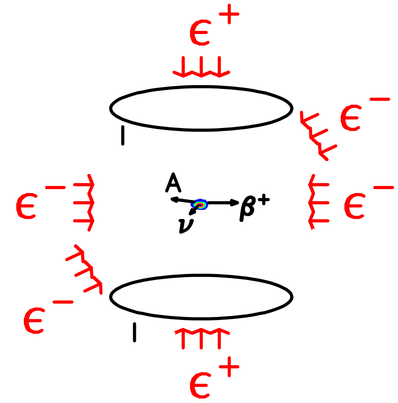
Summer Student Seminar
Wed. May 24, 2006, 9:30 a.m.

Laser Traps for Beta Decay Experiments

John Behr, TRIUMF



TRIUMF's neutral atom trap captures radioactive atoms in a 1 mm-sized cloud in a vacuum chamber. The atomic nuclei undergo beta decay, which produces three decay products: a β, a ν, and the daughter recoiling nucleus. The daughter nucleus has very little energy and would stop in a nanometer of material, but it freely escapes the trap. By measuring its momentum in coincidence with the β, the ν direction with respect to the β can be deduced more directly than in previous experiments.

As far as we know, the Standard Model weak interaction is mediated by "heavy light", "vector" bosons with spin 1 which are heavy partners of the photon. We see a β-ν correlation consistent with the Standard Model, and constrain the existence of other exchange bosons with spin 0. We also spin-polarize the nuclei with circularly polarized light, to test whether parity is fully violated in the weak interaction. We will wave our hands about a possible search for keV-mass ν's.

The mathematical proof that these traps cannot work will be presented, along with its experimental dodges. No laser pointers will be harmed during this presentation. If you can't read the t-shirt, you're sitting too far away.

Laser Traps for Beta Decay Experiments

I. Laser Cooling and Trapping

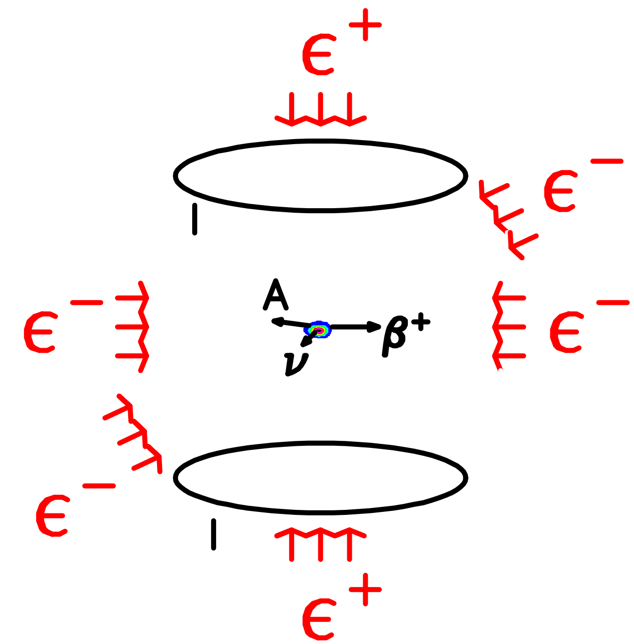
Why Laser traps Can't Work

II. Demonstrated Capabilities:

β^+–recoil coincidence $\Rightarrow \nu$ momentum

Best Limits on scalar interactions

Search for keV-mass ν_x ?



III. Promise: high known polarization:

How to polarize a nucleus with a laser

Search for right-handed ν's: need P $>$ 99%

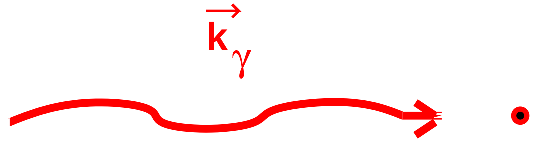
TRIUMF Neutral-Atom Trapping "TRINAT"

Simon Fraser U.	TRIUMF	Tel Aviv	Undergrad
****A.Gorelov**	J.A.Behr	D Ashery	A. Gaudin
	M.R.Pearson	Budapest	U. Prince Edw Isl
	K.P.Jackson	F.Glück	
	M. Dombsky	U.West.Ontario	
	P. Bricault	W.P.Alford	
U.British Columbia	*C.Höhr		U. Manitoba
**** R. Pitcairn**			G. Gwinner
**** D. Roberge**			
			Stony Brook?
			G.Sprouse (Fr?)
****Grad Students**			Maryland?
***Res. Assoc.**			L.Orozco (Fr?)

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

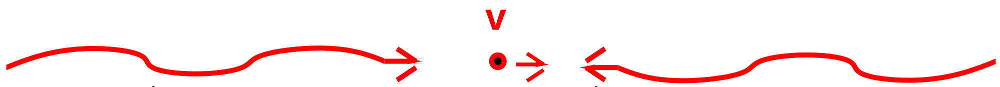
Laser Cooling

Radiation Pressure:

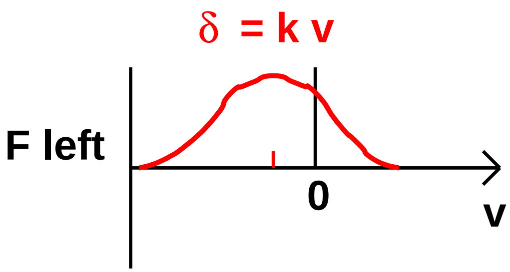


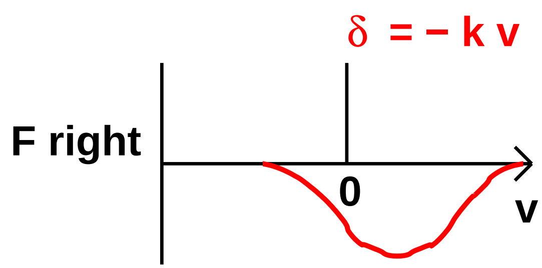
$$\Delta \vec{p} = \hbar \, \vec{k}_\gamma \qquad \vec{F} = \frac{d\vec{p}}{dt} = (\hbar \, \vec{k}_\gamma) \text{ (scattering rate)}$$

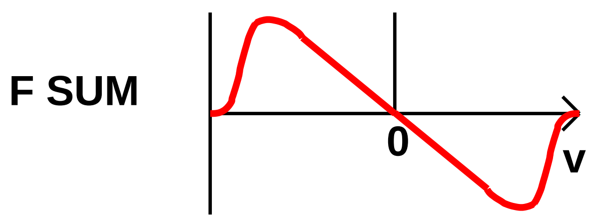
Equal intensity plane waves, redshifted, 1-D



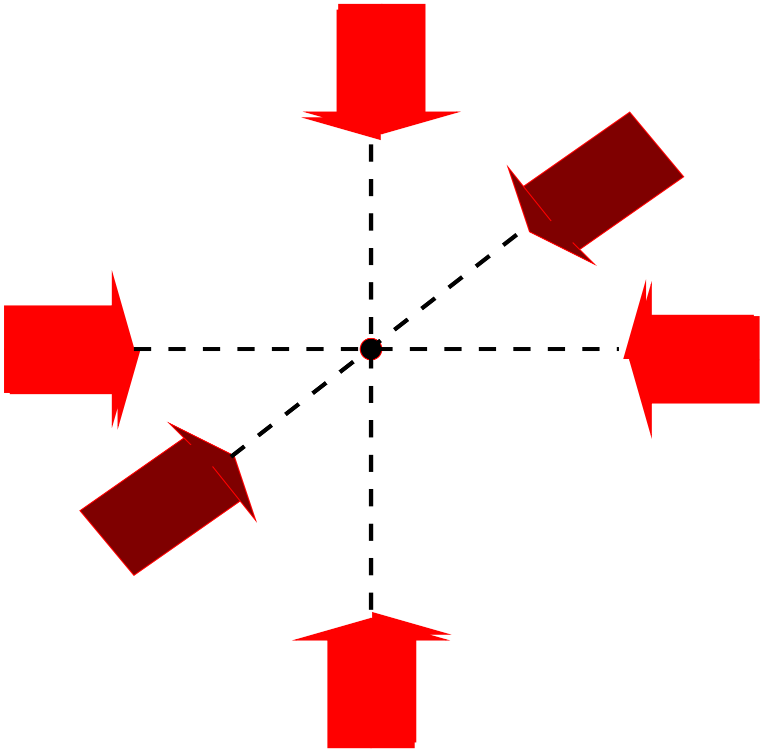
$$F = \frac{\hbar \vec{k}_\gamma (\Gamma/2 \;\; I/I_0)}{1+4(\frac{\delta - kv}{\Gamma})^2} - \frac{\hbar \vec{k}_\gamma (\Gamma/2 \;\; I/I_0)}{1+4(\frac{\delta + kv}{\Gamma})^2}$$







- slows efficiently for $v < v_{capture}$
- 10^4 photons to slow room T
- no spatial dependence (yet)



‘Optical molasses’

“Why Optical Traps Can’t Work”

Earnshaw Theorem:

$\vec{\nabla} \cdot \vec{E} = 0$

$\Rightarrow$ no electrostatic potential minimum for charge-free region

“Optical Earnshaw Theorem” (Ashkin + Gordon 1983):

Using Poynting’s theorem:

$$\vec{\nabla} \cdot \vec{S} = \frac{c}{4\pi} \vec{\nabla} \cdot (\vec{E} \text{ x } \vec{B}) \qquad = -\vec{J} \cdot \vec{E} - \frac{\partial u}{\partial t} = 0$$

$\Rightarrow$ no 3-D traps from spontaneous light forces with static light fields

Dodges !

