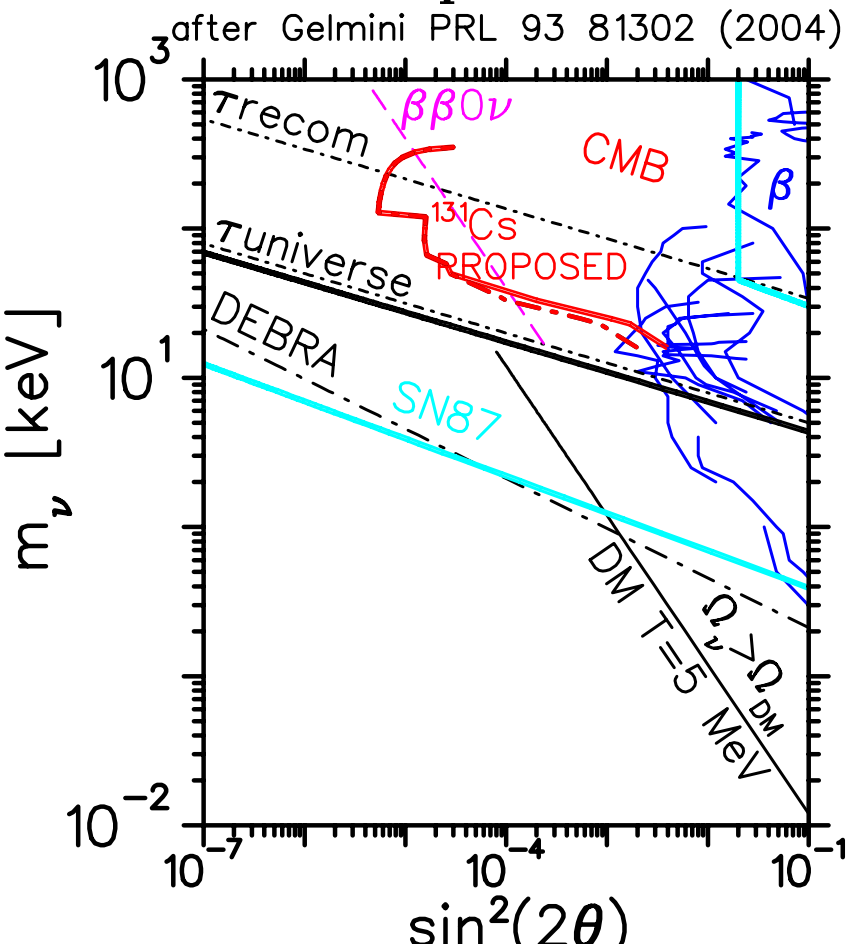
SN87A timescale: but Hidaka Fuller Oct06 5 keV helps SN



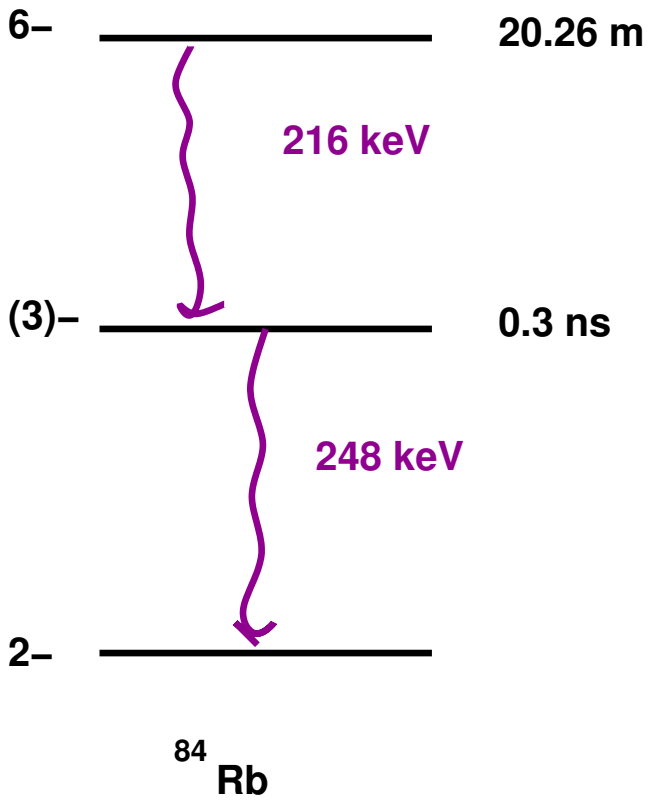


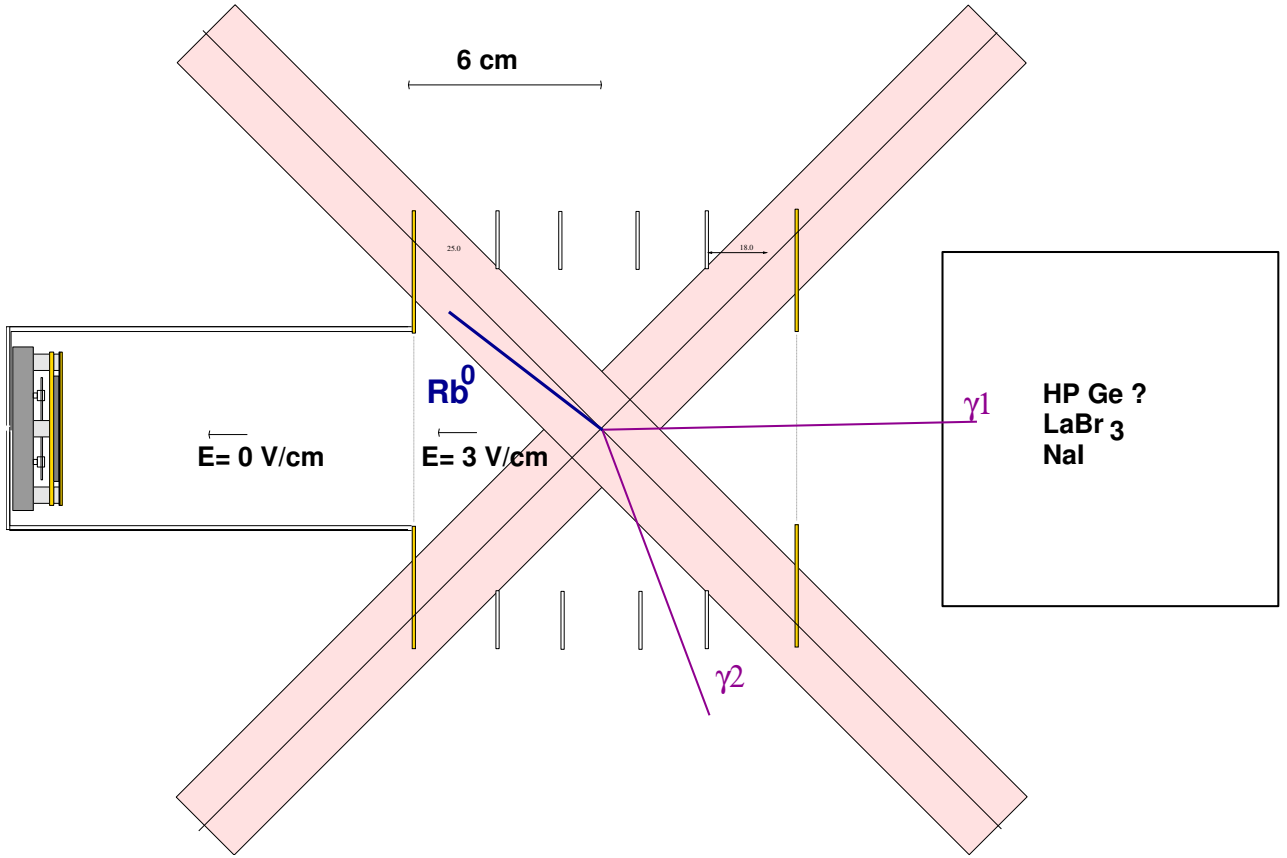
'Simpler' experiment

- Isomer decay → heavy axion search

(10's keV axions still possible Derbin JETP Lett 81 365 ('05))

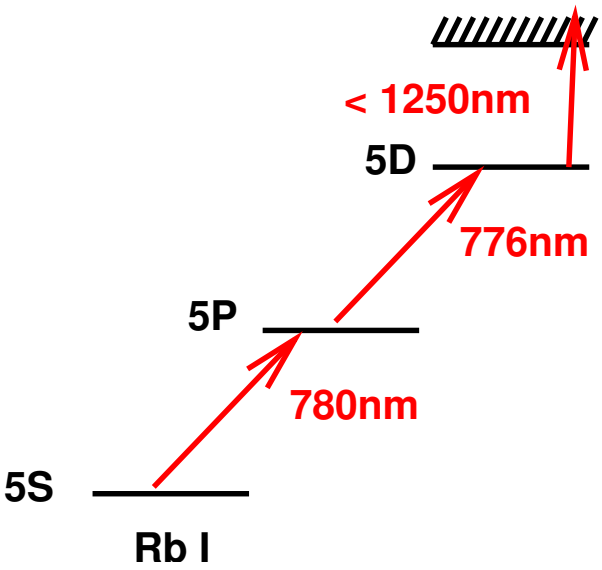
No X-rays, No Auger's But recoil is neutral, 0.5eV

