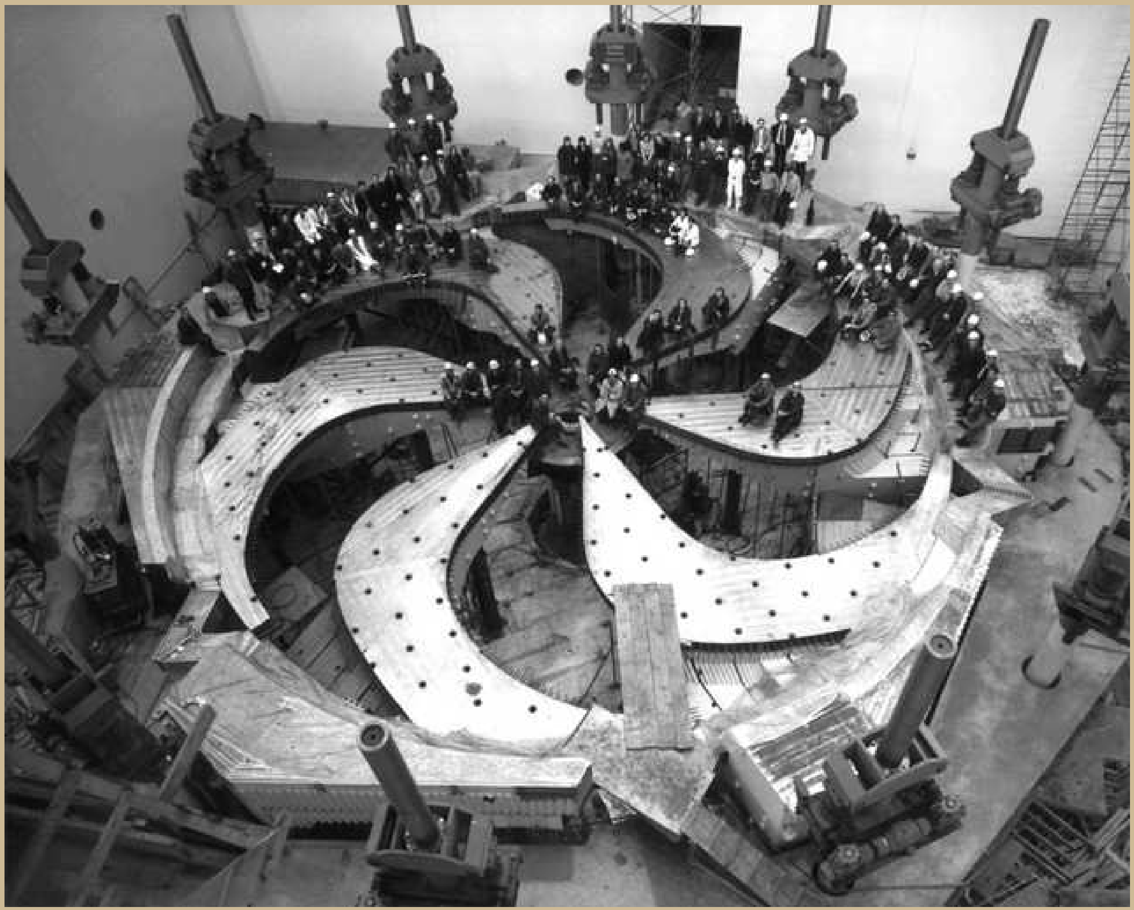
Weak (and ridiculously weak) interactions as tests of fundamental physics



Dan Melconian

Cyclotron Institute/Dept. of Physics & Astronomy

Texas A&M University

Presentation for REUs — July 25, 2012

Overview

1. Fundamental symmetries

- what is our **current understanding**?
- what lies **beyond**?

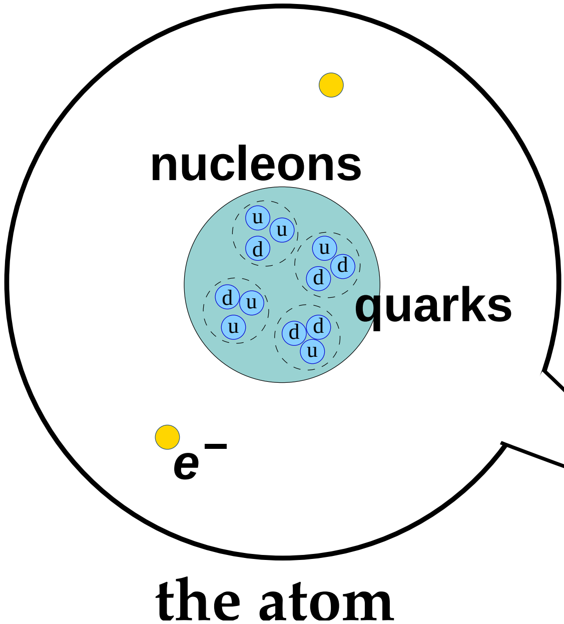
2. Tools of the trade

- **trapping** short-lived neutral atoms
- **polarizing** the atom cloud

3. Angular correlations using laser-cooled atoms

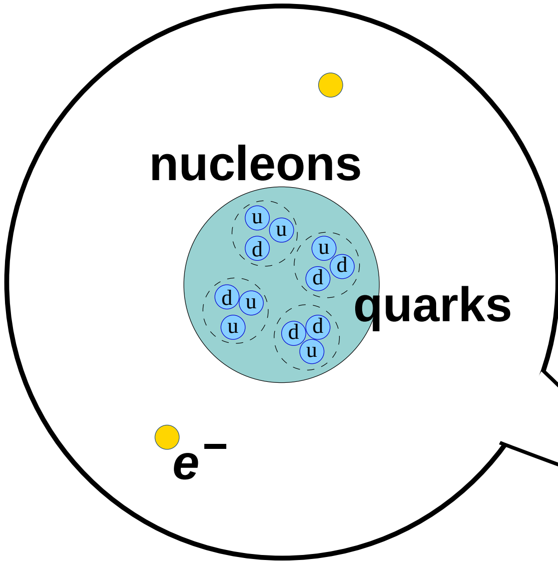
- angular correlations of **polarized ^{37}K**
- expected limits on right-handed currents

Scope of fundamental physics



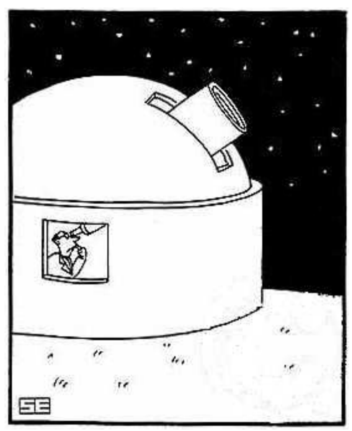
from the very smallest scales . . .