- Dipole Force traps (“optical tweezers”)
- Modify internal structure of atom with external fields

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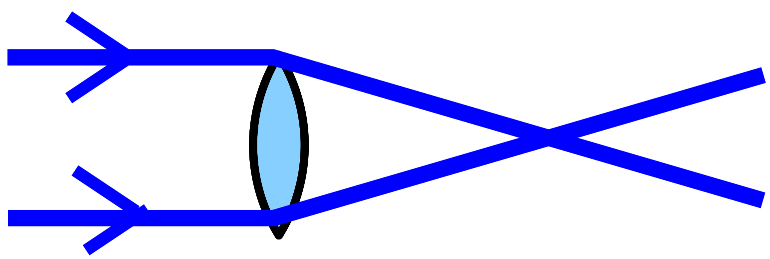

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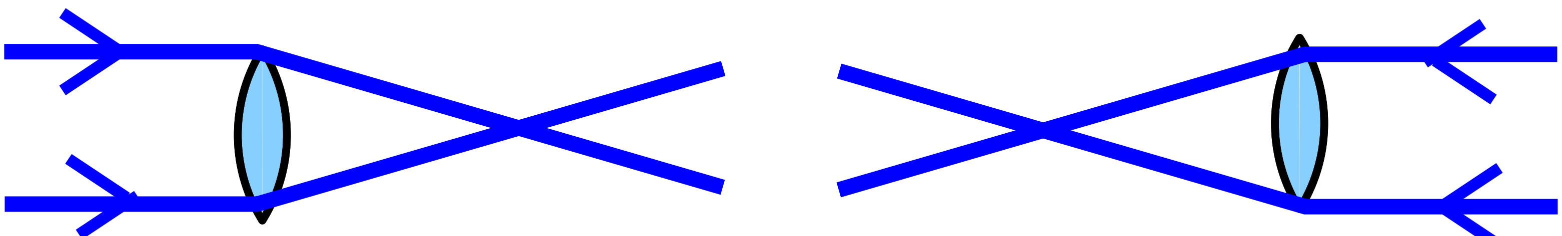

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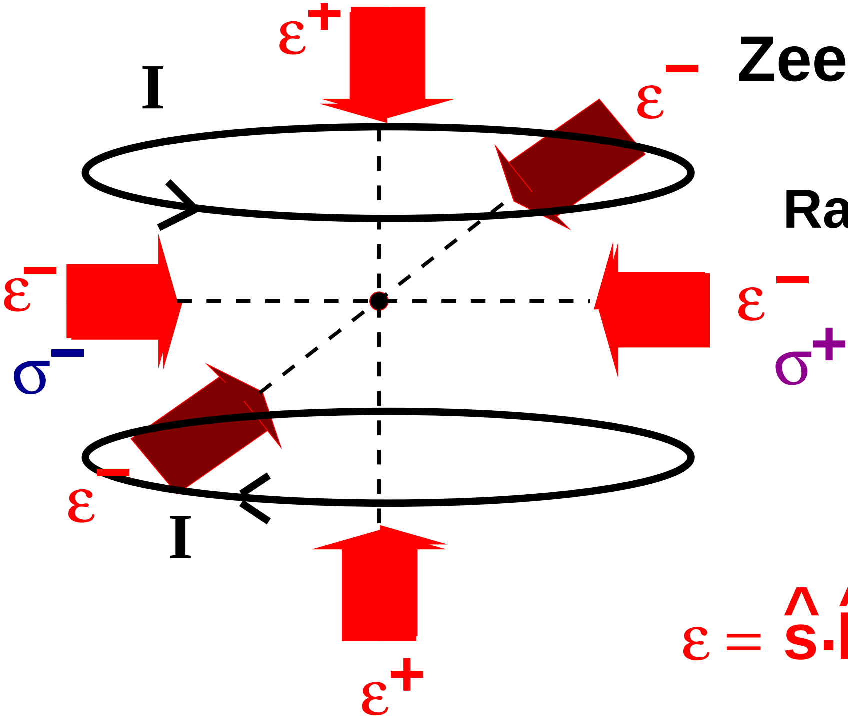
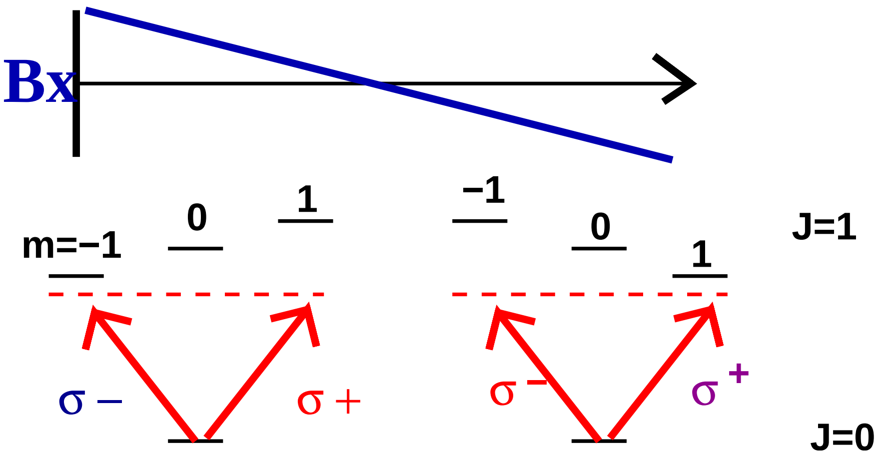
Zeeman Optical Trap (MOT)

Raab et al. PRL 59 2631 (1987)



Damped harmonic oscillator

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



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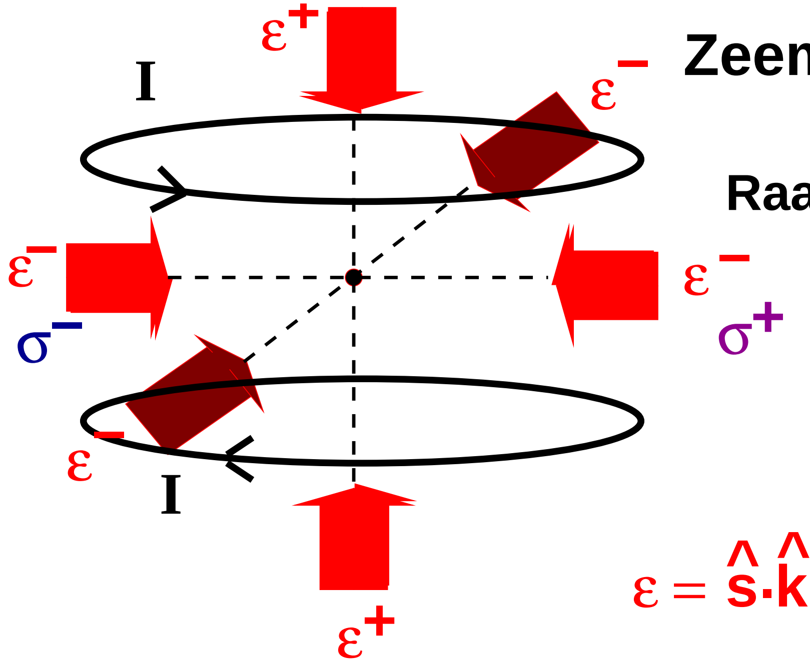

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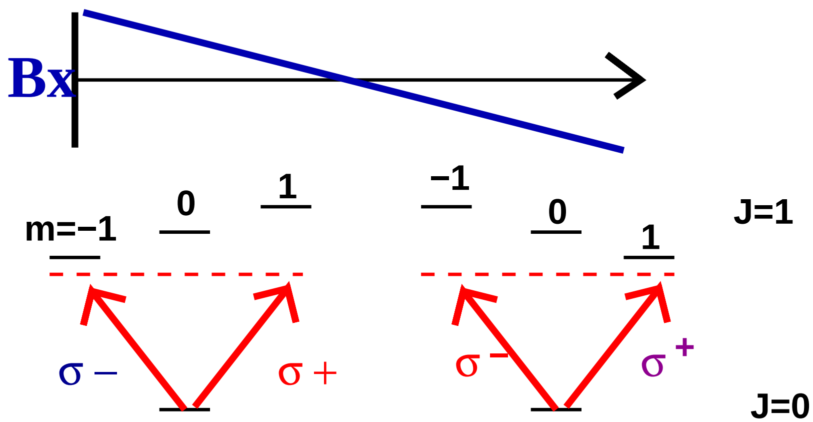