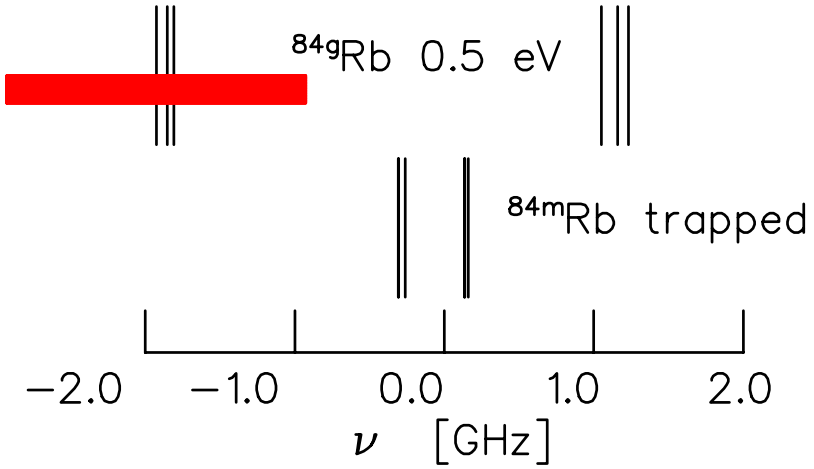




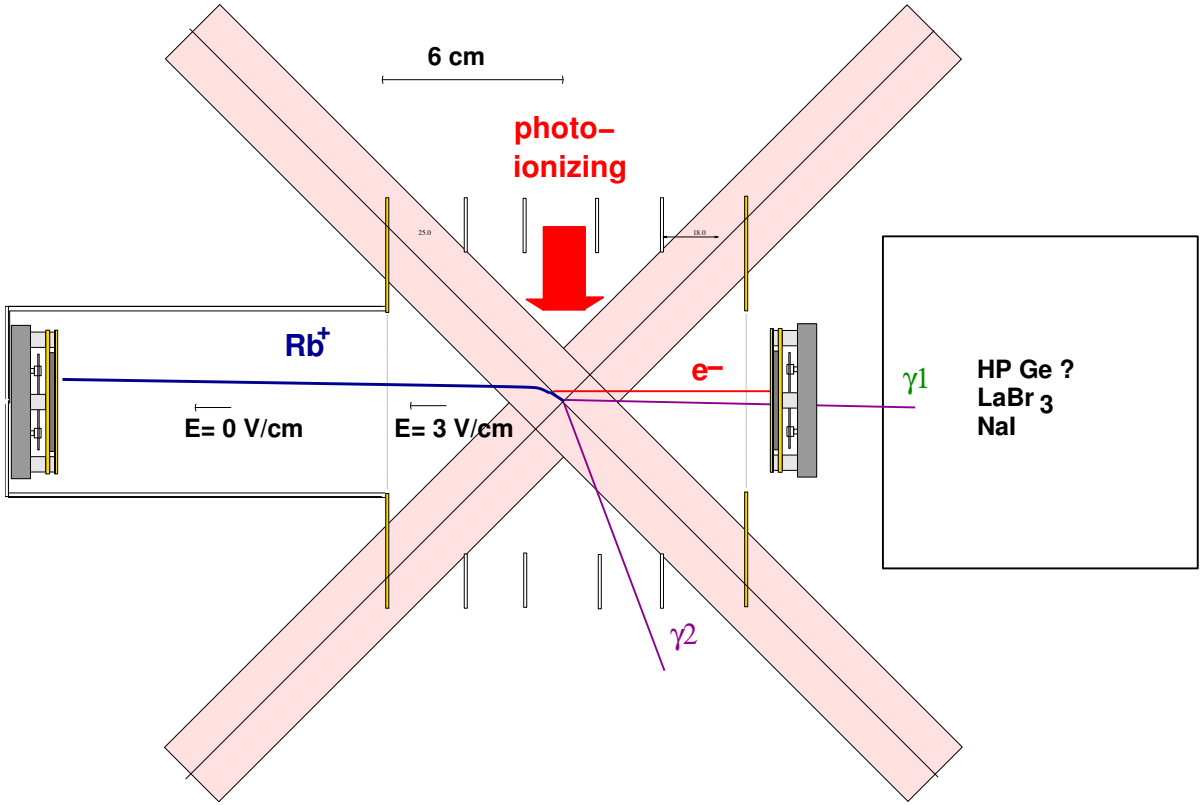
Limits on anything massive emitted from nuclear transition, independent of interaction in detector or lifetime

Isomer Decay: Must ionize neutral recoil





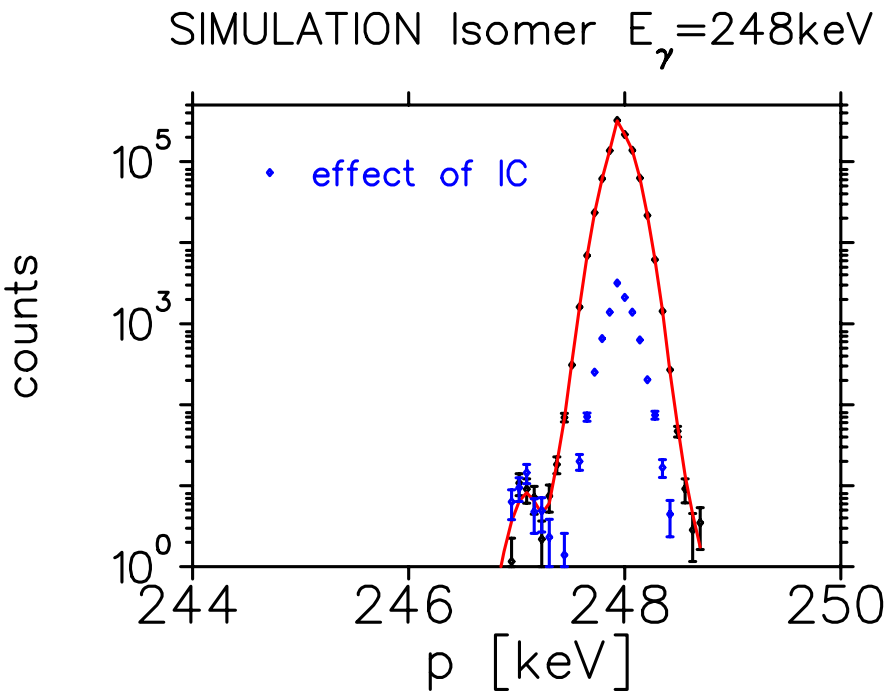
Thibault PRC 1981



Isomer decay: 'Uhm, are heavy axions still useful?'

- The original Peccei-Quinn axion solved the 'strong CP problem' with $m_{axion} \sim$ 100's keV. Couplings large enough to do so were ruled out long ago
(so people use μwave cavities now)
- There exist more exotic models that solve strong CP problem with arbitrarily small couplings. (e.g. Hall Watari PRD 70 115001 (2004), 'mirror universe' Berezhiana PLB 500 286 (2001))
- If direct limits can be improved they are still useful

There are M1 transitions in Cs isotopes that are highly internally converted.
IC removes 99% of hard-to-resolve massless γ-ray and turns it to $> 1^+$ ions that we can separate completely by TOF.



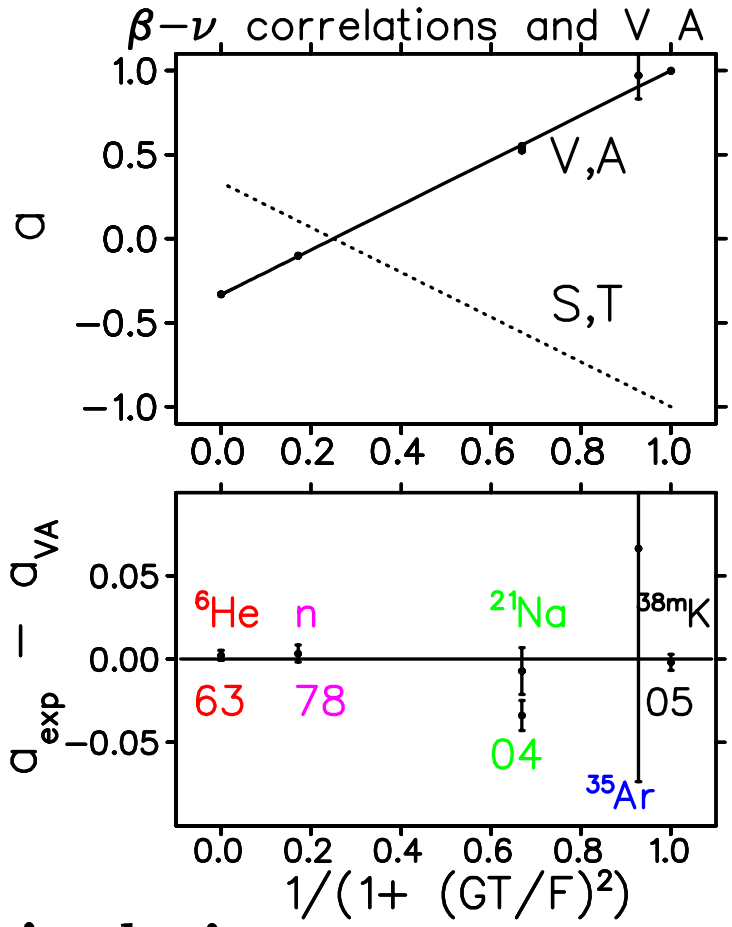
Searches for new interactions and exotic particles with neutral atom traps at TRIUMF

- ^{38m}K β-ν: Best general limits on scalars coupling to 1st generation Upgrade approved

- Search for wrong-handed interactions in ^{37}K

^{37}K $B_\nu/B_\nu^{SM} = 0.982 \pm 0.026 \pm 0.017$

Goal: improve 10x.



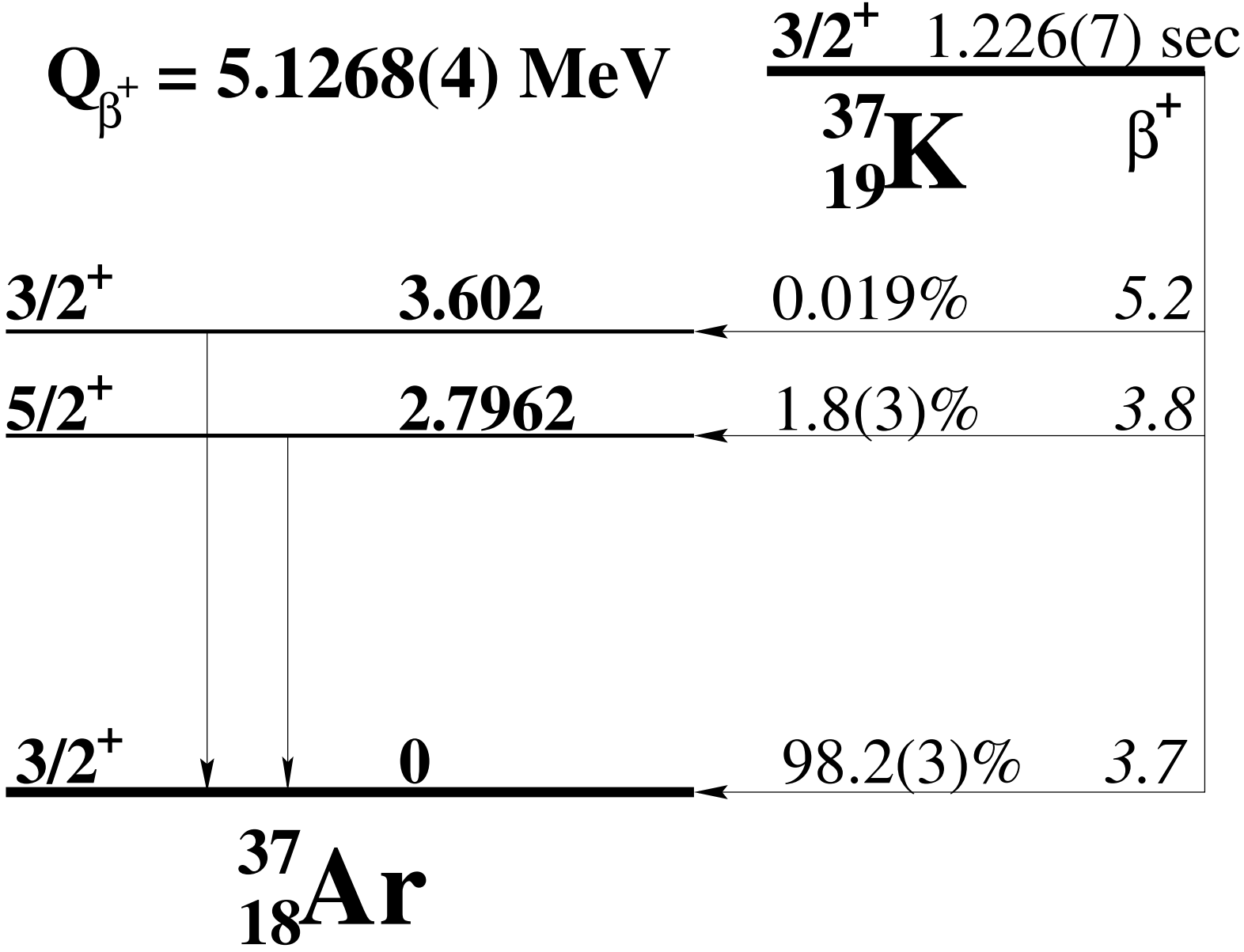
Experiments with daughter ions in 'singles':