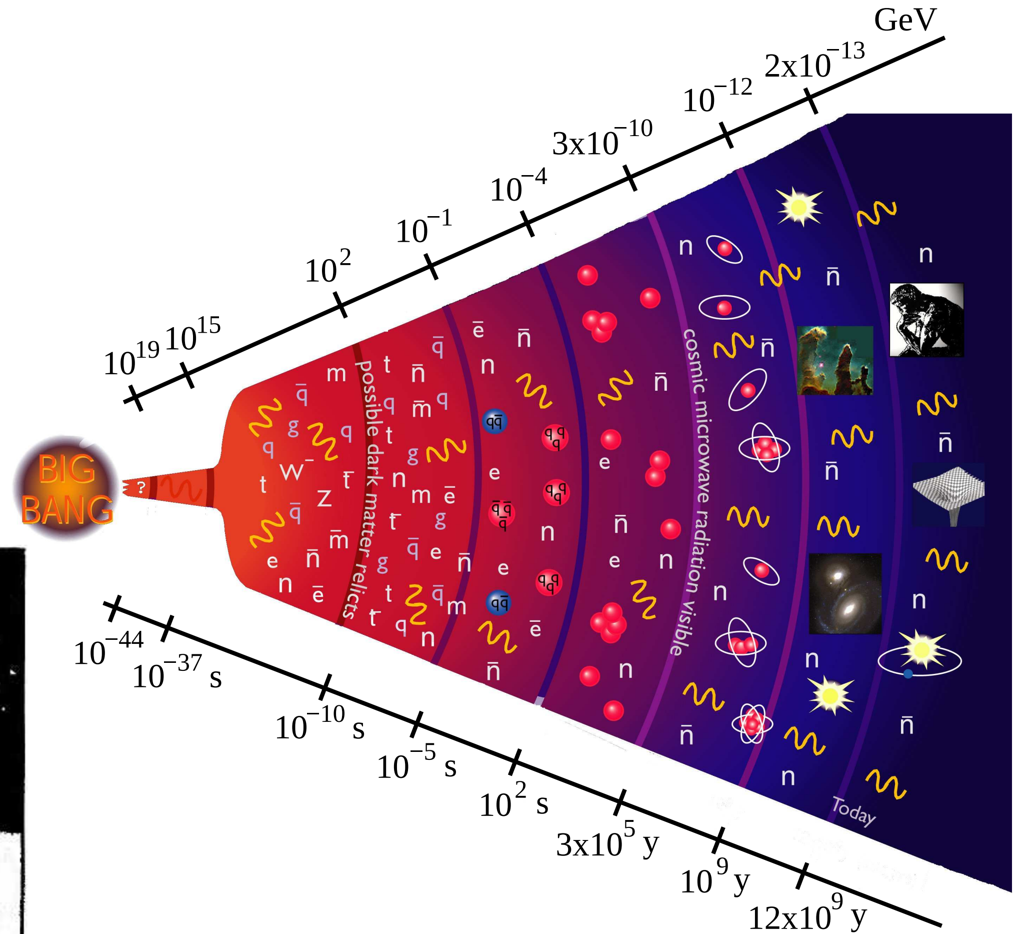
Scope of fundamental physics



the atom

from the very smallest scales . . .





. . . to the very **largest**

The Standard Model

All of the ***known*** elementary particles and their interactions are described within the framework of

THE *new* STANDARD MODEL

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and there's other symmetries too:

time	$\Leftrightarrow$	energy
space	$\Leftrightarrow$	momentum
rotations	$\Leftrightarrow$	angular momentum
	$\vdots$	

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- $$\underbrace{SU(3)}_{\text{strong}} \times \overbrace{\underbrace{SU(2)_L}_{\text{weak}} \times \underbrace{U(1)}_{\text{E\&M}}}^{\text{electroweak}} \quad + \quad \underbrace{\text{(classical general rel)}}_{\text{gravity}}$$

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- **quantum** + **special rel** $\Rightarrow$ **quantum field theory**
- Noether's theorem: symmetry $\Leftrightarrow$ conservation law
- $SU(3) \times SU(2)_L \times U(1)$: strong + electroweak
- **12 elementary particles** and **4 fundamental forces**

	1st	2nd	3rd	Q
leptons	$\begin{pmatrix}\nu_e \\ e\end{pmatrix}$	$\begin{pmatrix}\nu_\mu \\ \mu\end{pmatrix}$	$\begin{pmatrix}\nu_\tau \\ \tau\end{pmatrix}$	0 -1
quarks	$\begin{pmatrix}u \\ d\end{pmatrix}$	$\begin{pmatrix}c \\ s\end{pmatrix}$	$\begin{pmatrix}t \\ b\end{pmatrix}$	$+2/3$ $-1/3$

mediator	force
g	strong
$W^\pm$, Z°	weak
γ	EM

That's all fine and dandy, but. . .

Does the Standard Model work??

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- **predicted** the existence of the $W^{\pm}$, $Z_{\circ}$, g, c and t

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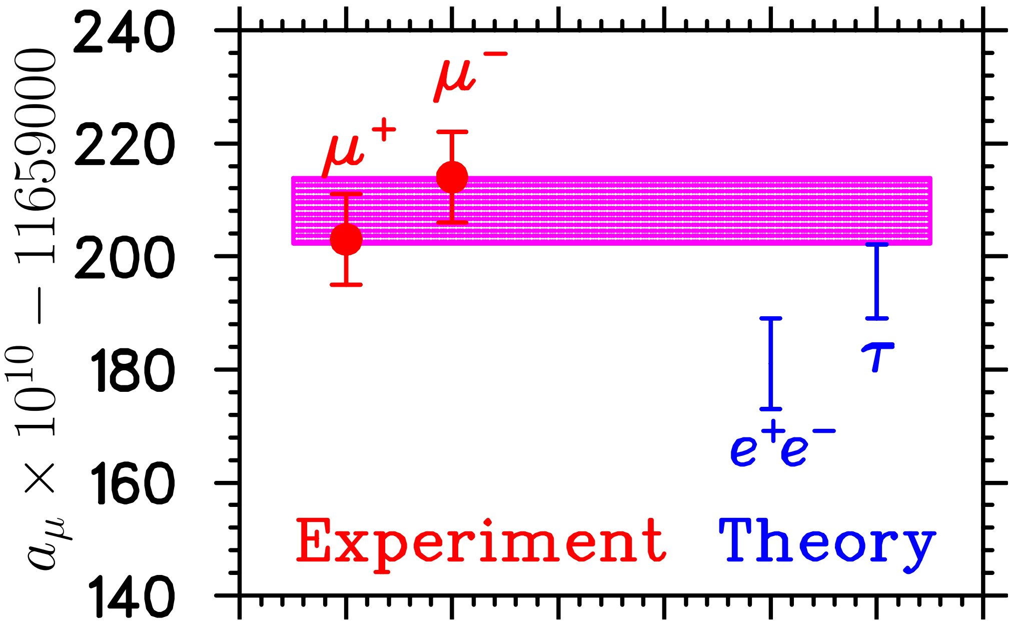

$$a_\mu \equiv \tfrac{1}{2}(g-2)$$

$$a_\mu(\mathrm{exp}) = 11\,659\,208(6) \times 10^{-10}$$

$$a_\mu(\mathrm{SM}) = 11\,659\,181(8) \times 10^{-10}$$

± 1 **part-per-*million*!!**

(PRL **92** (2004) 161802)

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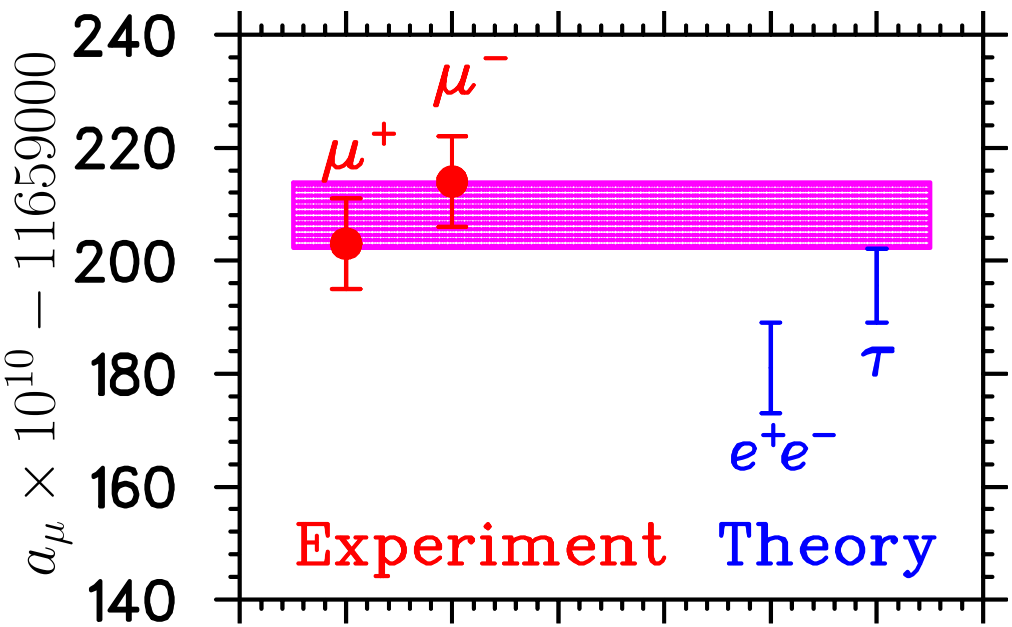