Bquad weak: recoils unperturebed

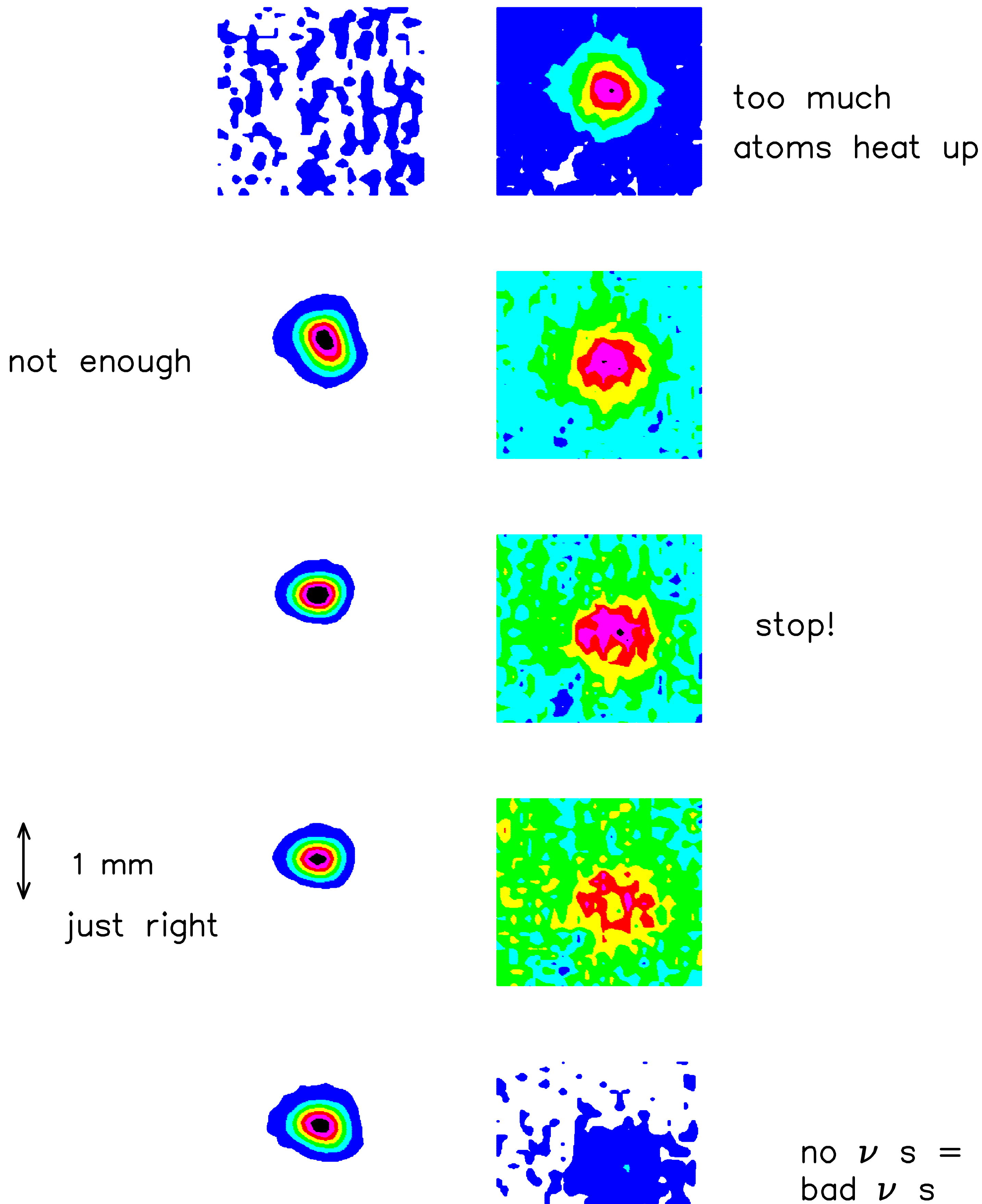
Velocities negligible

Vector polarization ~ 0
(Tensor alignment maybe)

Turn MOT off to polarize

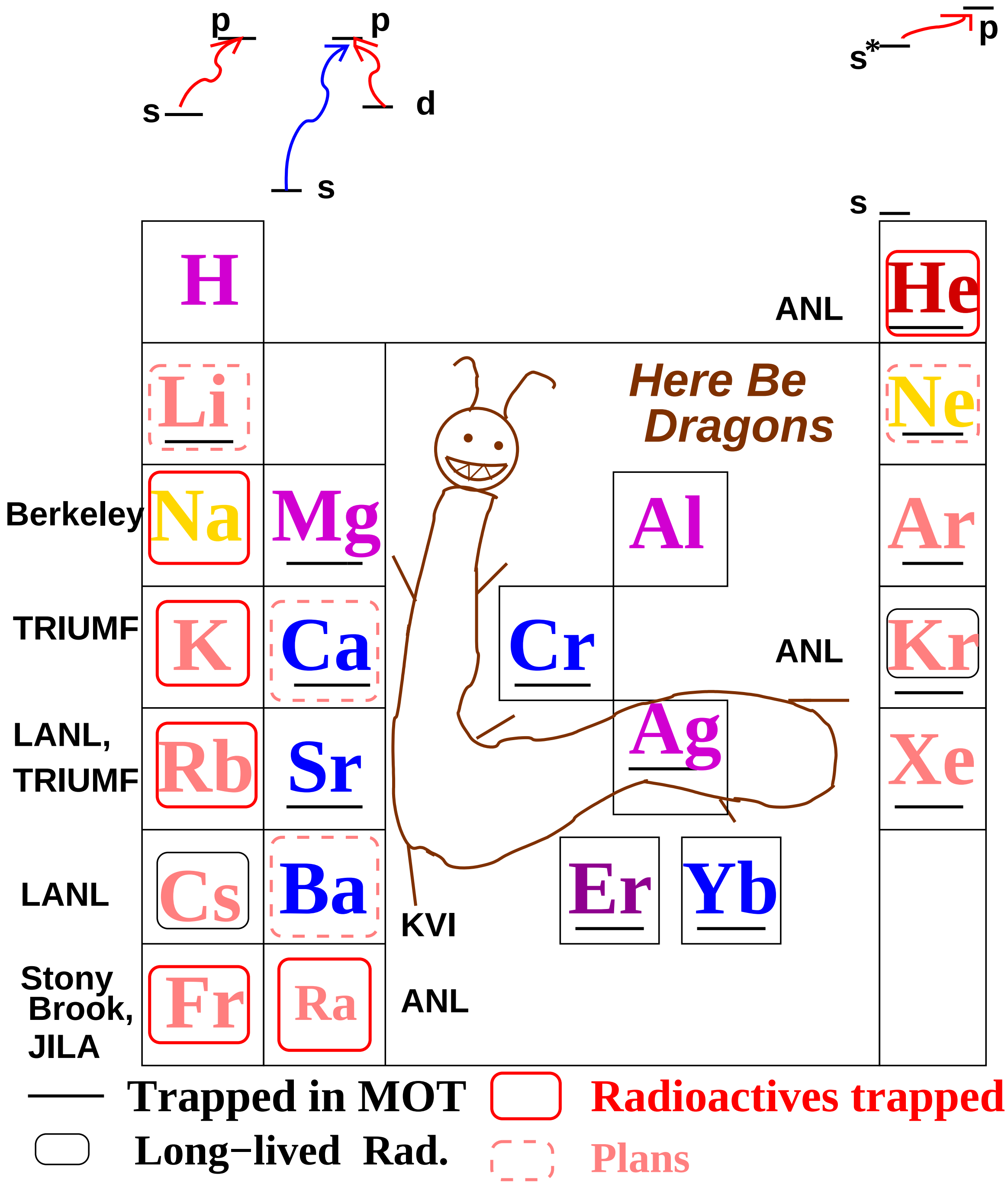
3000 atoms ^{38m}K $t_{1/2} = 1$ sec

laser power changes cloud size



What elements can be laser−cooled/trapped?

Need quasi−closed E1 transition ($J_e = J_g + 1$, $\pi_e = -\pi_g$)



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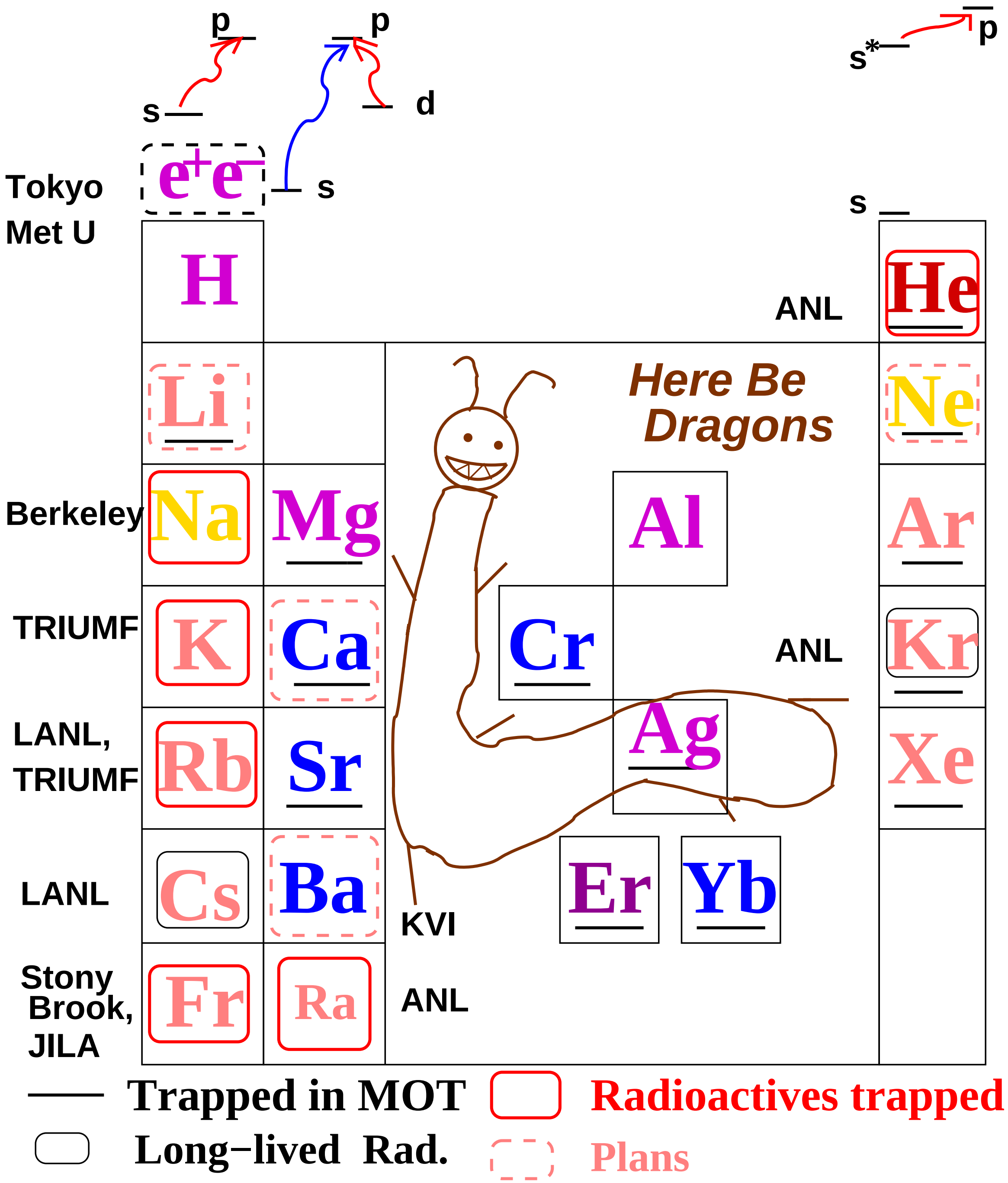