- Tensor interactions in ^{80}Rb: statistics for <0.007

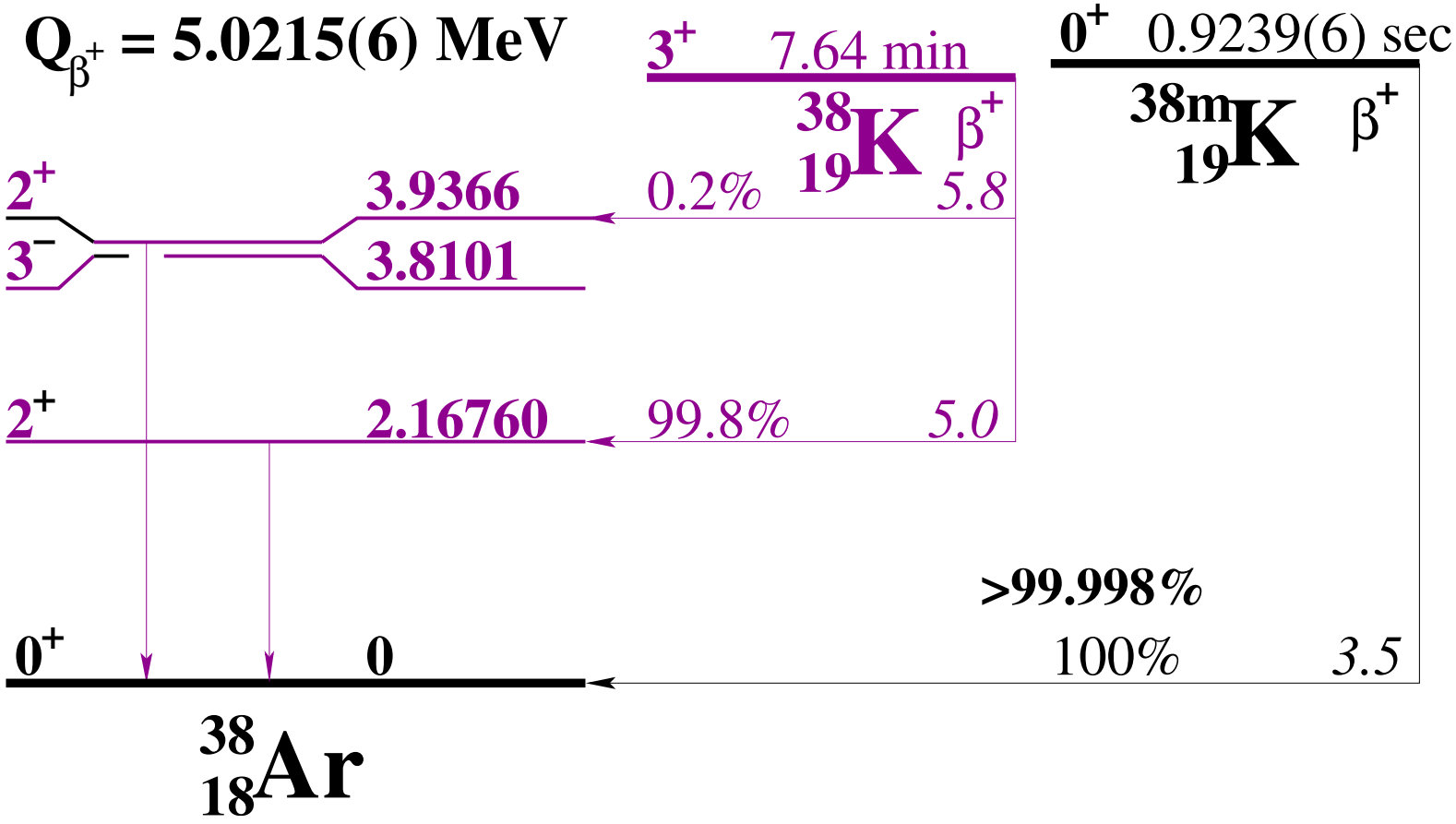
Planning two-body decays:

- Search for 20 keV sterile ν in ^{131}Cs e^- capture
- Search for 'heavy' axions in ^{84m}Rb, Cs isomer decay

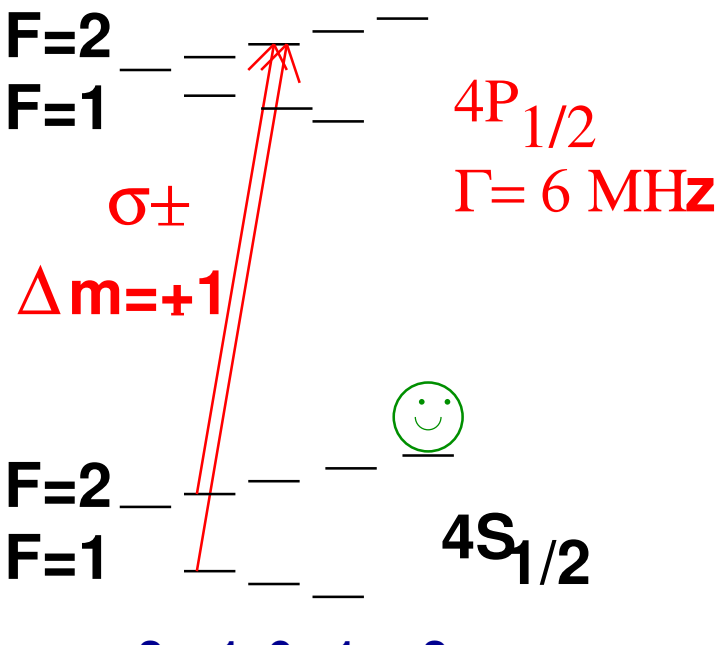
reserve slides


Q_{β^+} = 5.1268(4) MeV
3/2+ 1.226(7) sec
37 19K
β+
3/2+ 3.602 0.019% 5.2
5/2+ 2.7962 1.8(3)% 3.8
3/2+ 0 98.2(3)% 3.7
37 18Ar

Excited-state branch known to be negligible



Polarization by Optical Pumping



$\vec{F} = \vec{I} + \vec{J}$ for ^{37}K I=3/2

Need for β decay:
Nuclear vector polarization P=$<I_z>$
tensor alignment from $<I_z^2>$

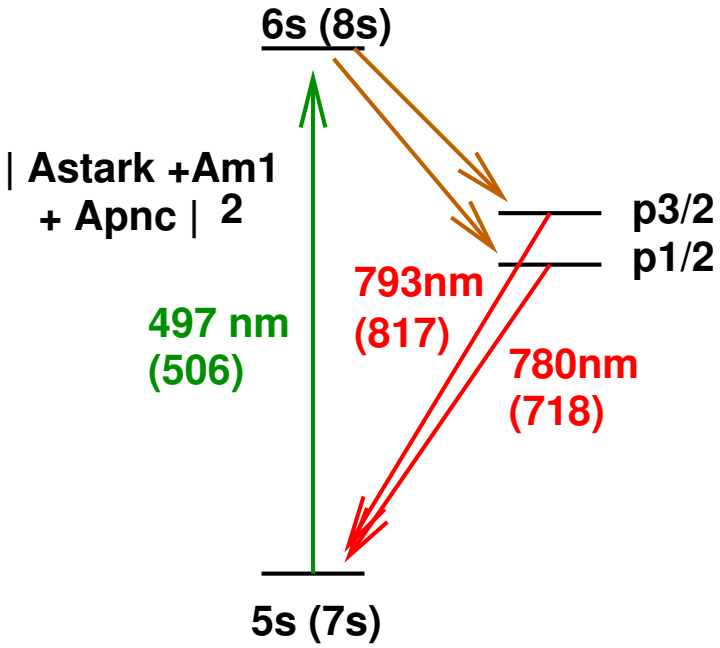
σ^+ light along quantization axis
Small B_{bias} field to avoid levels mixing via stray field

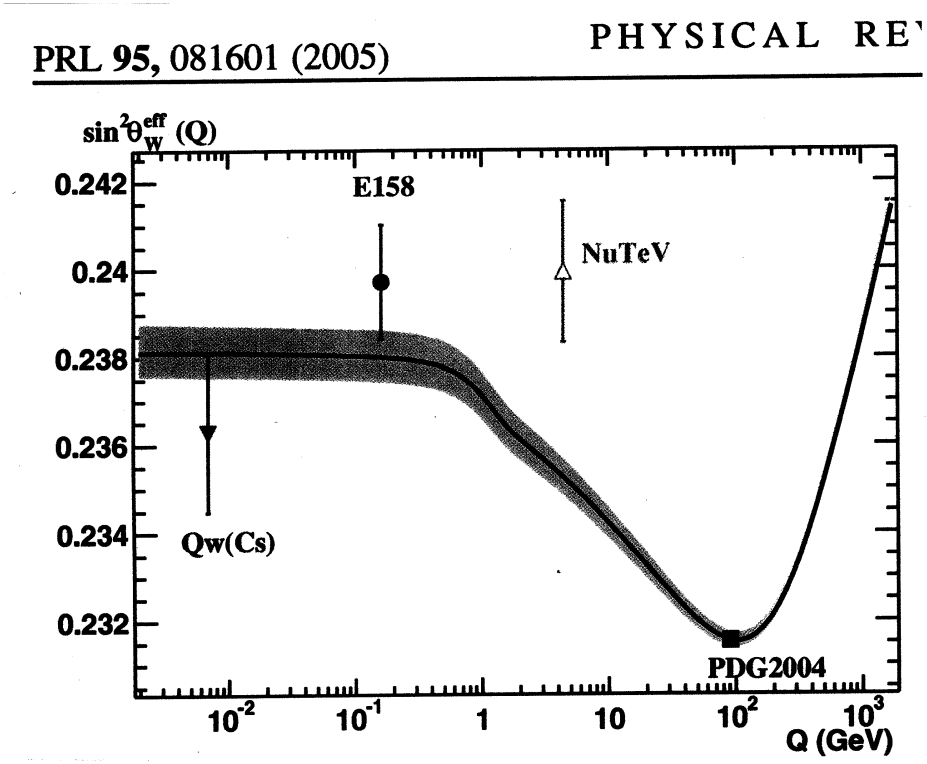
Photon excites electron, but eigenstates are mixed I,J with good F
$|F\ m_F\rangle = \sum |I\ m_I\ J\ m_J\ \rangle\ \langle I\ m_I\ J\ m_J\ |\ F\ m_F\ \rangle$ So nucleus is polarized