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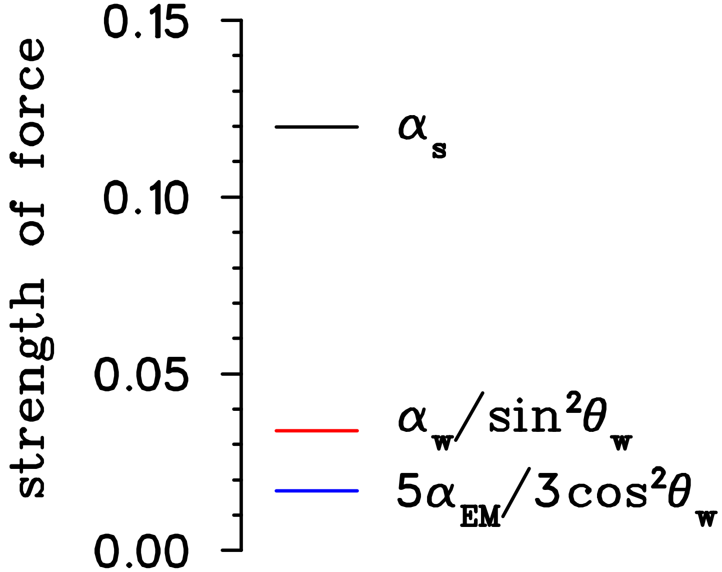
Wow . . . this is

the most precisely tested theory ever conceived!

But there are still questions . . .

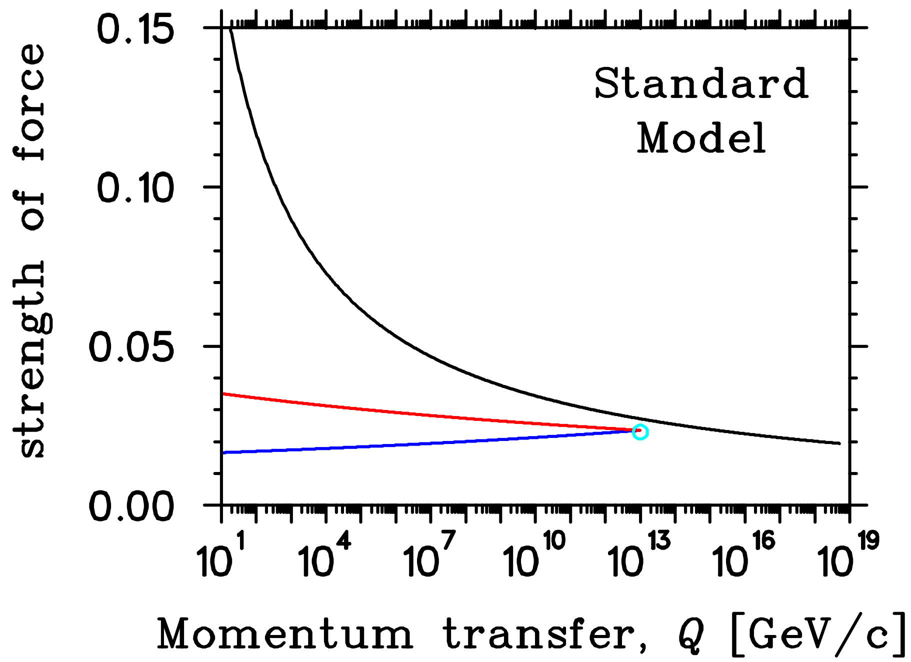
- values of parameters: does our "ultimate" theory *really* need **25** arbitrary constants? Do they **change** with time?
- dark matter: SM physics makes up **only 4%** of the energy-matter of the universe!
- baryon asymmetry: why more **matter** than **anti-matter**?
- strong CP: do **axions** exist? **Fine-tuning**?
- neutrinos: **Dirac** or **Majorana**?
- fermion generations: why **three** families?
- weak mixing: Is the CKM matrix **unitary**?
- parity violation: is parity **maximally** violated in the weak interaction? No **right-handed** currents?
- EW symmetry breaking: how do the fermions acquire **mass**? Mass **hierarchy**?
- gravity: of course can't forget about a **quantum** description of **gravity**!

At our energy scales, we see four distinct forces . . .



Beyond the Standard Model

But these coupling 'constants' **aren't** really *constant*: $\boldsymbol{\alpha_i \rightarrow \alpha_i(Q)}$

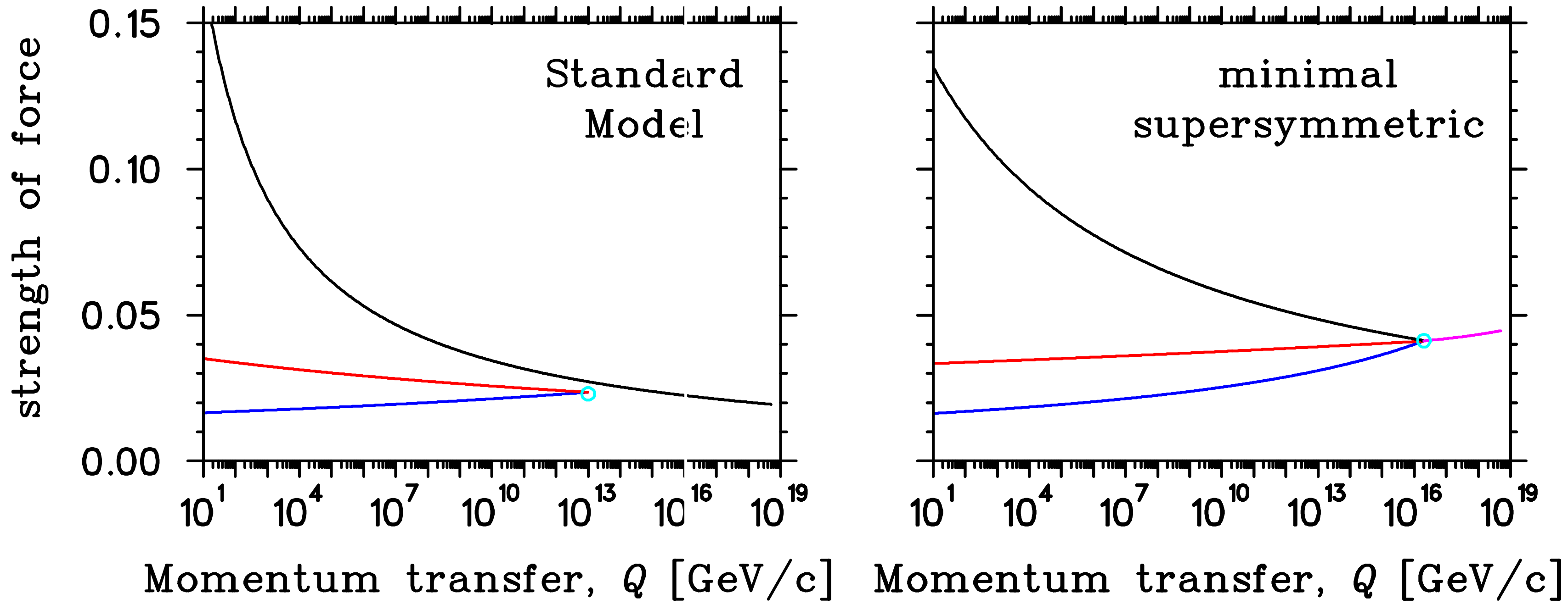


$\rightarrow$ electromagnetic and weak strengths equal at $\approx 10^{13}$ GeV

$\rightarrow$ strong force gets weaker, but doesn't unify with EW. . . .

Beyond the Standard Model

But what if there is **new physics** we haven't seen yet?



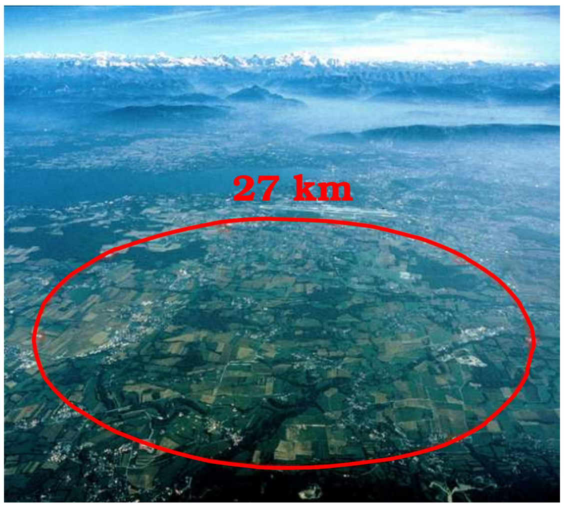
the running of the coupling constants would be affected;
maybe they converge at some GUT scale?