Electroweak Interactions: what we "know"

- **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" "V-A"

- **What we can test:**

1) Are there spin-0 Scalar Bosons ?
$I^\pi = 0^+ \rightarrow 0^+$ β^+-ν $\sigma \sim 0.5\%$ is useful

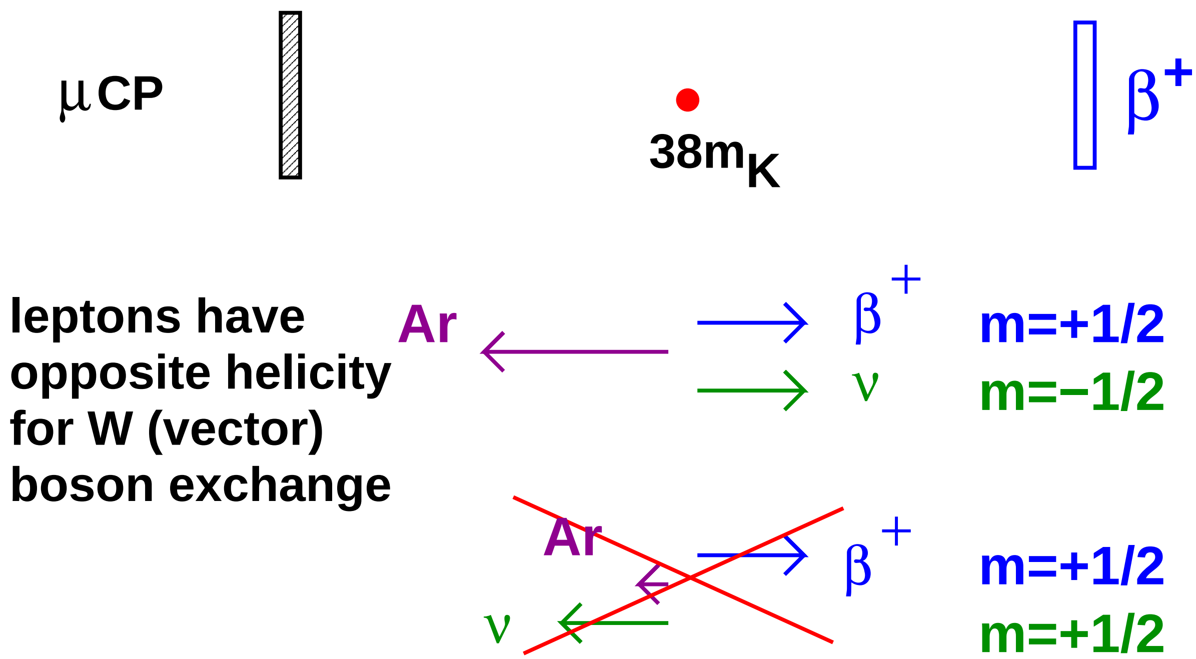
2) Right-handed ν's ? "V+A"?
Polarized observables with $\sigma \approx 0.1\%$ needed.

Vector and Scalar bosons and the β-ν angular distribution

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

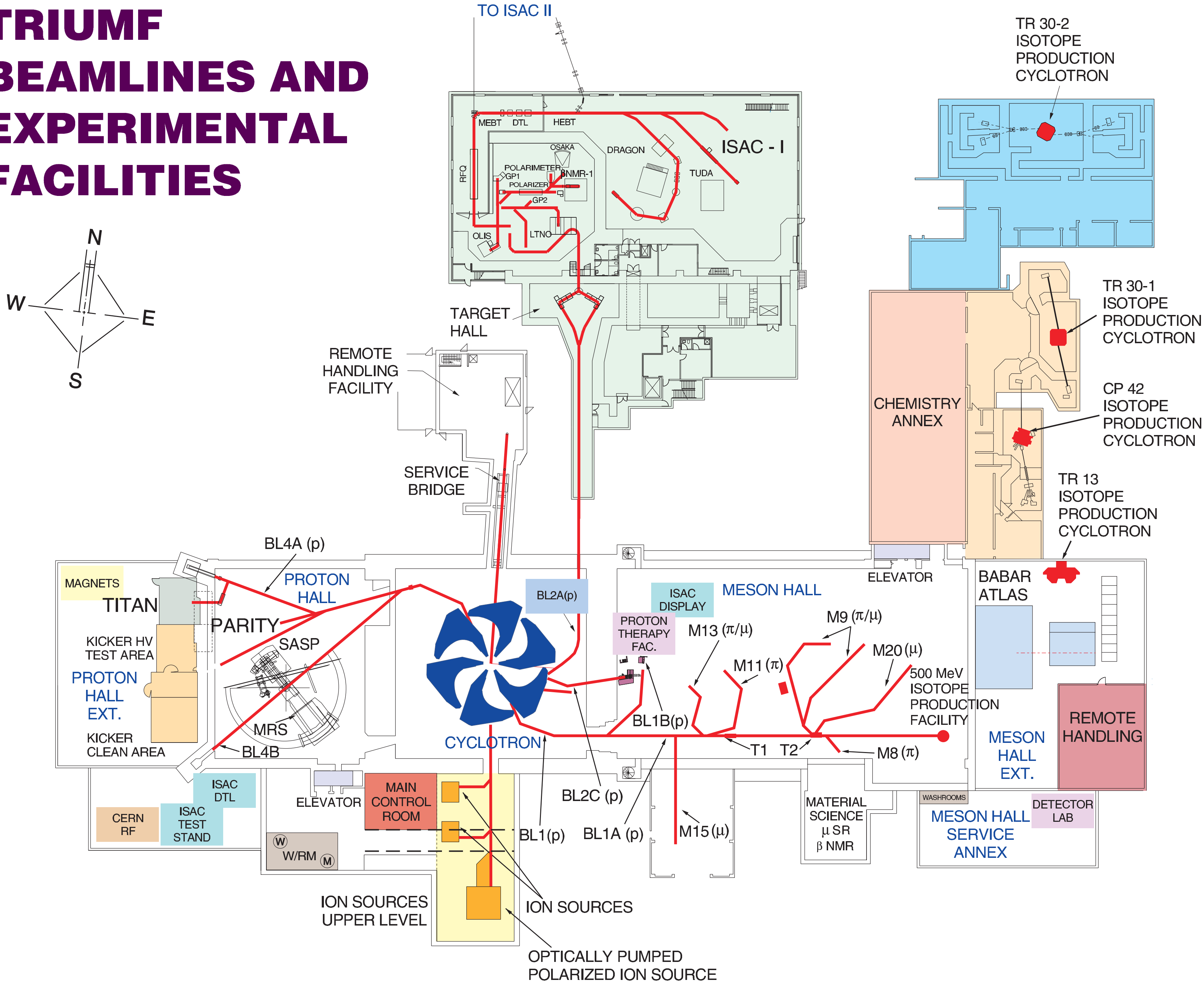
$$W[\theta_{\beta\nu}] = 1 \; + \; b\frac{m}{E} \; + \; a \, \frac{v_\beta}{c} \cos\theta_{\beta\nu}$$

a= +1



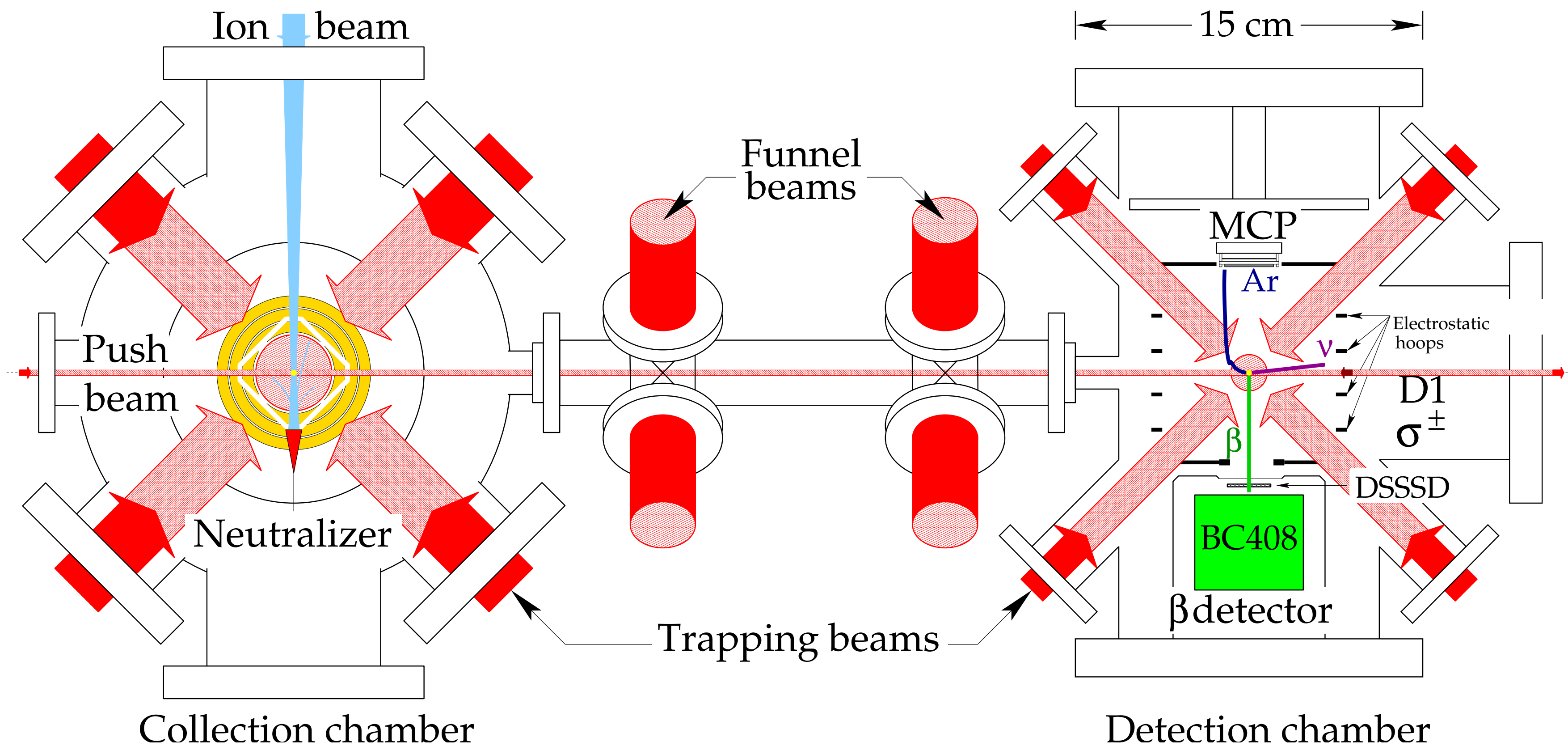
For scalar exchange, lepton helicities are same: a= -1