Can use 'rate eqs.' $\frac{dN}{dt} = \sum N_g A_{ik} - N_e B_{ik} - N_e \Gamma$
But may need OBE's $\frac{d\rho}{dt} = \frac{1}{i\hbar}[H,\rho] - R_{spont}$ to include coherent effects
Tremblay PRA 41 4989 (1990)

M1 strength in Rb 5s → 6s (Gwinner, Manitoba)
(eventually in Fr)

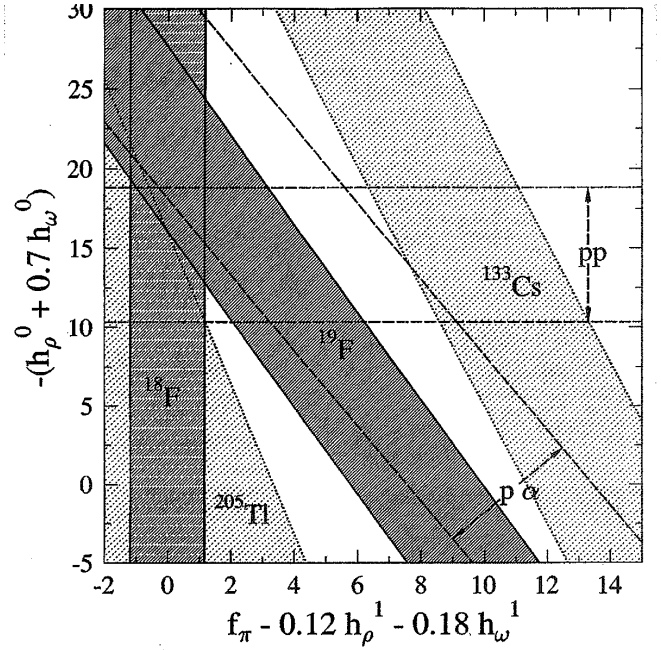
Sensitive to 'negative energy states' i.e. radiative corrections
(Savukov 1999)

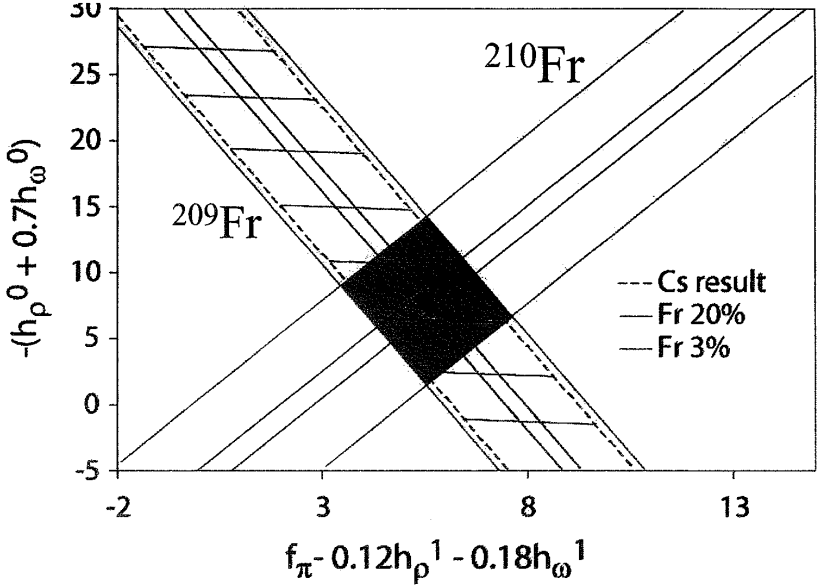




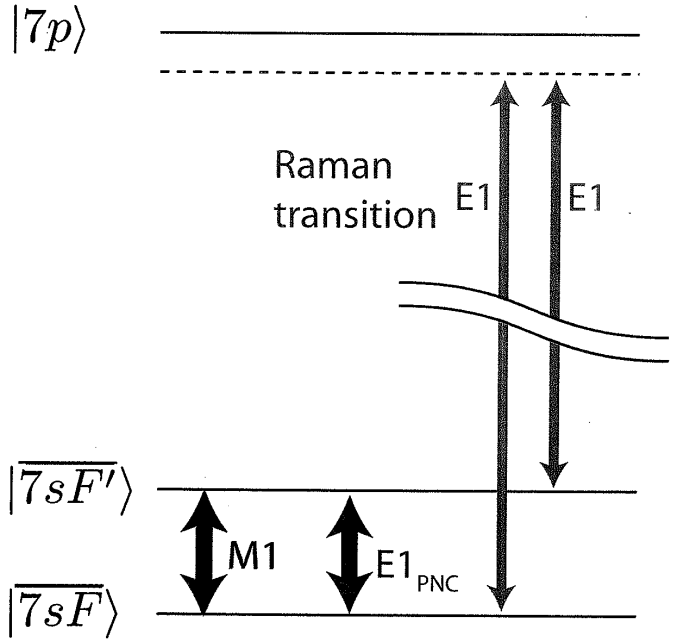
A step towards atomic PNC

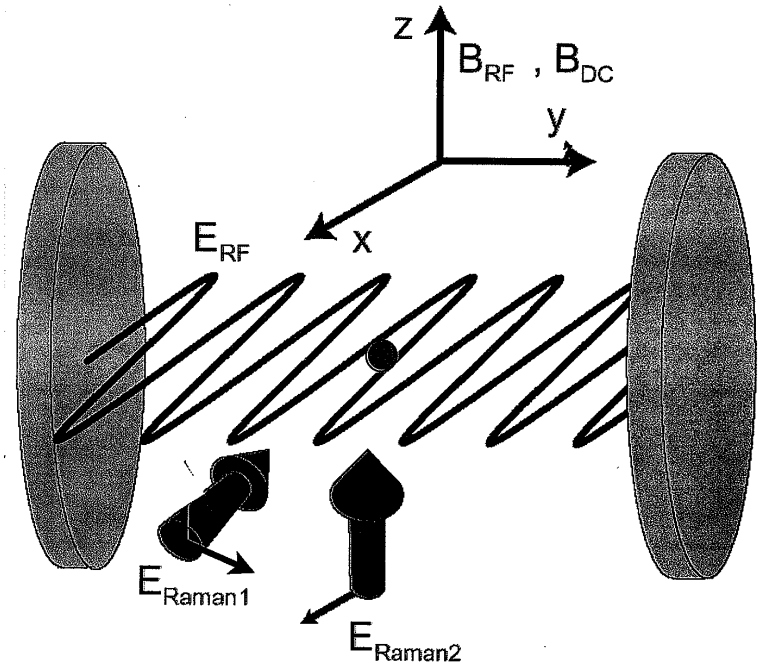
Proposed: Fr Anapole moments: weak N-N Gwinner/Orozco E1065





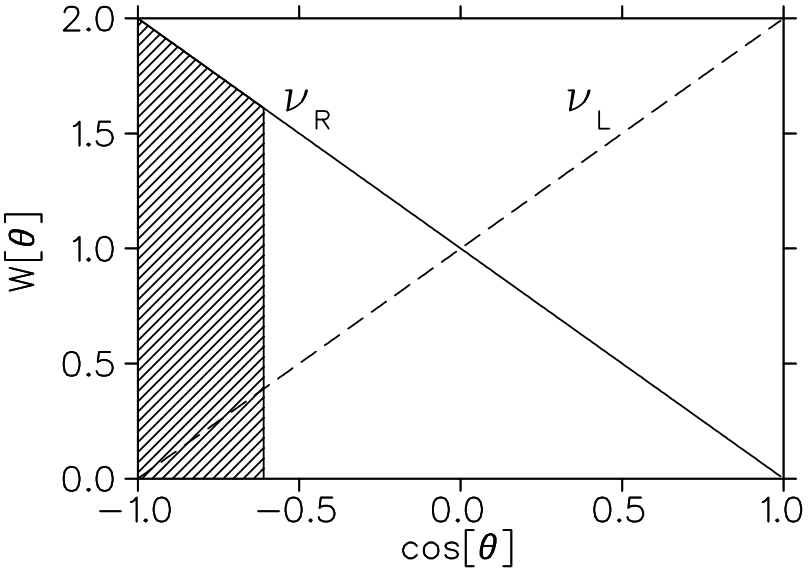
Constraints of couplings from measuring two francium isotopes

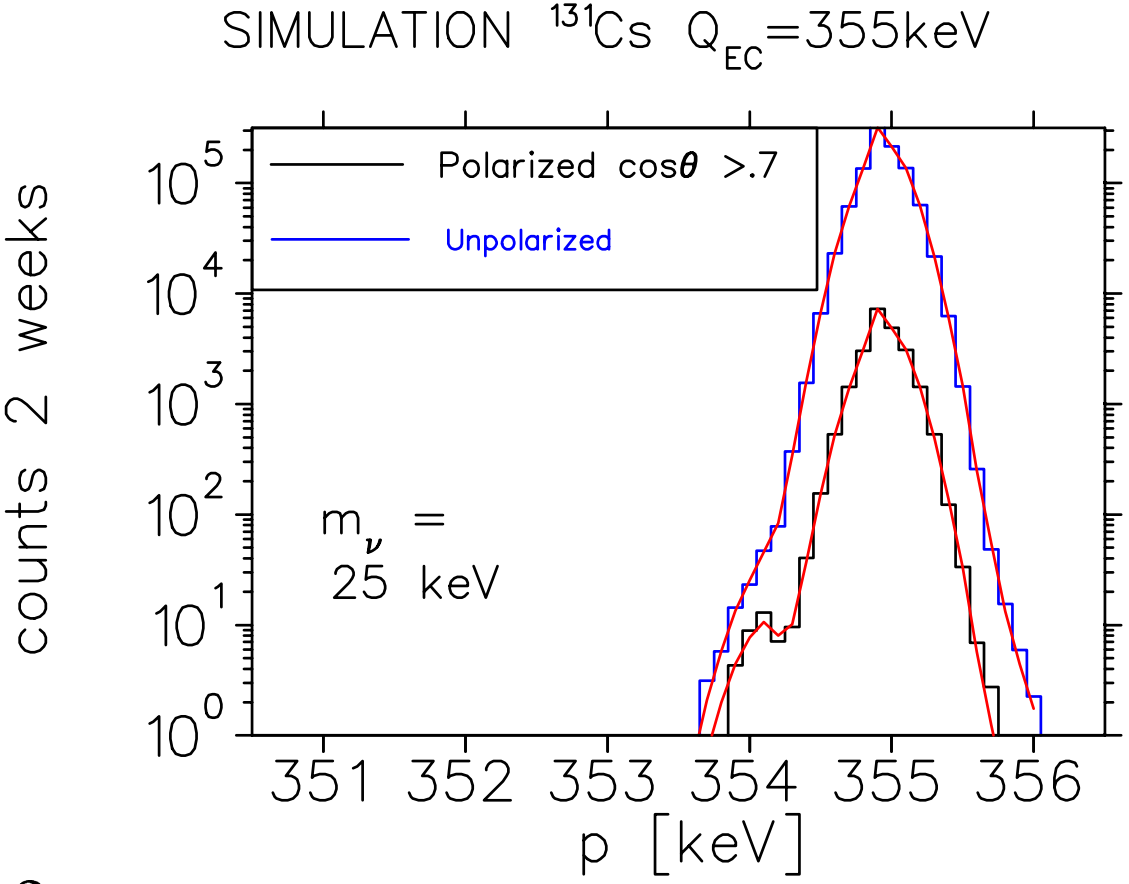




20 KeV-mass sterile ν's: Spin-Polarized ^{131}Cs

For ν_L, $\mathbf{W[\theta_{Xe}] = 1 + \cos[\theta_{Xe}]}$ (because $\mathbf{I^\pi = 5/2^+ \rightarrow 3/2^+}$ is maximal)
If $\nu_S = \nu_R$, $\mathbf{W[\theta_{Xe}] = 1 + v/c \cos[\theta_{Xe}]}$