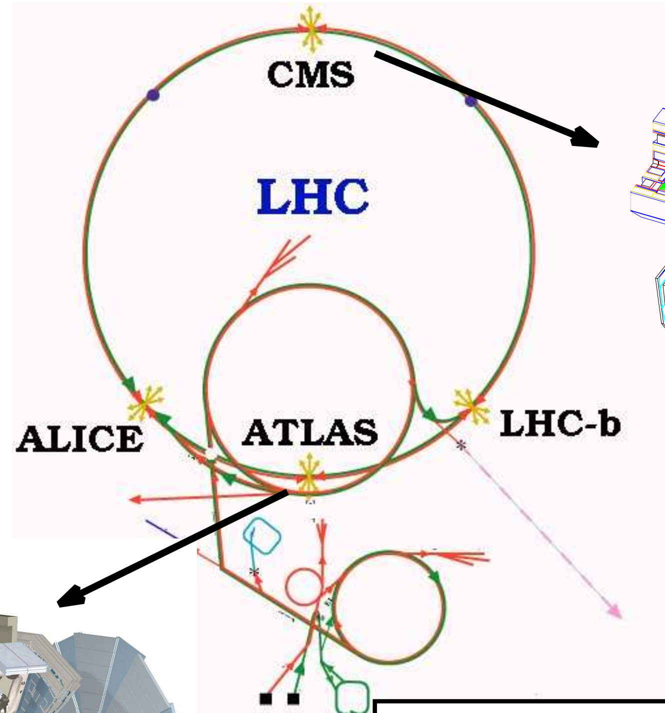
Are the three theories of **E & M**, **weak** and **strong** interactions all **low-energy limits** of **one unifying** theory?

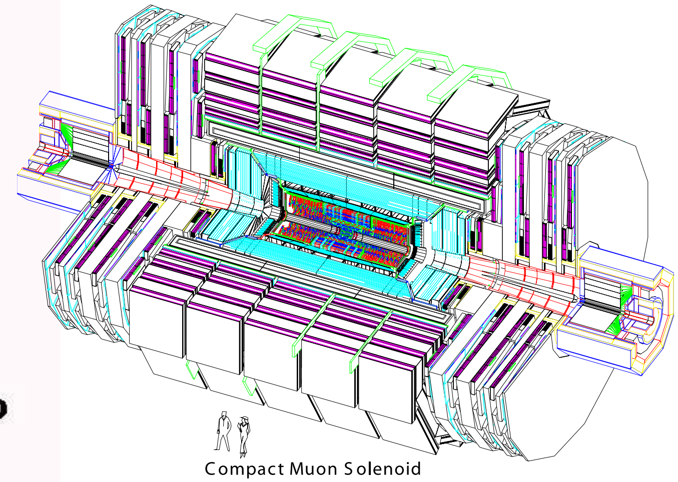
How do we test the SM?

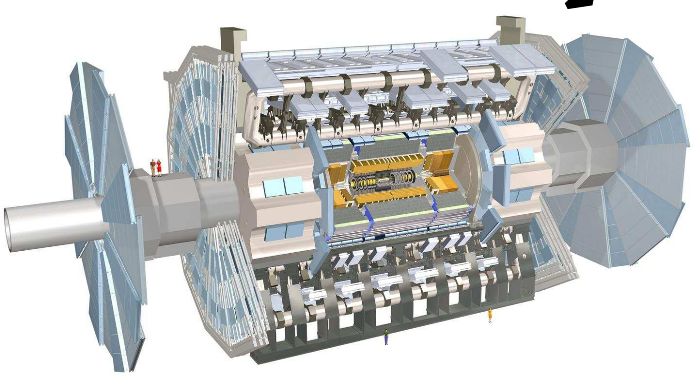
colliders: CERN, SLAC, FNAL, BNL, KEK, DESY, ...

direct search of particles









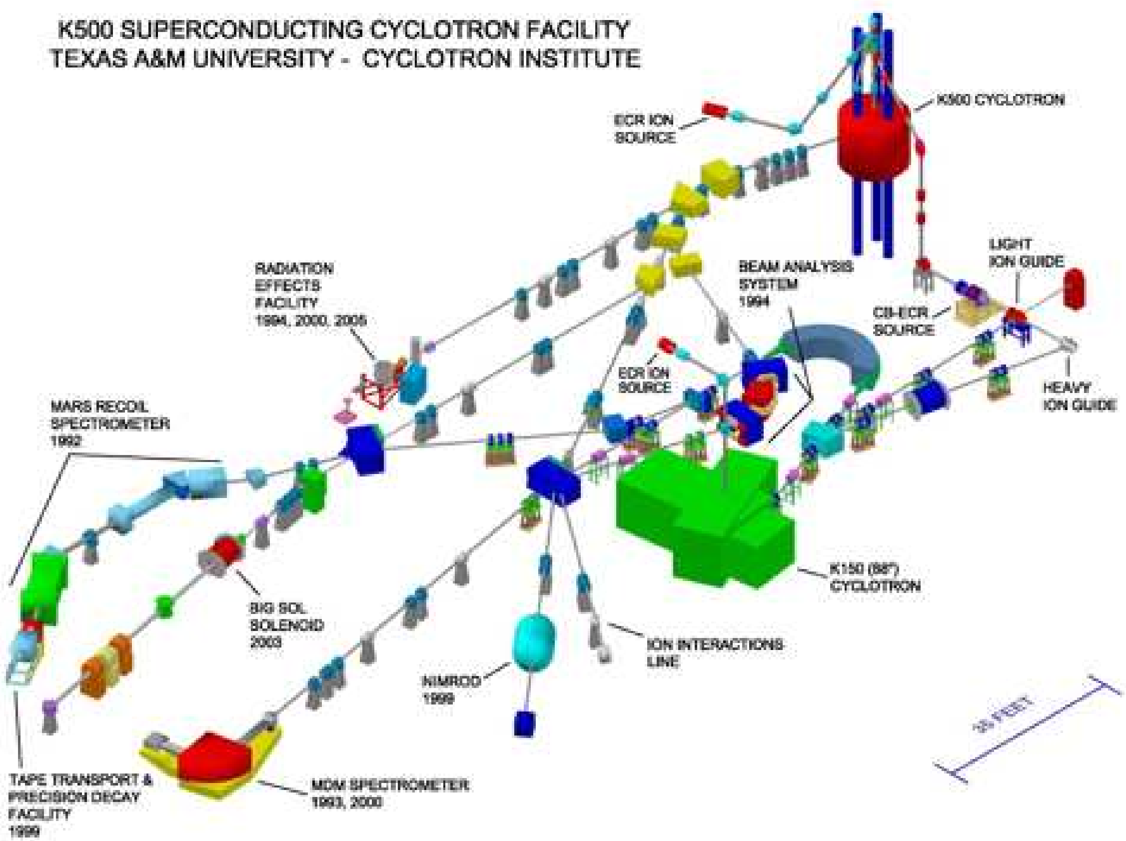
"go big or go home"

- large multi-national collabs
- billion $ price-tags

How do we test the SM?