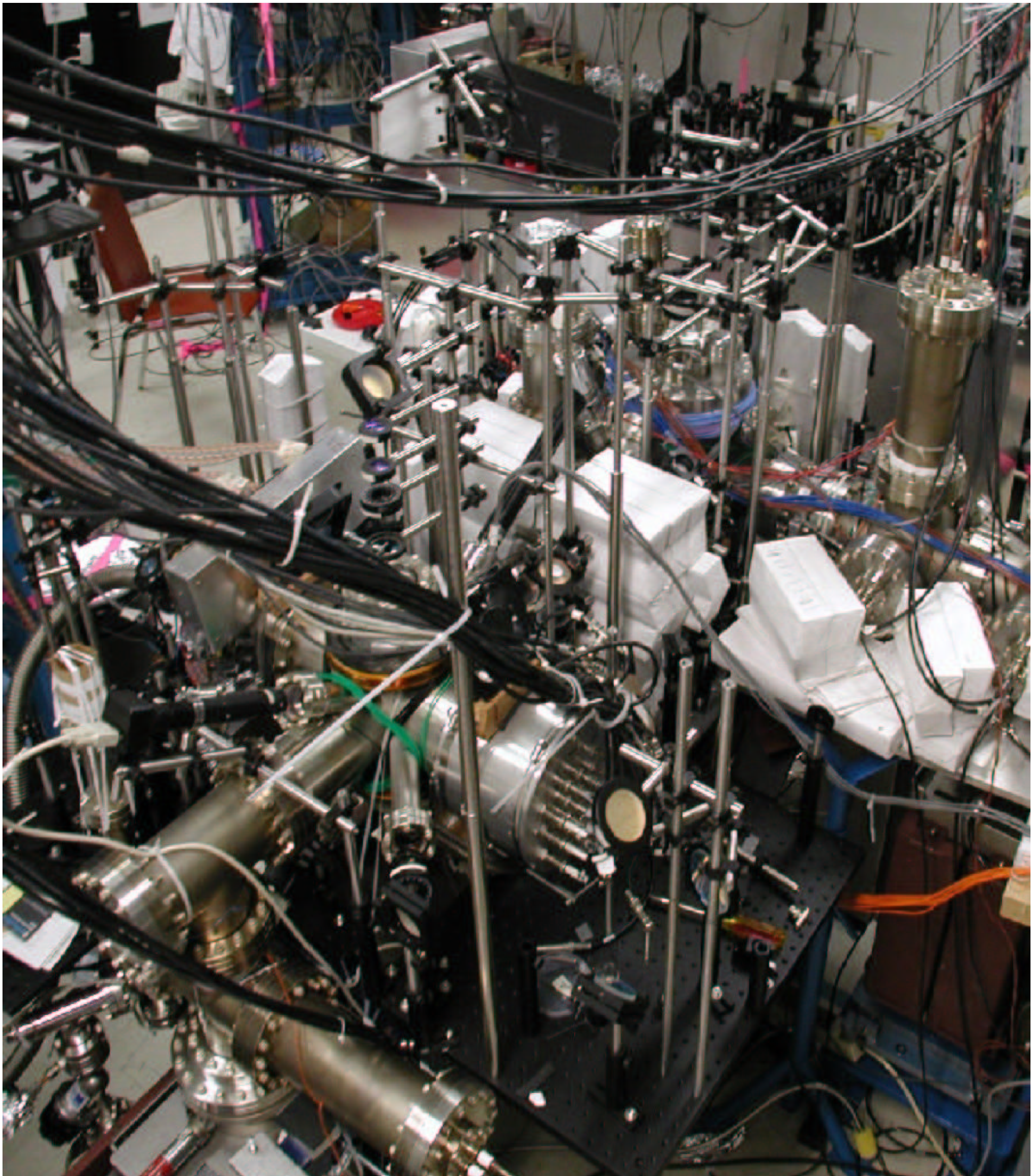
TRIUMF BEAMLINES AND EXPERIMENTAL FACILITIES