- **Improve statistical error by $\sim 2\times$**
- **Reduce syst. error, accidental coincidences by $\sim 10\times$ by minimizing ν_L detection**
- **Measure experimental lineshape with ν_R 'OFF'**
- **Measure whether ν_S is left or right-handed**

(• High-statistics RHC/tensor test? Recoil-order corrections $\sim 2\times 10^{-3}$, $\propto E_\nu/m_n$)

Scalar Hamiltonian in 'modern' chirality notation

$$H_S = [(C_S + C'_S)\bar{e}(1-\gamma_5)\nu_e^{(L)} + (C_S - C'_S)\bar{e}(1+\gamma_5)\nu_e^{(R)}]\bar{u}d$$

$$W[\theta_{\beta\nu}] = 1 + b m_\beta/\langle E_\beta\rangle + \; a\; v/c\; \cos[\theta_{\beta\nu}]$$

$$a = \frac{|C_V|^2 + |C'_V|^2 - |C_S|^2 - |C'_S|^2 + (\frac{\alpha Z m}{p})2Im(C_S C_V^* + C'_S C'_V*)}{|C_V|^2 + |C'_V|^2 + |C_S|^2 + |C'_S|^2}$$

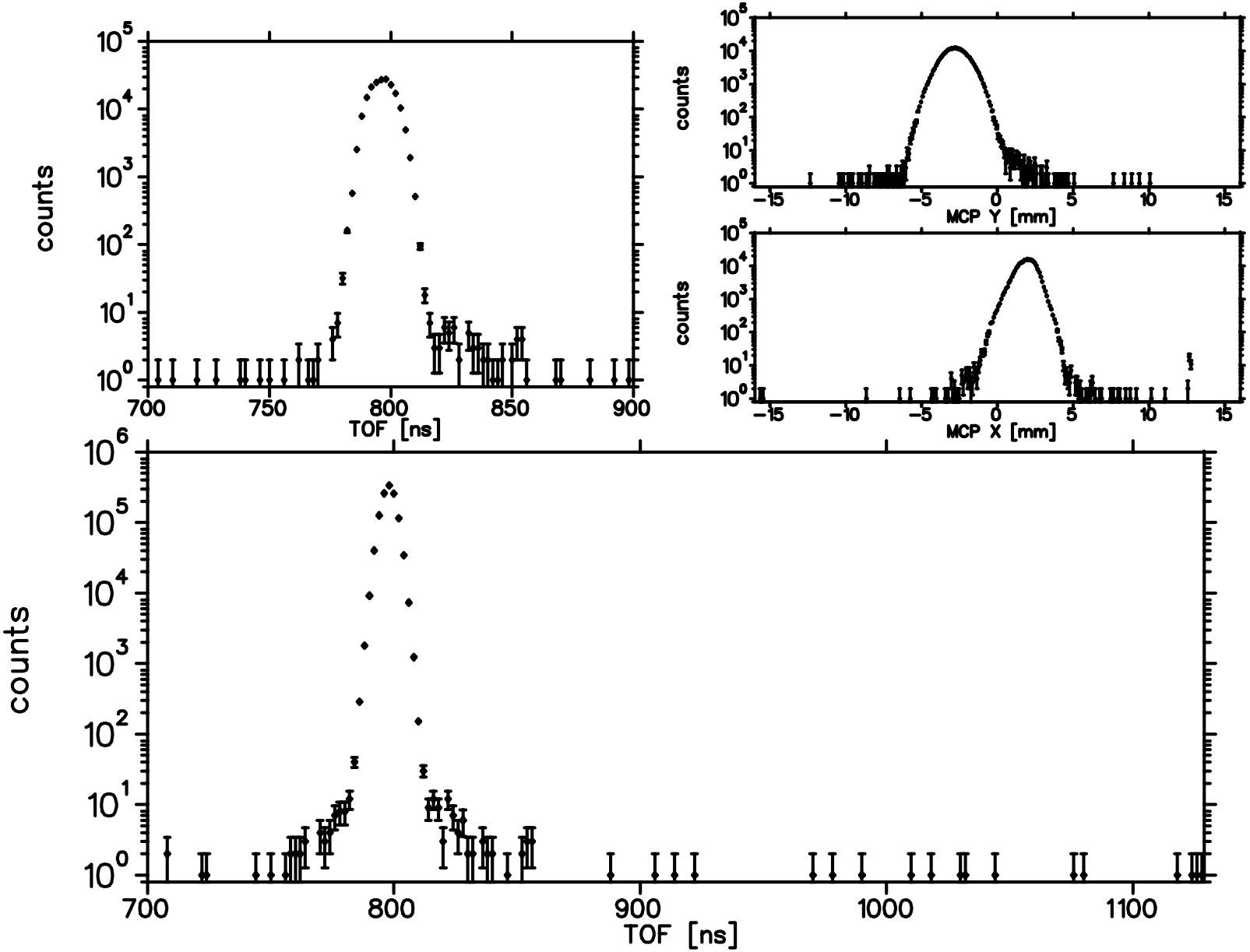
Note the sensitivity to $Im(C_S + C'_S)$

$$b = \frac{-2\sqrt{1-\alpha^2 Z^2}\; Re(C_S C_V^* + C'_S C'_V*)}{|C_V|^2 + |C'_V|^2 + |C_S|^2 + |C'_S|^2}$$