nuclear physics: radioactive ion beam facilities (ISOL/frag)

indirect search via precision measurements



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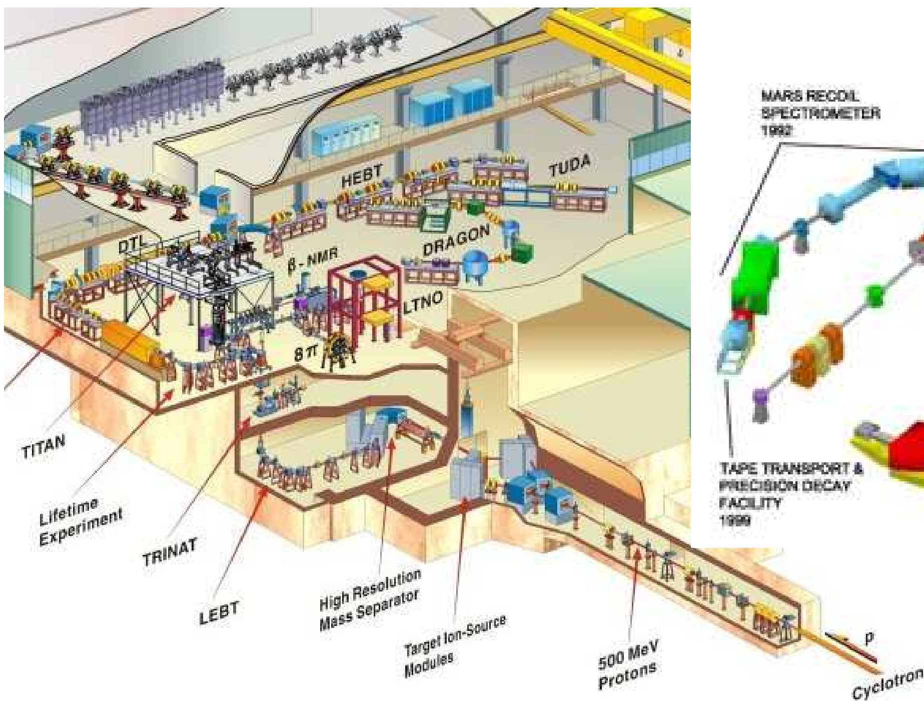

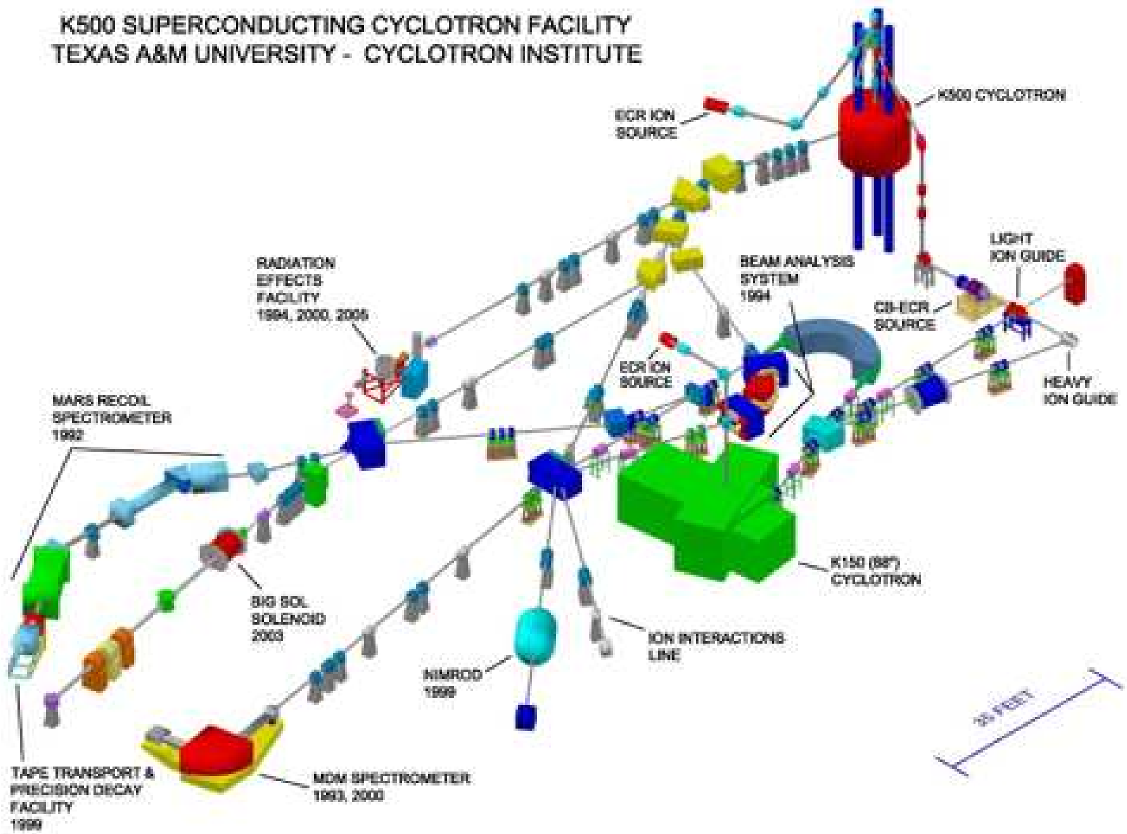

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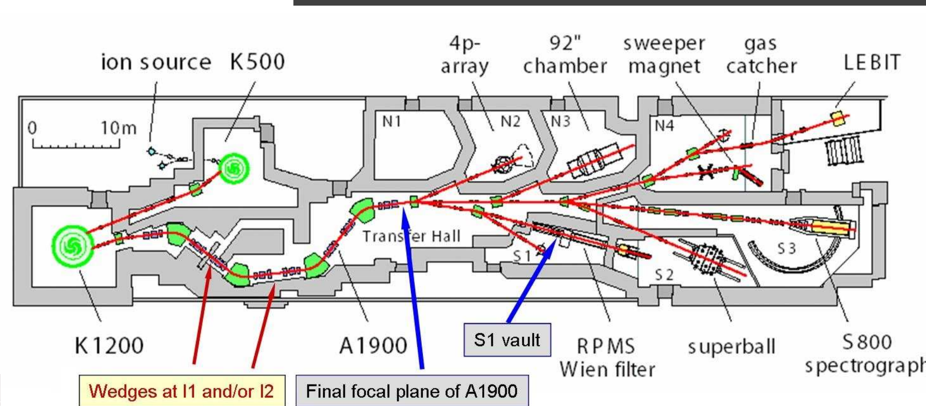