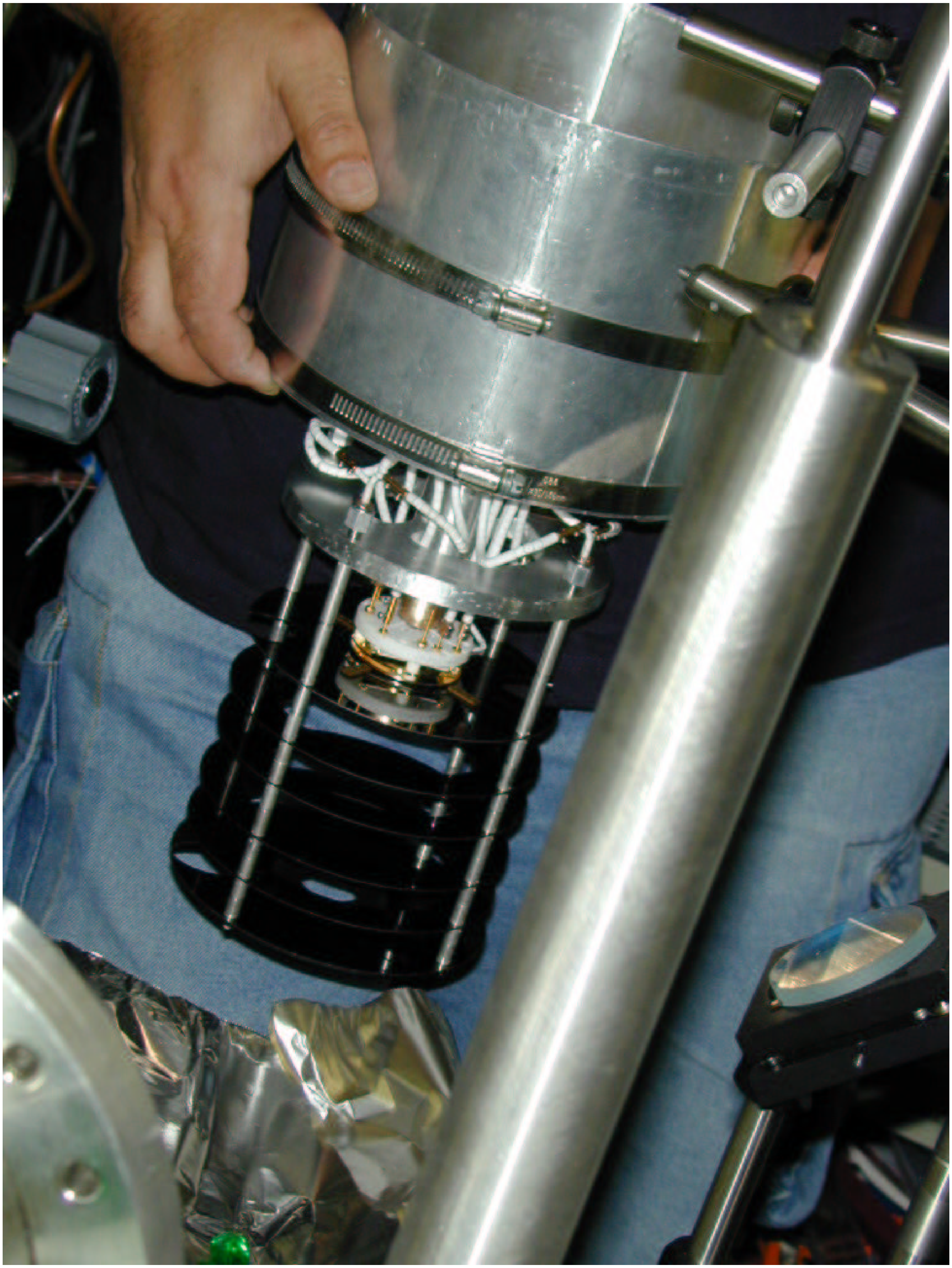


TRIUMF's Neutral Atom Trap

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





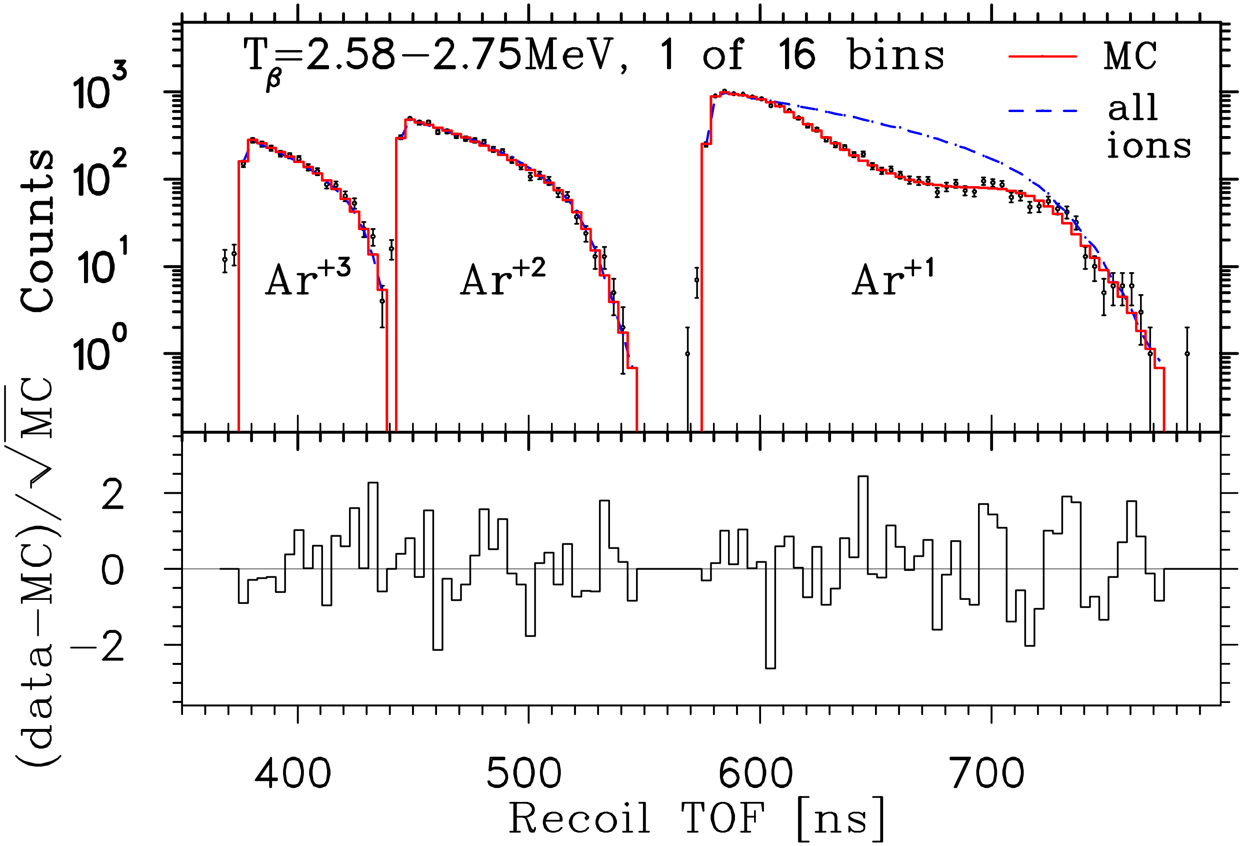


^{38m}K $0^+ \rightarrow 0^+$

β-ν correlation

Recoil TOF[T_β],

C.L. of total fit 52%



Gorelov PRL Apr 2005

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

Best general constraints on scalars coupling to 1st generation

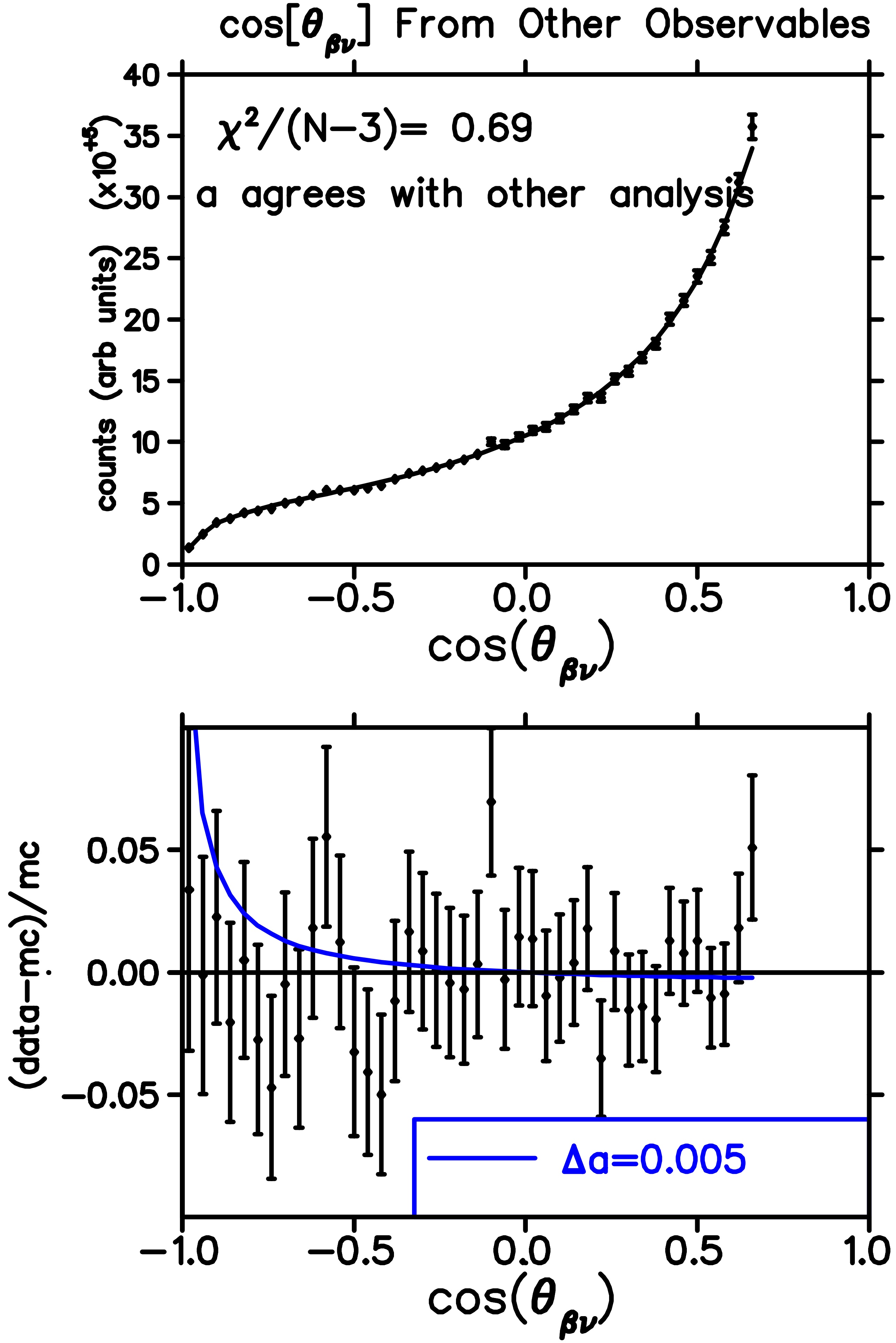
Upgrade approved: Goal 3x better

$\tilde{a} = a/(1 + b m_\beta / \langle E_\beta \rangle)$

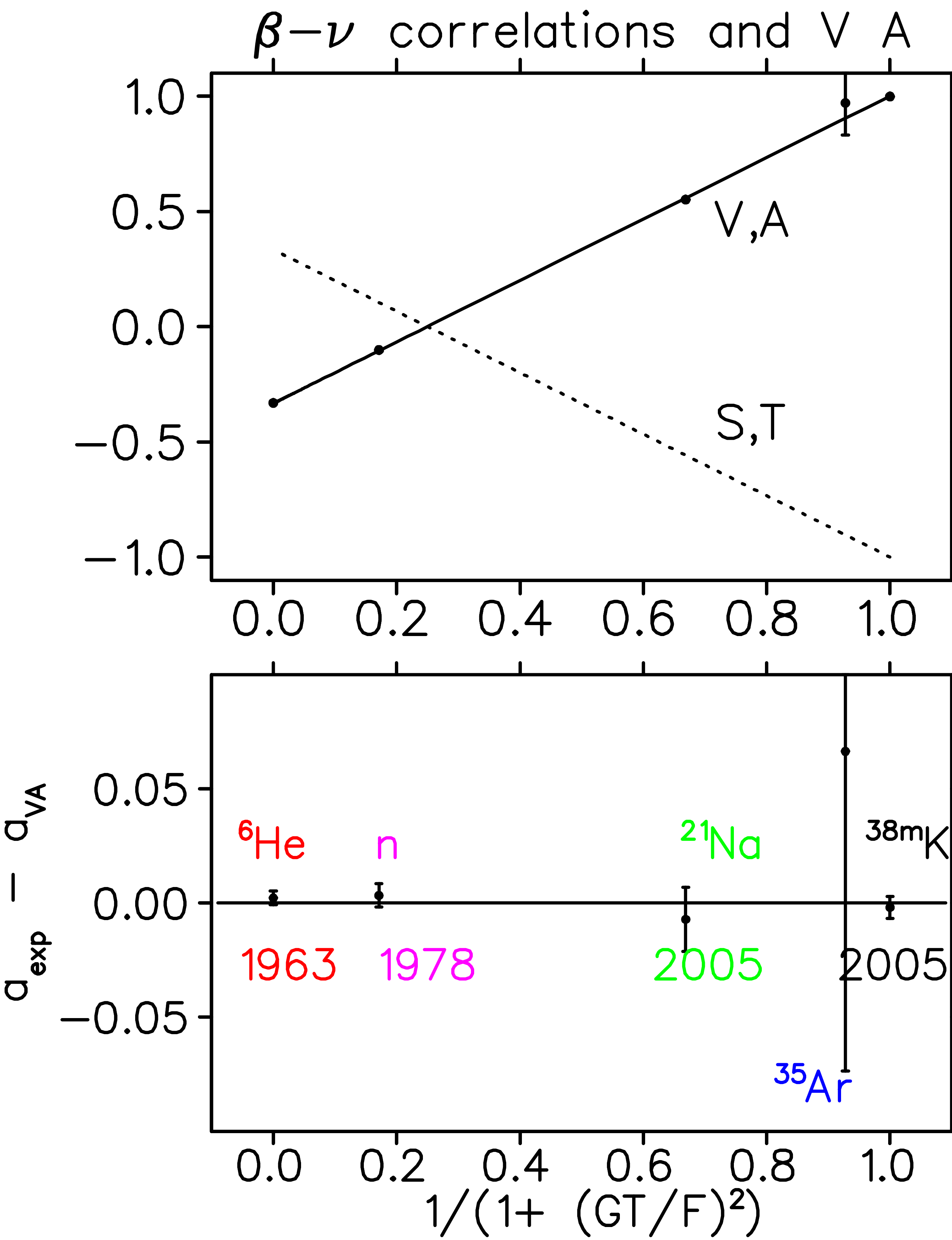
Complementary to $\pi \rightarrow e\nu$ (B. Campbell et al. NPB 709 419 (2005))