$$a \approx 1 - (|C_S|^2 + |C'_S|^2)$$

$$b \approx -Re(C_S + C'_S)$$

Photoionization images MOT in 3D, so can optimize it

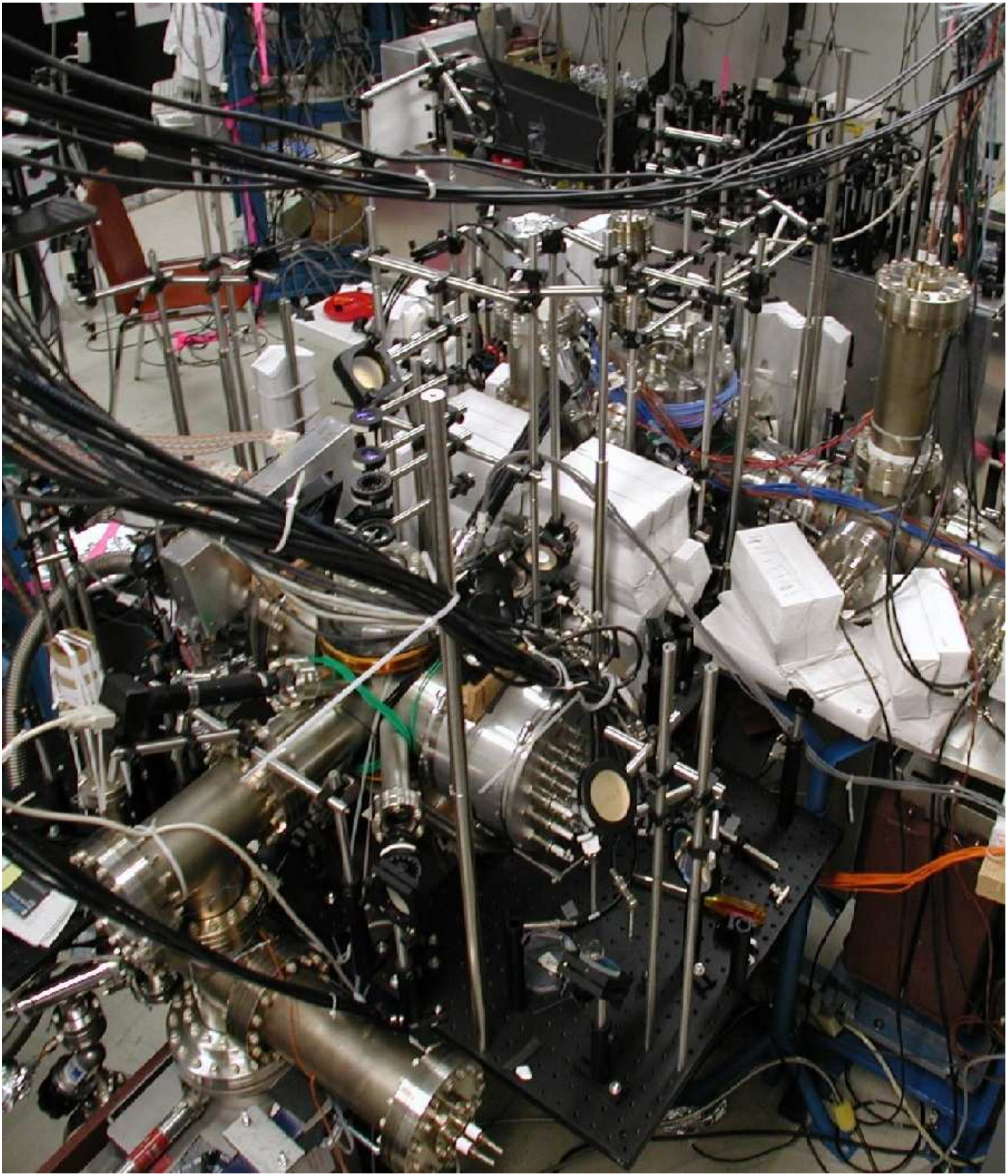


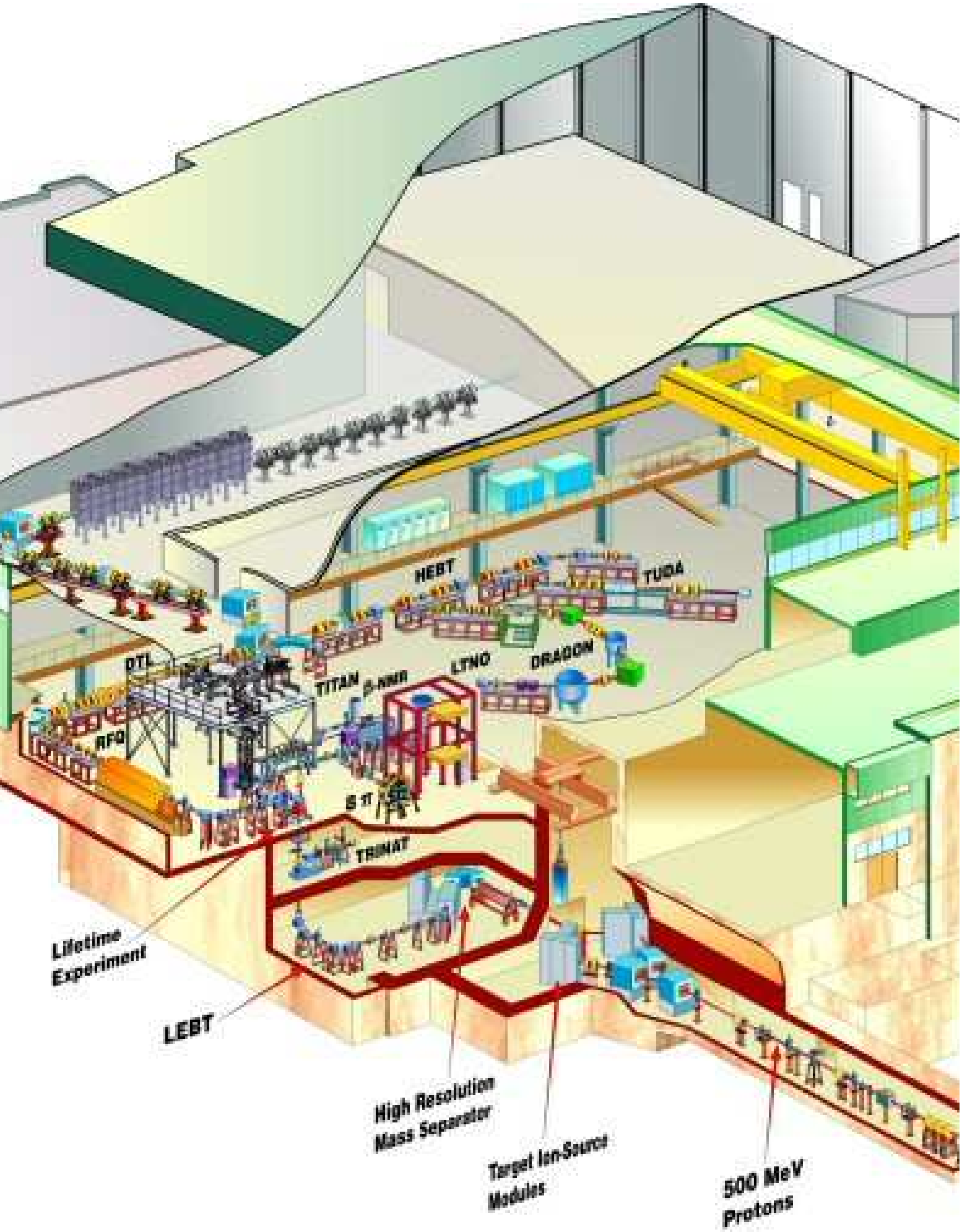
^{38m}K β^+-ν Error Budget $\tilde{a}$=0.9981±0.0030(stat)

Error	PRL	Future
$\vec{E}$ field/trap width :	0.17%	0.04%
E field nonuniformity	0.14%	0.03%
β^+ backscattering bkgd	None	None
$E_{\beta+}$ Detector Response:		
Lineshape tail/total	0.06%	0.03%
511 keV Compton sum	0.09%	0.04%
Calibration, nonlinearity	0.17%	0.08%
MCP Eff[E_{Ar+}]	0.07%	0.03%
MCP Eff[θ]/XY position	0.08%	0.04%
e^- shakeoff [E_{recoil}]	0.18%	0.08%
Sum systematics	0.37%	0.14%
Total error	0.48%	0.19%

Planned Improvements:
- Larger MCP
- E_β calibration from interwoven background-free ^{37}K
- $1/\sqrt{5}$ statistical error (conservative) larger ISAC yields more laser power
- Permanent mask on MCP for position info test

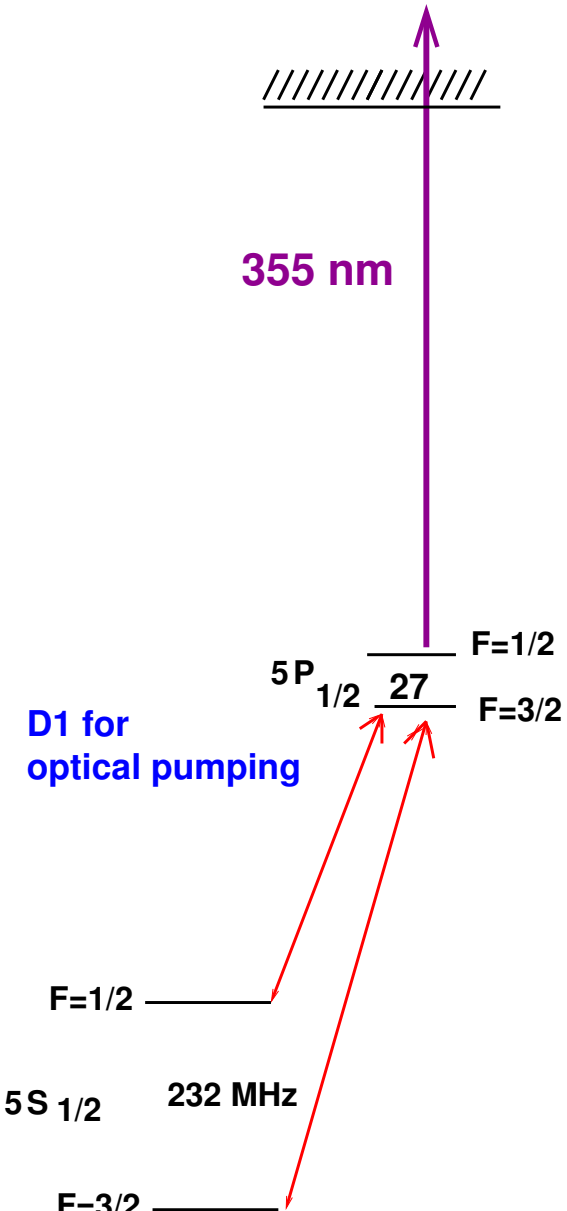
- Most systematic errors determined by statistics-limited data evaluation.
- Further improvements possible: use all kinematic information.

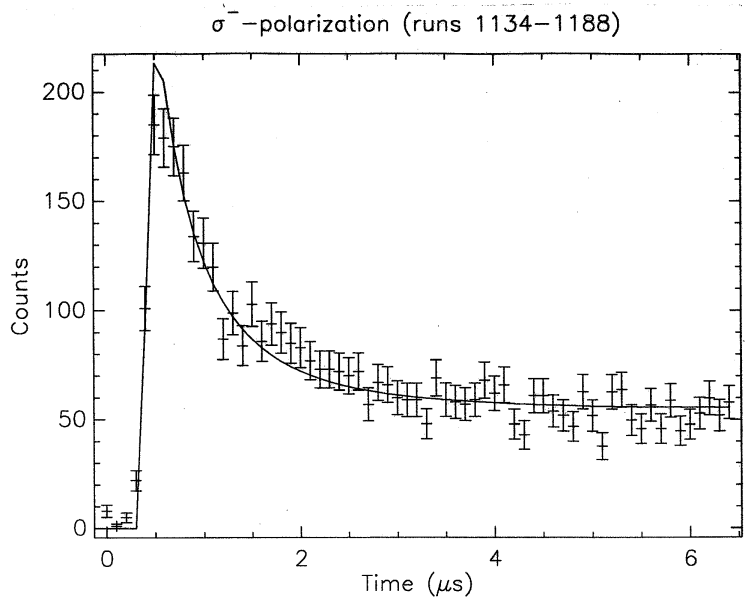


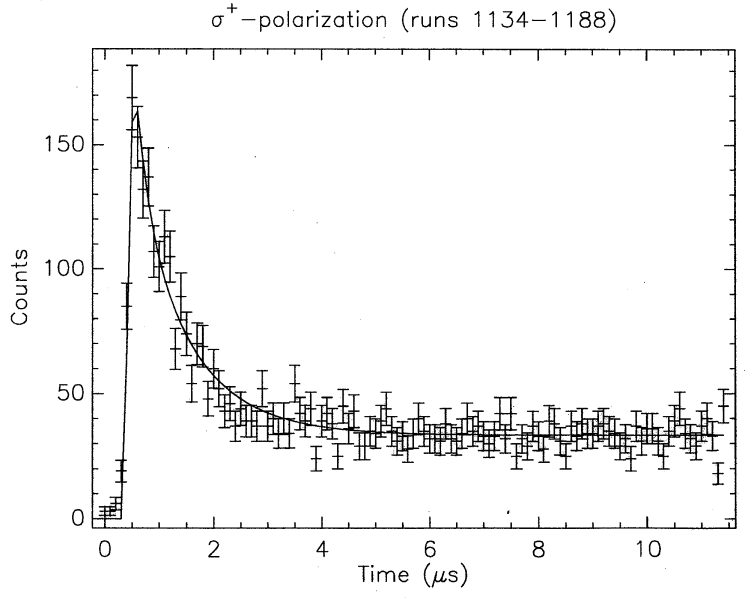

HEBT
TUDA
DTL
TITAN
β-NMR
LTNO
DRAGON
RFQ
8 π
TRINAT
Lifetime Experiment
LEBT
High Resolution Mass Separator
Target Ion-Source Modules
500 MeV Protons

^{80}Rb Photoionization Diagnostic

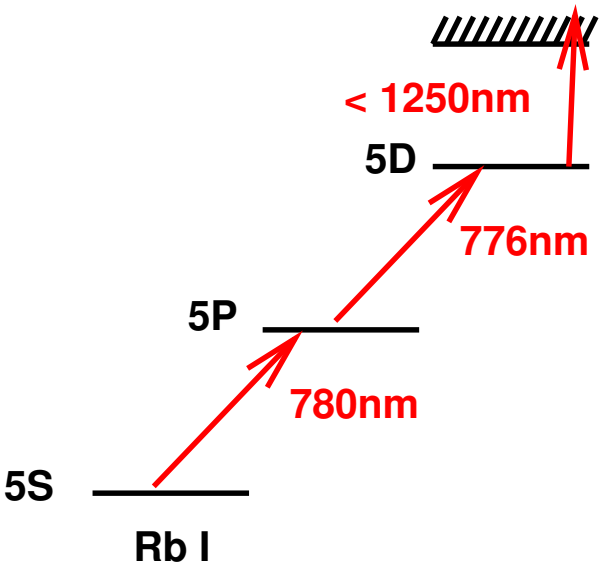
- **Polarization ≈55-75% by optical pumping (MOT quad B on) measured by β asymmetry, atomic excited state population**
  Trap location shifts by < 0.1 mm $\Rightarrow$ A correction < 0.004