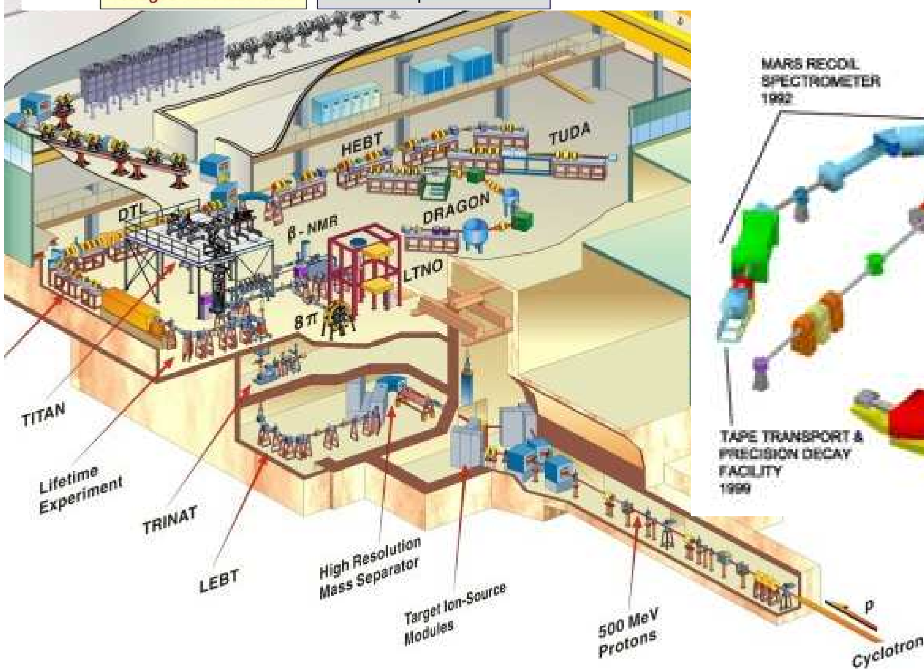

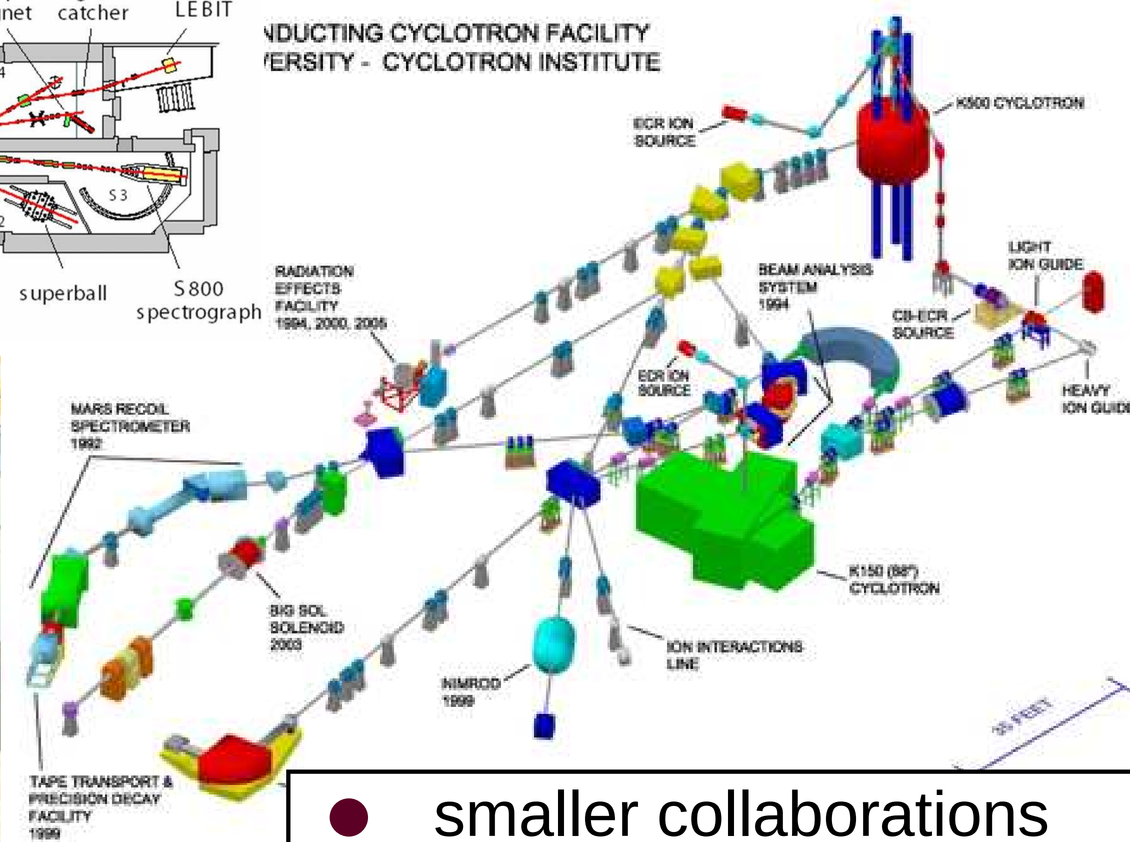

- smaller collaborations
- contribute to all aspects
- “table-top” physics

How we all *test the SM*

- **colliders**: CERN, SLAC, FNAL, BNL, KEK, DESY . . .
- **nuclear physics**: traps, exotic beams, neutron, EDMs, $0\nu\beta\beta$, . . .
- **cosmology** & **astrophysics**: SN1987a, Big Bang nucleosynthesis, . . .

- **muon decay**: Michel parameters: ρ, δ, η, and ξ
- **atomic physics**: anapole moment, spectroscopy, . . .

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all of these techniques are **complementary** and **important**

- different experiments probe different (new) physics
- if signal seen, cross-checks crucial!

often they are **interdisciplinary**

(fun and a great basis for graduate students!)

History up to 1957

- 1768: Kant debates nature of incongruent counterparts

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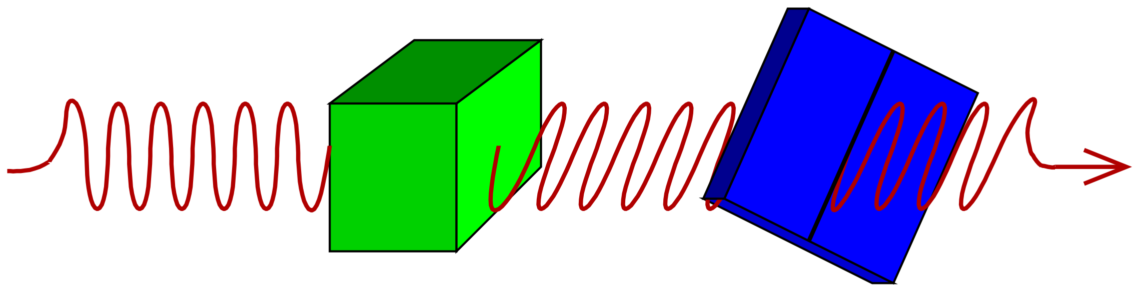

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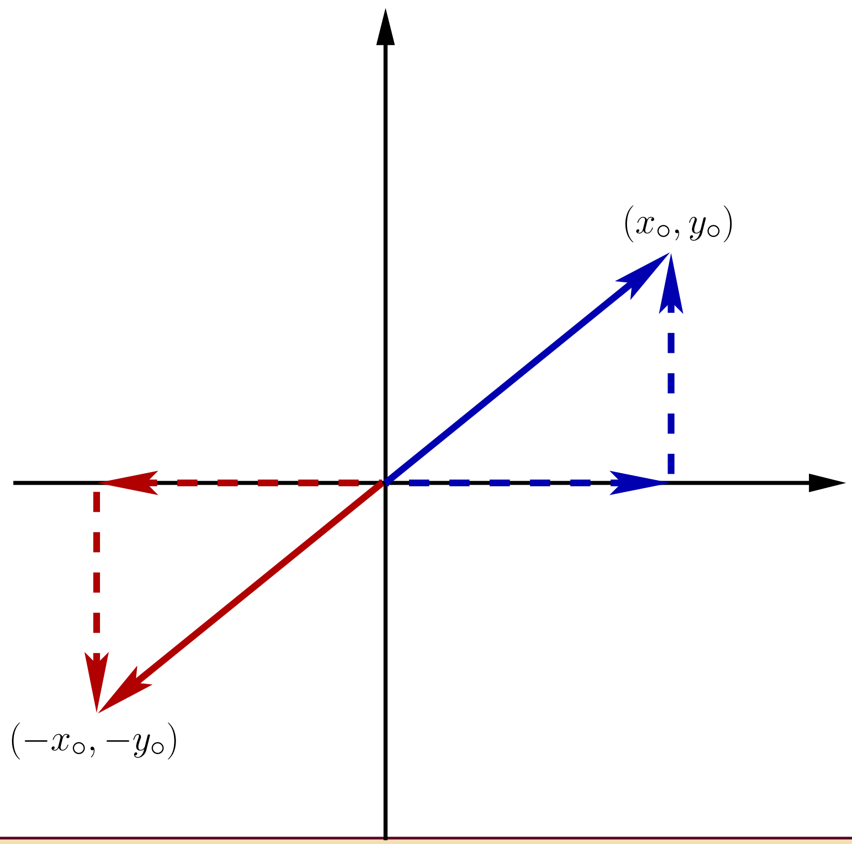
$\boldsymbol{V} = (x_\circ, y_\circ)$