(Adelberger ^{32}Ar β-delayed proton emission PRL 1999

$\tilde{a}$=0.9989 ± 0.0052 ± 0.0039 still under re-analysis)

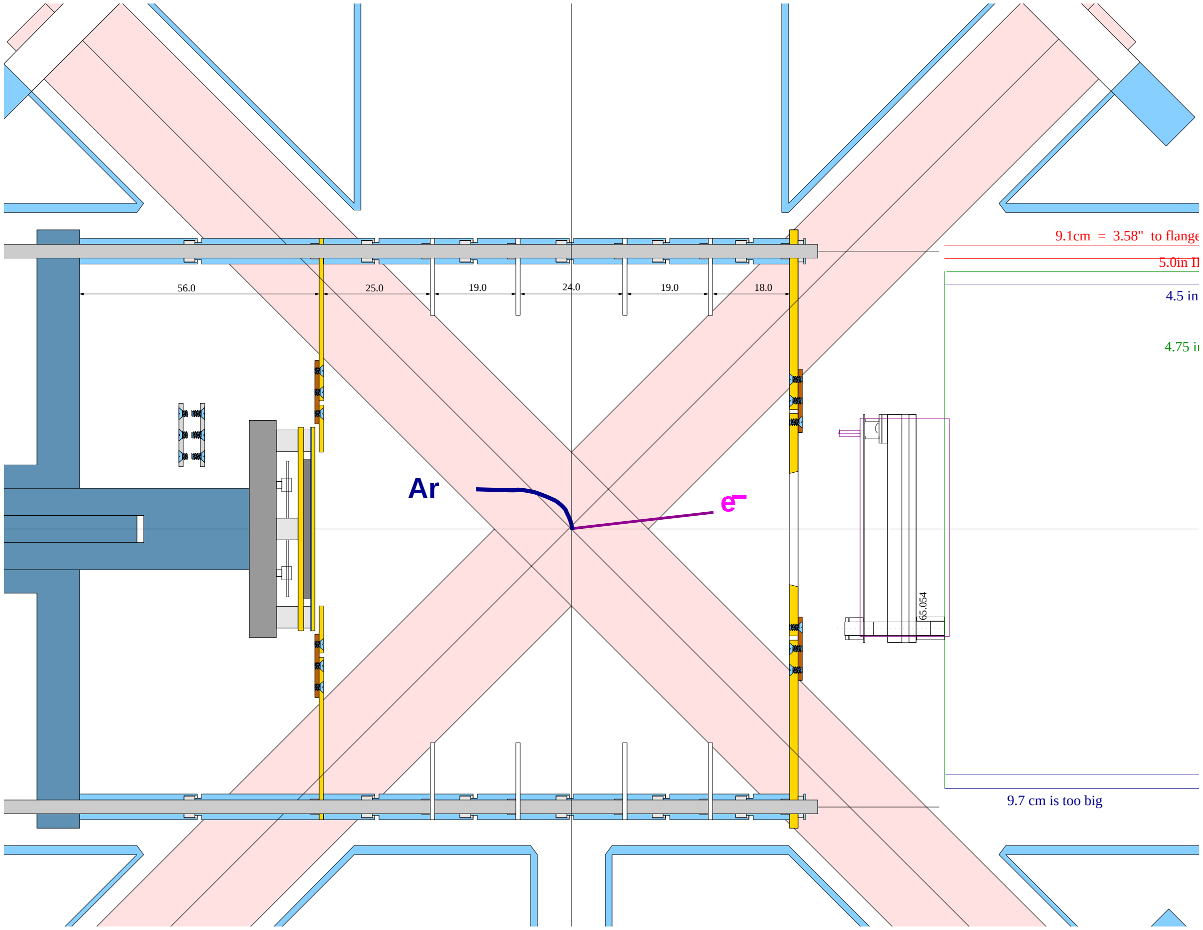


cos[θβν] From Other Observables
χ²/(N−3)= 0.69
a agrees with other analysis
counts (arb units) (x10+5)
cos(θβν)
(data-mc)/mc
Δa=0.005
cos(θβν)



β−ν correlations and V A
1.0
0.5
0.0
−0.5
−1.0
V,A
S,T
0.0 0.2 0.4 0.6 0.8 1.0
a_exp − a_VA
0.05
0.00
−0.05
6He
n
21Na
38mK
1963
1978
2005
2005
35Ar
1/(1+ (GT/F)²)

New: Geometry with e^- detector



For E1070:

- **High-statistics**
- **free of β bias**
- **expect collection for all e−'s < 100 eV**

Also with higher statistics:

^{80}Rb tensor search by recoil singles: Lots of data Dec 05

^{37}K A_{recoil} gives Fermi/GT interference, right-handed currents; A_β

^{36}K isospin mixing becomes practical: A_{recoil}, A_β

^{74}Rb Q-value

keV sterile ν's $|\nu_e\rangle = \cos\theta\ |\nu_{m=0}\rangle + \sin\theta\ |\nu_x\rangle$

- **dark matter, pulsar kicks... Dodelson PRL 1994 Biermann PRL 2006**
- **Admixture $\sim 10^{-8}$ Abazajian PRD 2005**

  'like rare K decay' $\rightarrow$ Need $\sim$zero background

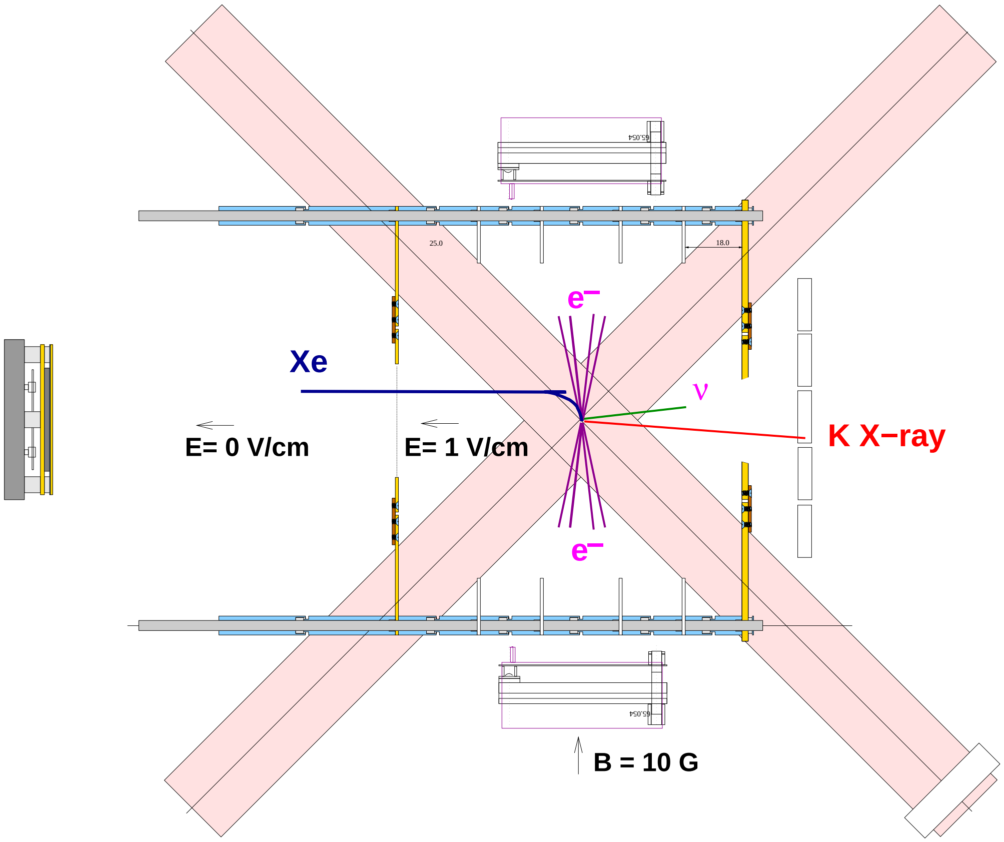
- **10^{-5} admixture conceivable at 20 keV ('do you care?'):**

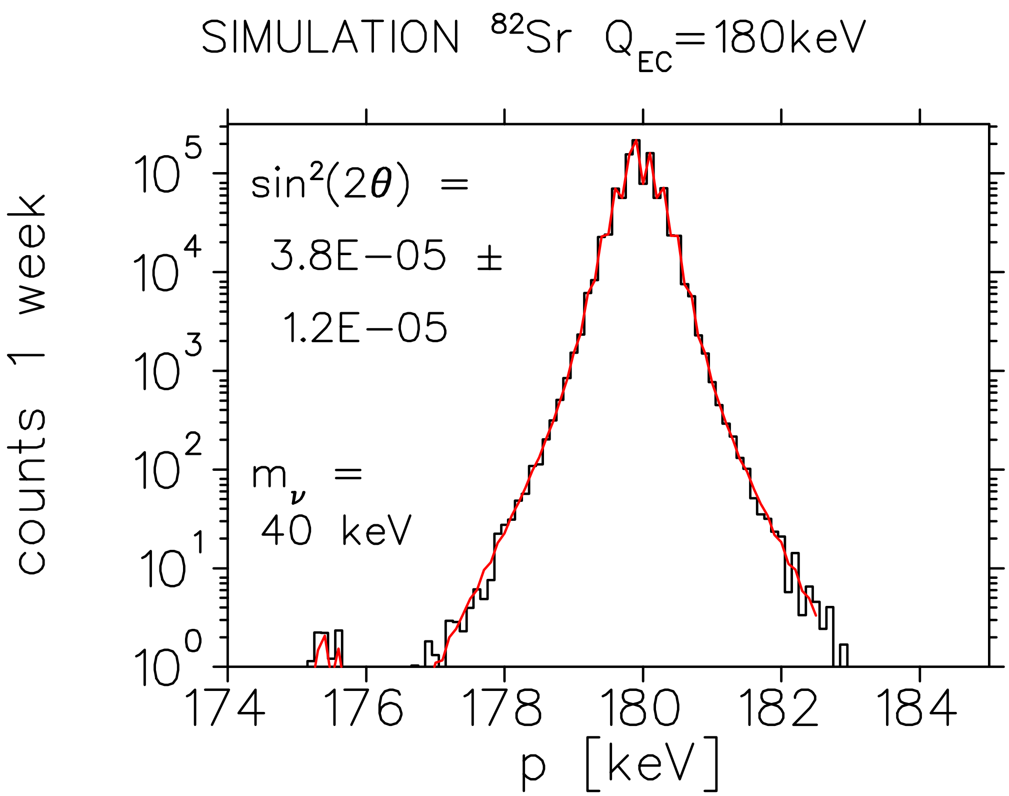
Electron Capture

$^{131}Cs + e^- \rightarrow \nu + ^{131}Xe$ (or ^{82}Sr or ^{7}Be)