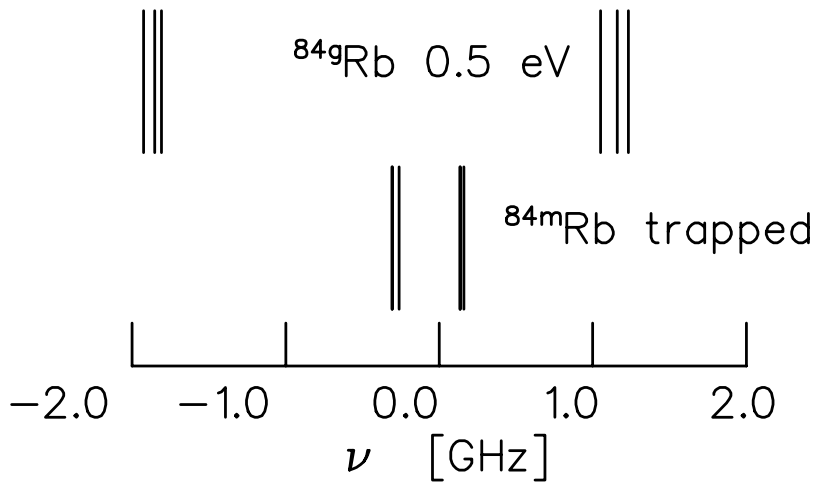




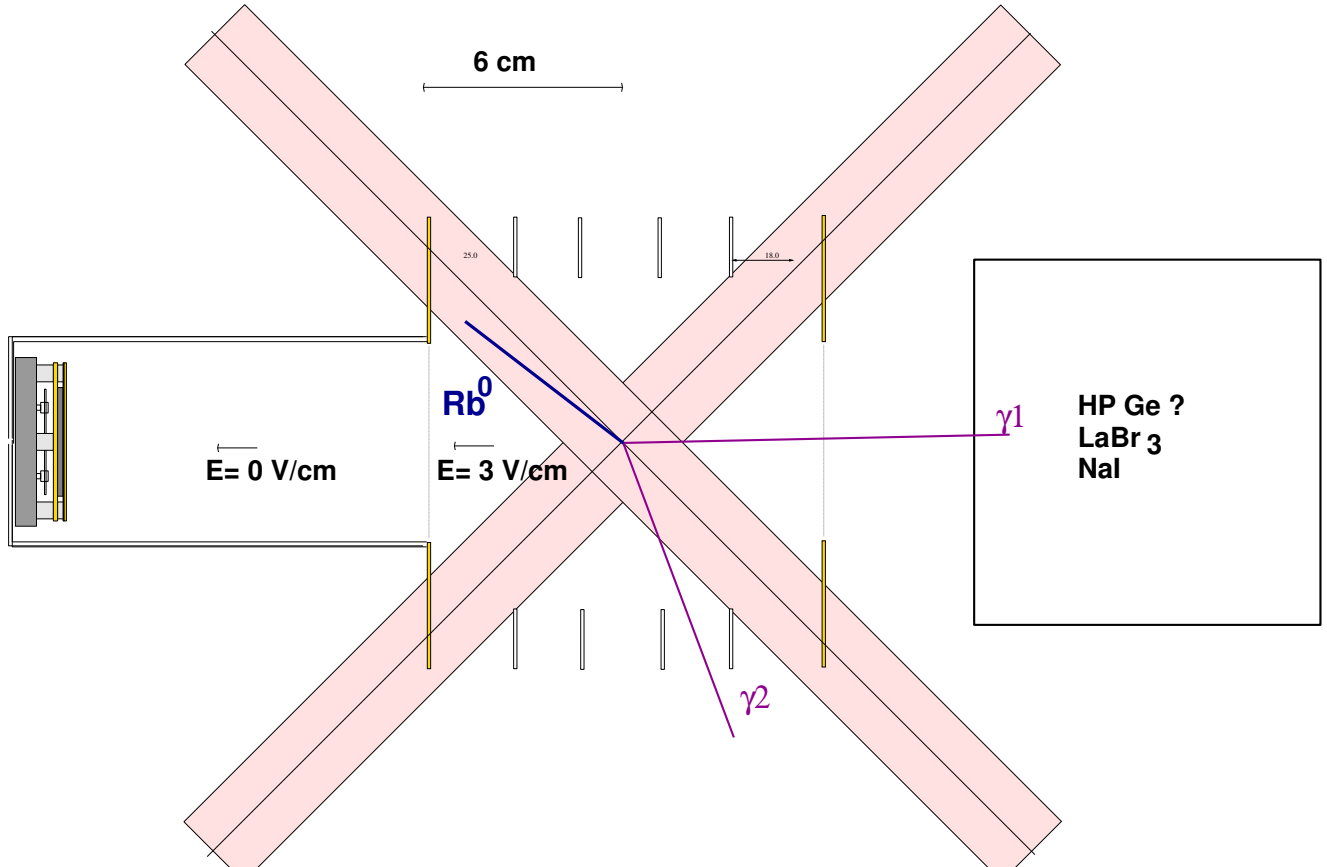


Isomer Decay: Must ionize neutral recoil

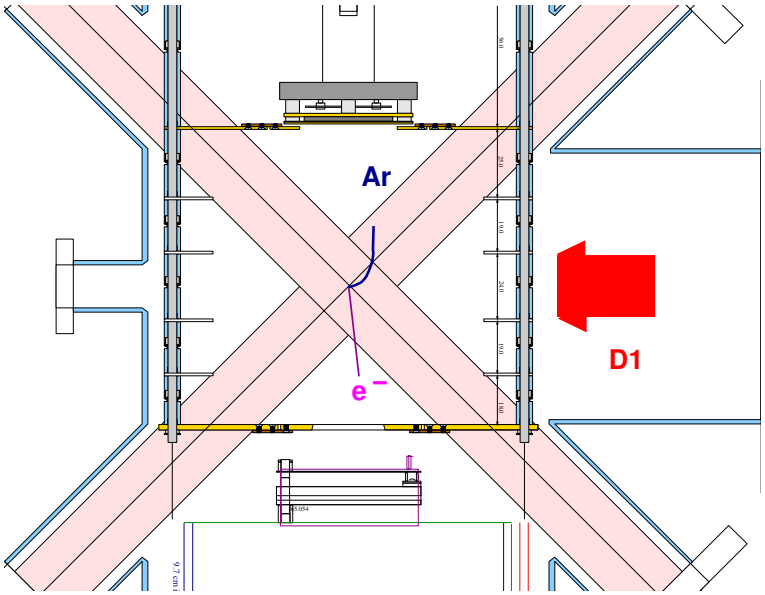




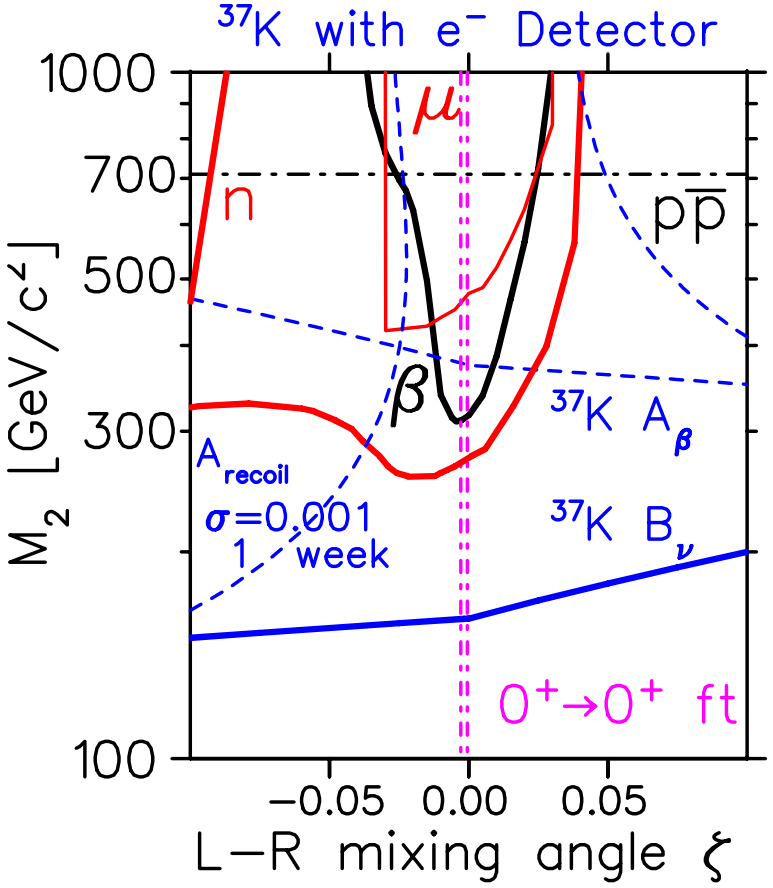
Thibault PRC 1981



$^{37}\vec{K}$ Future



PROJECTED



$P_z\ B_\nu\ \vec{I}\cdot\vec{p}_\nu$

ν asymmetry

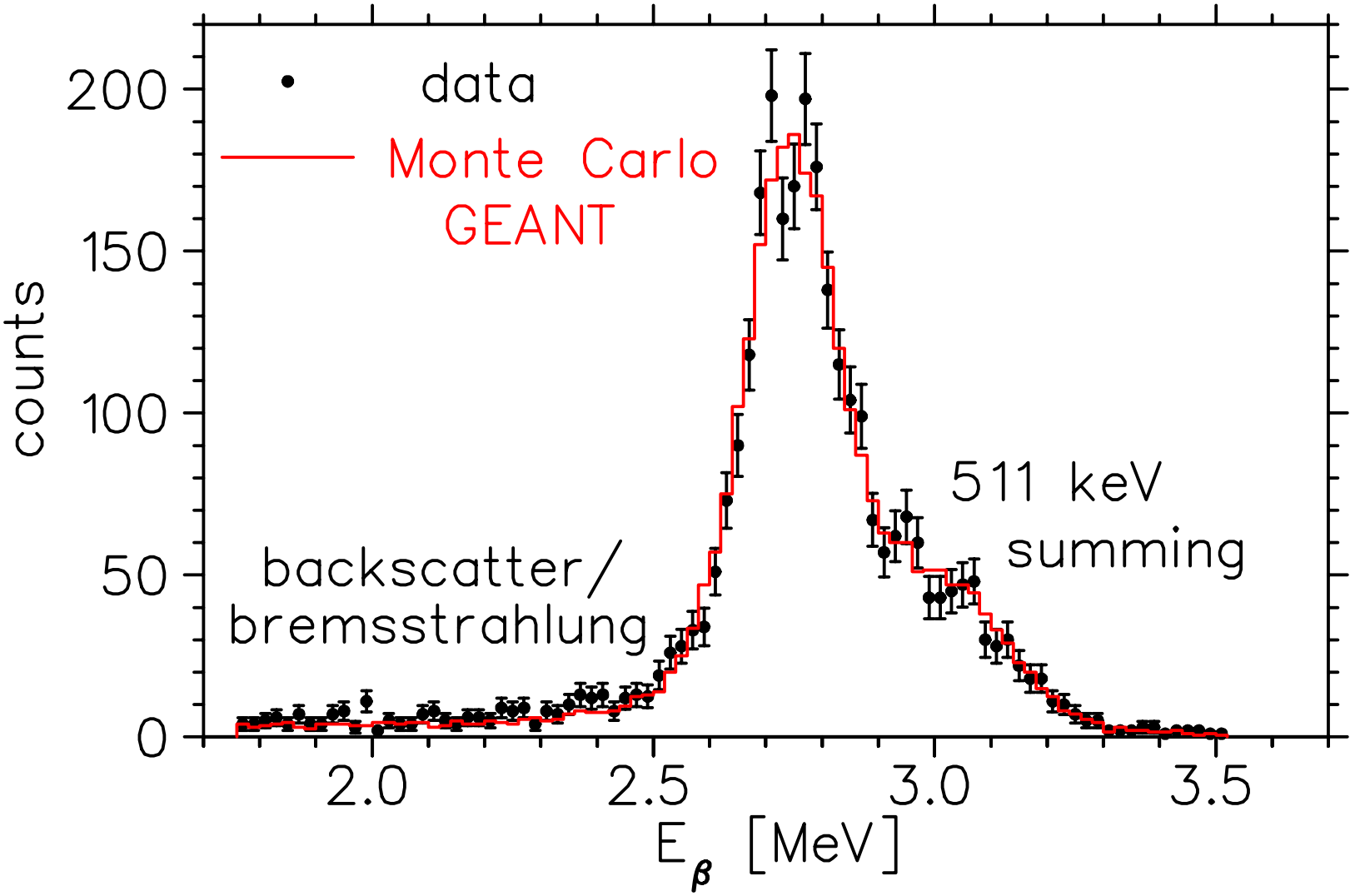
$P_z = 0.97 \pm 0.01$

$B_\nu = -0.755 \pm 0.020 \pm 0.013$

$(B_\nu^{SM} = -0.769)$

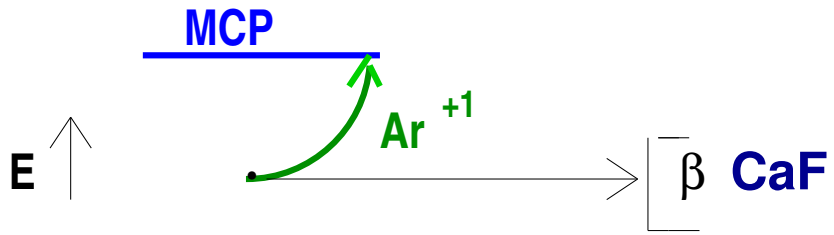
- **Recoil asymmetry:**
  high statistics
  sensitive to RHC

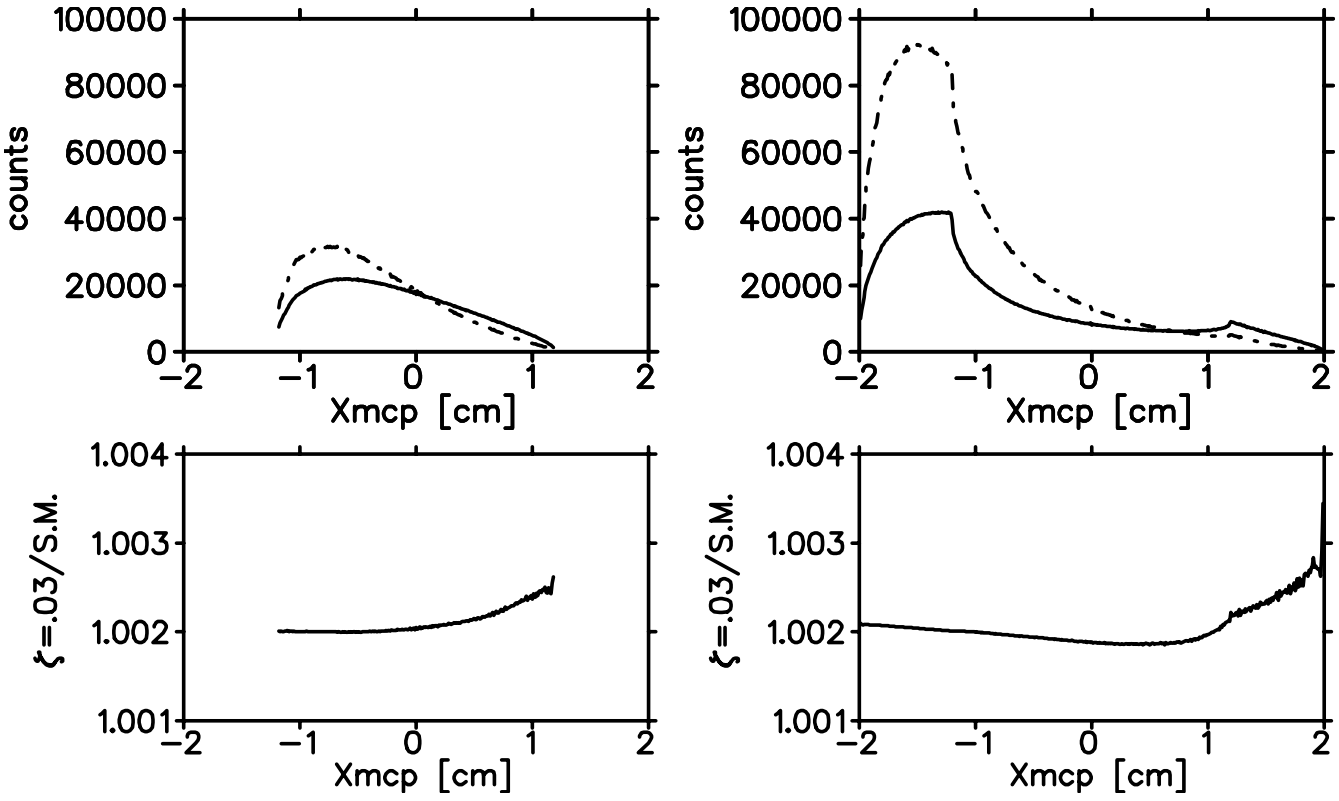
Corrections given by CVC


data
Monte Carlo
GEANT