$\hat{P}\boldsymbol{V} = -\boldsymbol{V}$



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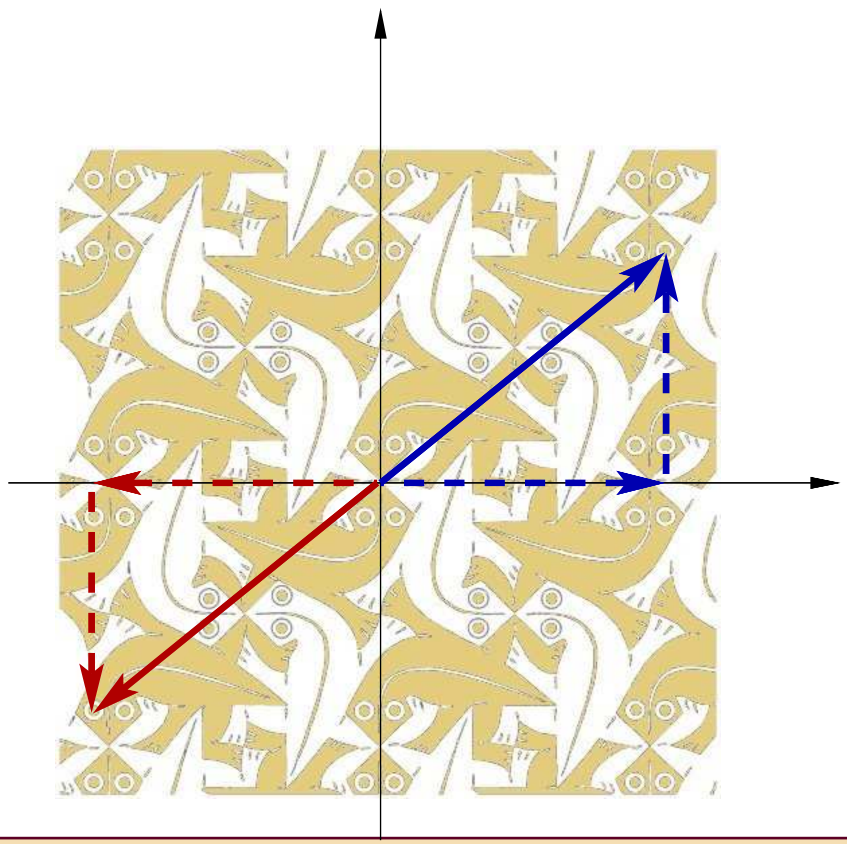
$\boldsymbol{A}$ = M.C. Escher reptiles

$\hat{P}\boldsymbol{A} = +\boldsymbol{A}$



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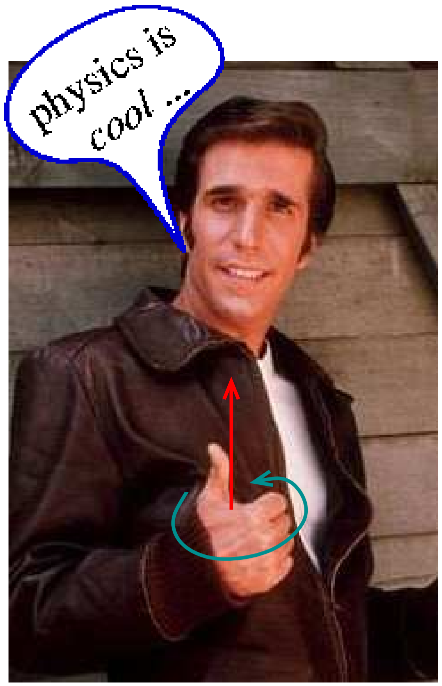
intrinsic parity $\Leftrightarrow$ helicity or “handedness”



$$\boldsymbol{r} \times \boldsymbol{p} \rightarrow (-\boldsymbol{r}) \times (-\boldsymbol{p}) = \boldsymbol{r} \times \boldsymbol{p}$$

(spin is an **axial** vector)

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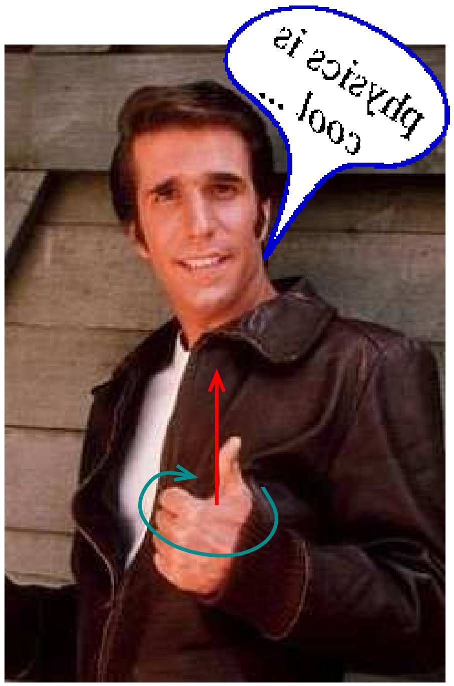
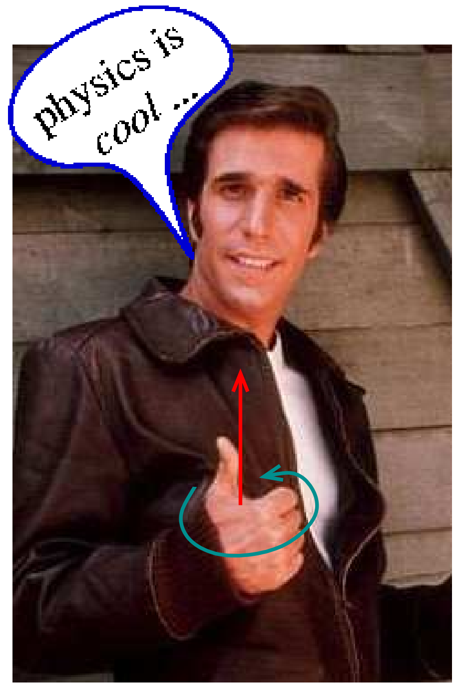


“Left-handed”



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intrinsic parity $\Leftrightarrow$ helicity or “handedness”

- 1927: Wigner shows Maxwell’s equations conserve parity
- 1934: Fermi’s theory of β decay:

$$\frac{dW}{dE_e} = \frac{G_F^2}{(2\pi)^5}\, p_e E_e (E_e - A_\circ)^2\, |\mathcal{M}_{fi}|^2$$

$$\mathcal{M}_{fi} = \int \psi^* \, \Gamma_i \, \psi, \qquad \Gamma_i = (S, P, V, A, T)$$

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- 1953: Dalitz points out the “$\theta - \tau$ puzzle”:

$$\theta^+ \to \pi^0\pi^+ \text{ and } \tau^+ \to \pi^+\pi^+\pi^-$$

(but same lifetime, mass, . . .)

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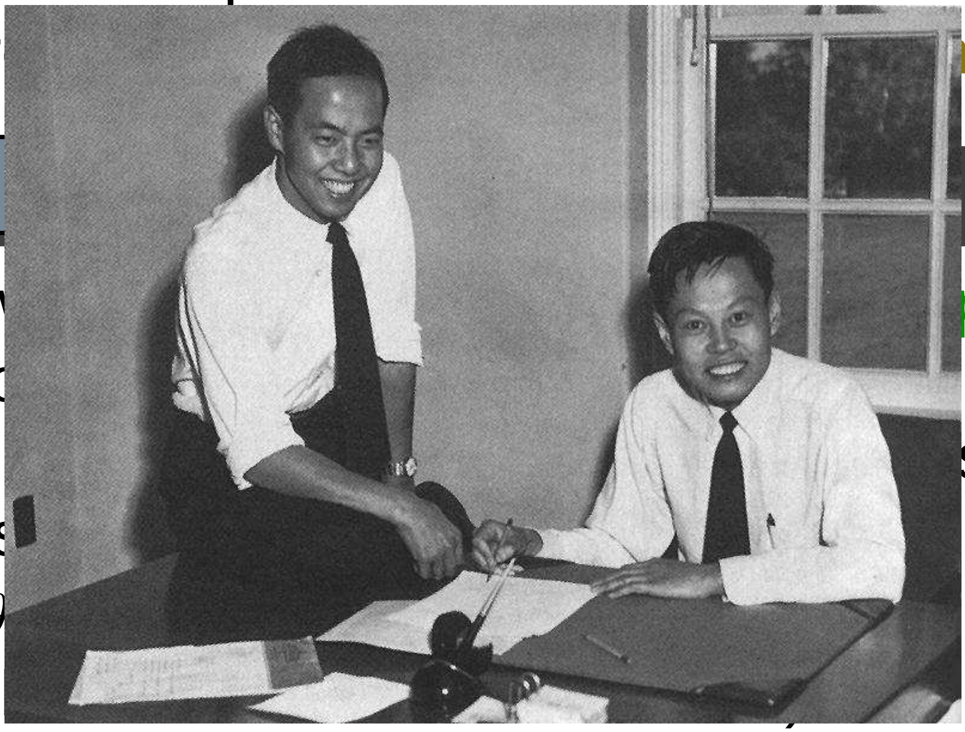

- 1956: prompted Lee and Yang to question current convention

> . . . existing experiments do indicate parity conservation in strong and electromagnetic interactions, but that for weak interactions . . . parity conservation is so far only an extrapolated hypothesis unsupported by experimental evidence.