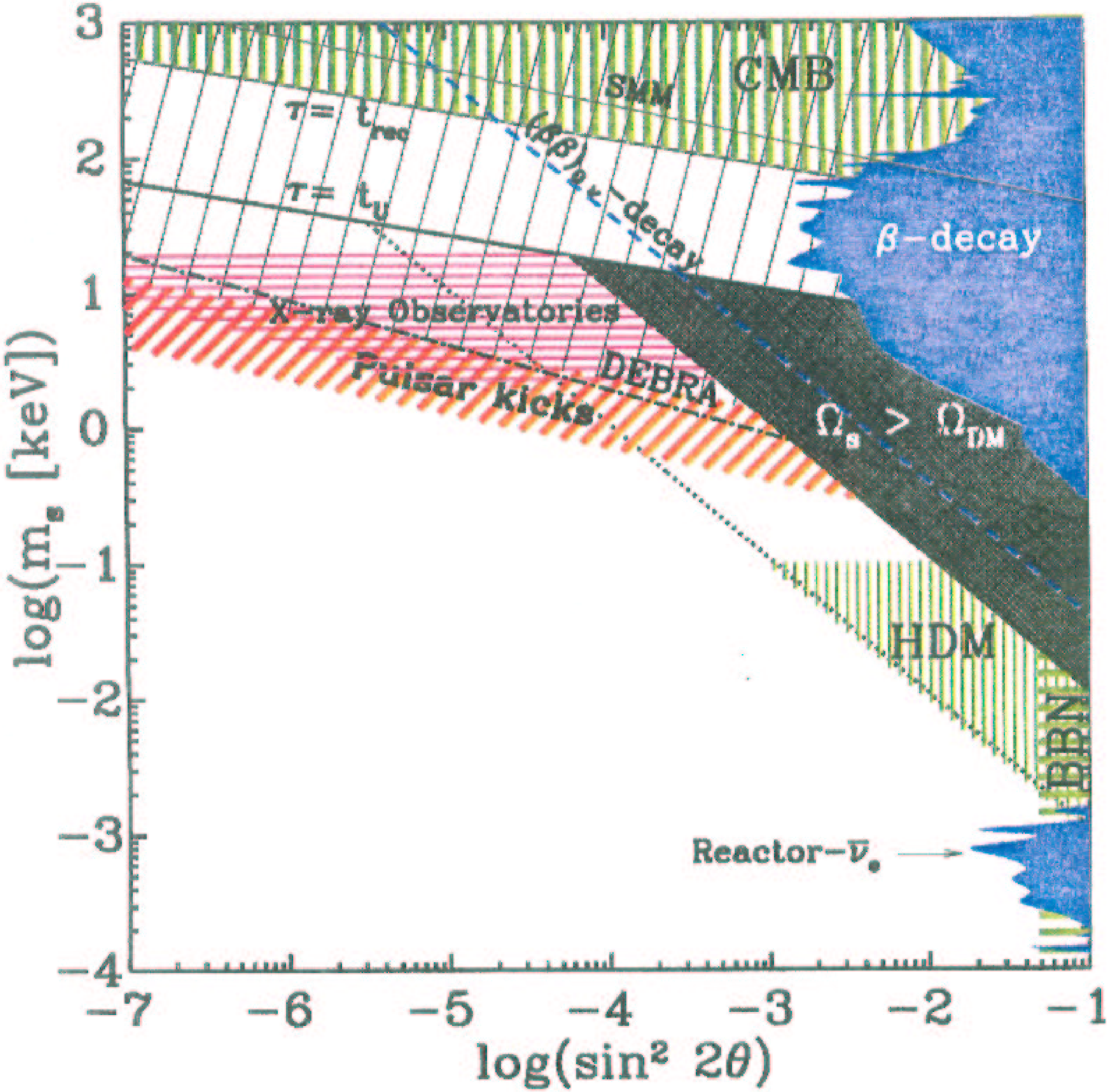
p'$\approx$ p $(1 - m^2_{\nu x}/2Q^2) \Rightarrow \delta p/p \sim 0.001$

Must measure momenta of all shakeoff e^-'s to 10% and K X-ray direction





Gelmini PRL 93 80312 (2004) "low reheating" T<<100 MeV



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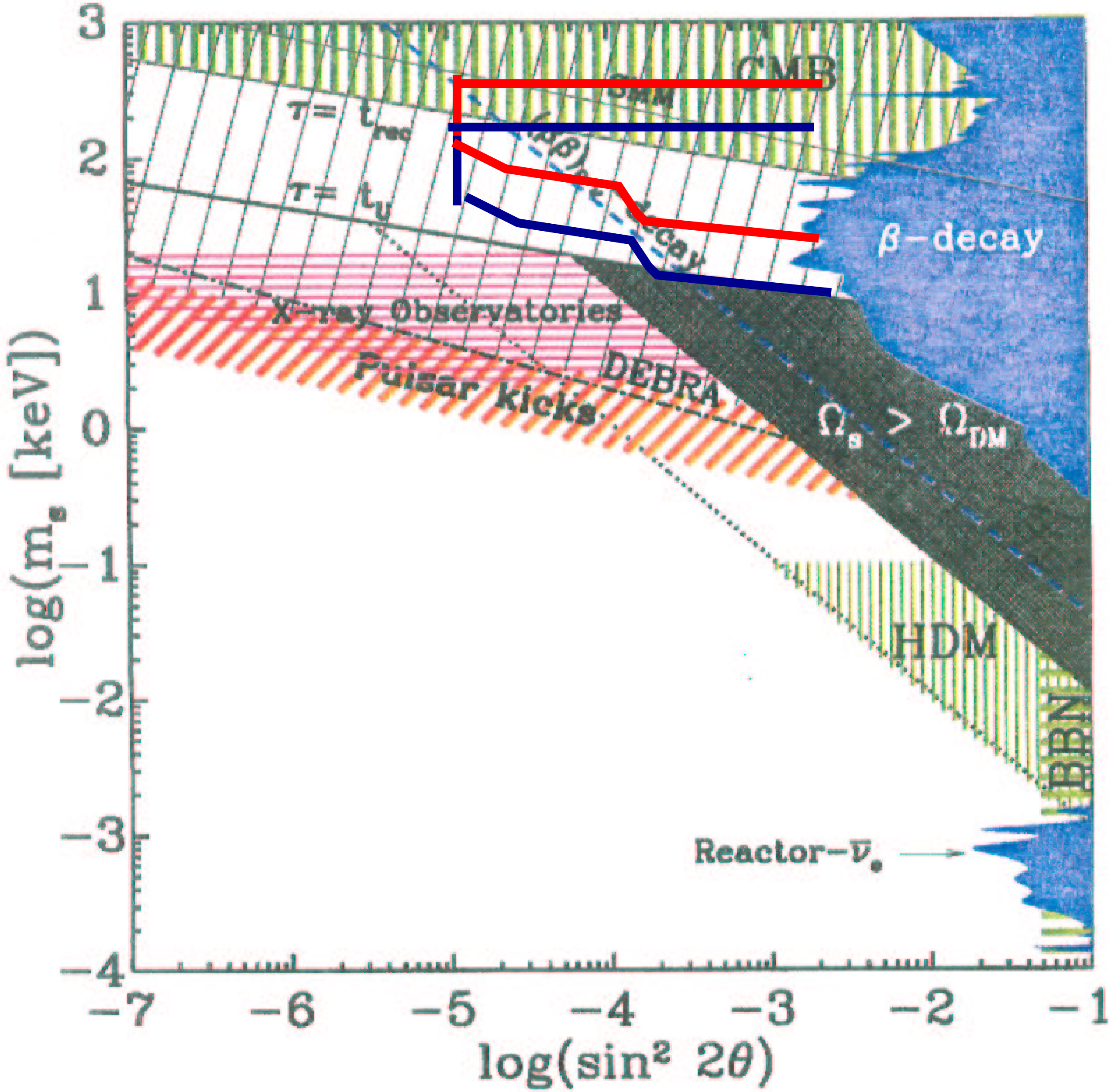

Projected:

131Cs EC

82Sr EC

'1 week counting'

Boyarsky astro−ph/512509 plots Ω_s $\sin^2 2\theta$

Laser Traps for Beta Decay Experiments

[Refs.: Nobel Prize Lectures: Rev. Mod. Phys. 70 Jul 1998;
and J.A.B. NIM**B204** 526 (2003)]

- **MOT provides a localized, backing-free source ideal for β^+-recoil coincidence studies**
- **Neutral atom trap technology provides (?) highly polarized nuclei with known polarization**