counts
200
150
100
50
0
2.0
2.5
3.0
3.5
E_β [MeV]
backscatter/
bremsstrahlung
511 keV
summing

Another example of a lepton helicity-driven argument

Rslow vanishes independent of $\frac{M_F g_V V_{ud}}{M_{GT} g_A}$

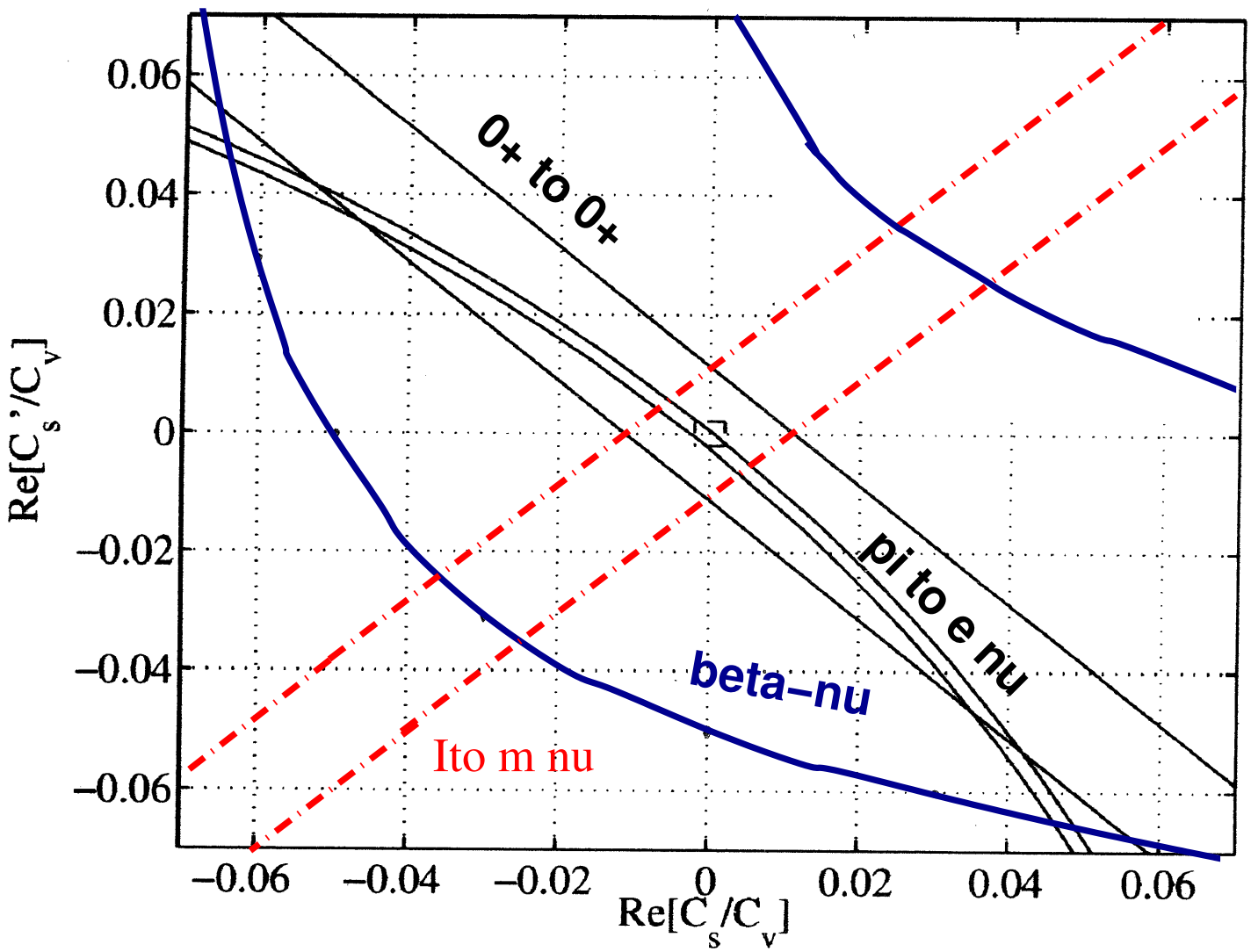




Larger MCP helps in sensitivity and statistics

Also, $\frac{\text{slow(+)}-\text{slow(}-\text{)}}{\text{fast(+)} - \text{fast(}-\text{)}} = \frac{A-B}{A+B}$ **is independent of P**

Ito PRL '05: Order-of-magnitude naturalness constraint (Opportunity?): scalars coupling to wrong-handed ν's give the SM ν a mass contribution. **We should constrain its size**



Campbell and Murray NPB 2005