(Feynman bets parity is conserved)

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$K^+ \to \pi^0\pi^+$ and $K^+ \to \pi^+\pi^+\pi^-$

(**same** particle; parity *not* conserved)

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- 1957: Wu (^{60}Co), Garwin (μ^+) favour $(\boldsymbol{V} - \boldsymbol{A})$ interaction

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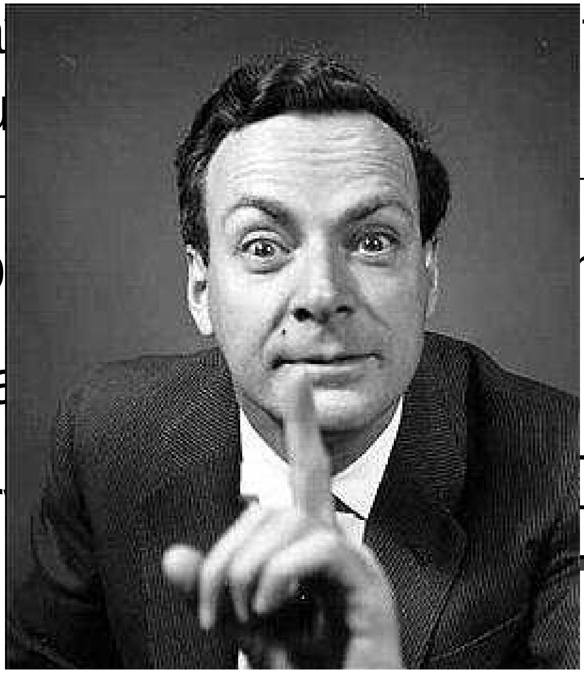

(Feynman loses $50)

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$$K^+ \to \pi^0 \ldots$$

(... conserved)

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β decay has a long history of developing our understanding of fundamental symmetries

The Standard Model (and beyond)

The **Electroweak Interaction**: SU(2)$_L \times$U(1) $\Rightarrow$ $W^{\pm}_L, Z^{\circ}, \gamma$

Built upon **maximal** parity violation:

Vector $\hat{P}|\Psi\rangle = -|\Psi\rangle$

$$H_{\rm SM} = G_F V_{ud}\ \overline{e}(\gamma_\mu - \gamma_\mu\gamma_5)\nu_e\ \overline{u}(\gamma^\mu - \gamma^\mu\gamma_5)d$$

Axial $-$ vector $\hat{P}|\Psi\rangle = +|\Psi\rangle$

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low-energy limit of a **deeper** SU(2)$_R\times$SU(2)$_L\times$U(1) theory?

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low-energy limit of a **deeper** SU(2)$_R$×SU(2)$_L$×U(1) theory?

$\Rightarrow$ 3 more vector bosons: $W_R^{\pm}, Z'$

Simplest extensions: "*manifest left-right symmetric*" models

$\rightsquigarrow$ only 2 new parameters: W_2 mass and a mixing angle, ζ

$$|W_L\rangle = \cos\zeta|W_1\rangle - \sin\zeta|W_2\rangle$$
$$|W_R\rangle = \sin\zeta|W_1\rangle + \cos\zeta|W_2\rangle$$

RHCs would affect correlation parameters

$$A_\beta = \frac{-2\rho}{1+\rho^2}\left(\sqrt{\frac{3}{5}} - \frac{\rho}{5}\right)$$

$$B_\nu = \frac{-2\rho}{1+\rho^2}\left(\sqrt{\frac{3}{5}} + \frac{\rho}{5}\right)$$

and $$R_{\text{slow}} = 0$$

RHCs would affect correlation parameters

In the presence of **new physics**, the **angular distribution of β decay** will be affected.

$$A_\beta = \frac{-2\rho}{1+\rho^2}\left(\sqrt{\frac{3}{5}} - \frac{\rho}{5}\right) \quad \rightarrow \quad \frac{-2\rho}{1+\rho^2}\left[(1-xy)\sqrt{\frac{3(1+x^2)}{5(1+y^2)}} - \frac{\rho(1-y^2)}{5(1+y^2)}\right]$$

$$B_\nu = \frac{-2\rho}{1+\rho^2}\left(\sqrt{\frac{3}{5}} + \frac{\rho}{5}\right) \quad \rightarrow \quad \frac{-2\rho}{1+\rho^2}\left[(1-xy)\sqrt{\frac{3(1+x^2)}{5(1+y^2)}} + \frac{\rho(1-y^2)}{5(1+y^2)}\right]$$

and $\quad R_{\text{slow}} = 0 \quad \rightarrow \quad y^2$

where $x \approx (M_L/M_R)^2 - \zeta$ and $y \approx (M_L/M_R)^2 + \zeta$

are RHC parameters that are zero in the SM.

RHCs would affect correlation parameters

In the presence of **new physics**, the **angular distribution of β decay** will be affected.

$$A_\beta = \frac{-2\rho}{1+\rho^2}\left(\sqrt{\frac{3}{5}} - \frac{\rho}{5}\right) \quad \to \quad \frac{-2\rho}{1+\rho^2}\left[(1-xy)\sqrt{\frac{3(1+x^2)}{5(1+y^2)}} - \frac{\rho(1-y^2)}{5(1+y^2)}\right]$$

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where $x \approx (M_L/M_R)^2 - \zeta$ and $y \approx (M_L/M_R)^2 + \zeta$

are RHC parameters that are zero in the SM.

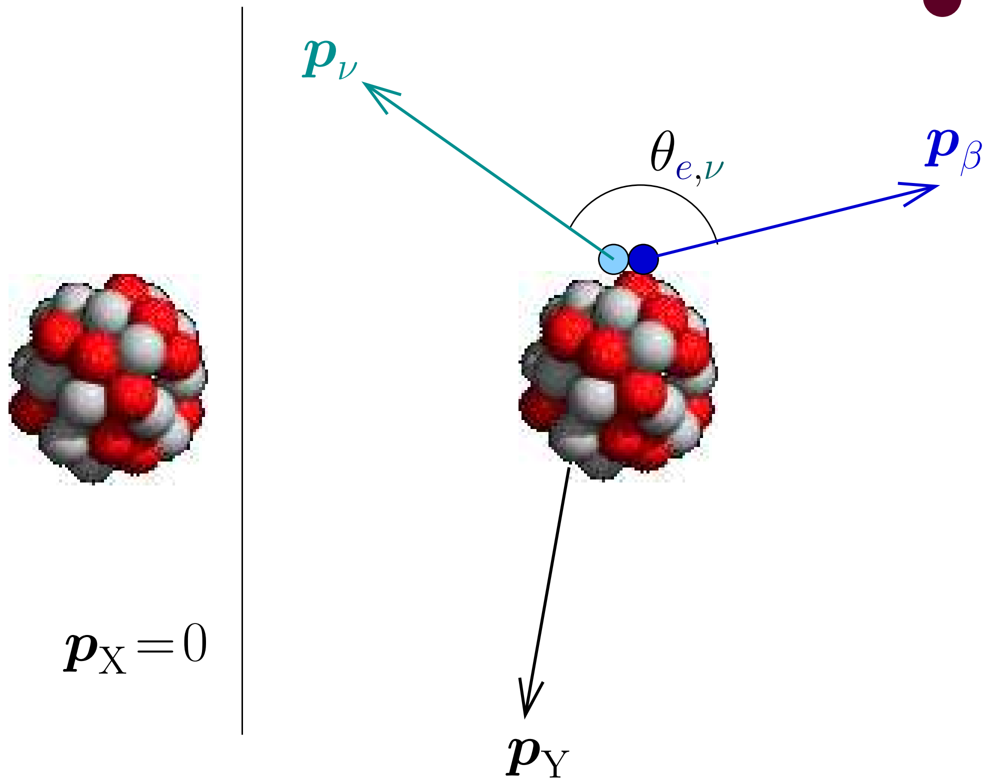
$\Rightarrow$ Precision measurements test the SM

Goal must be $\lesssim \mathbf{0.1\%}$

(see Profumo, Ramsey-Musolf and Tulin, PRD **75** (2007))

The Gameplan:

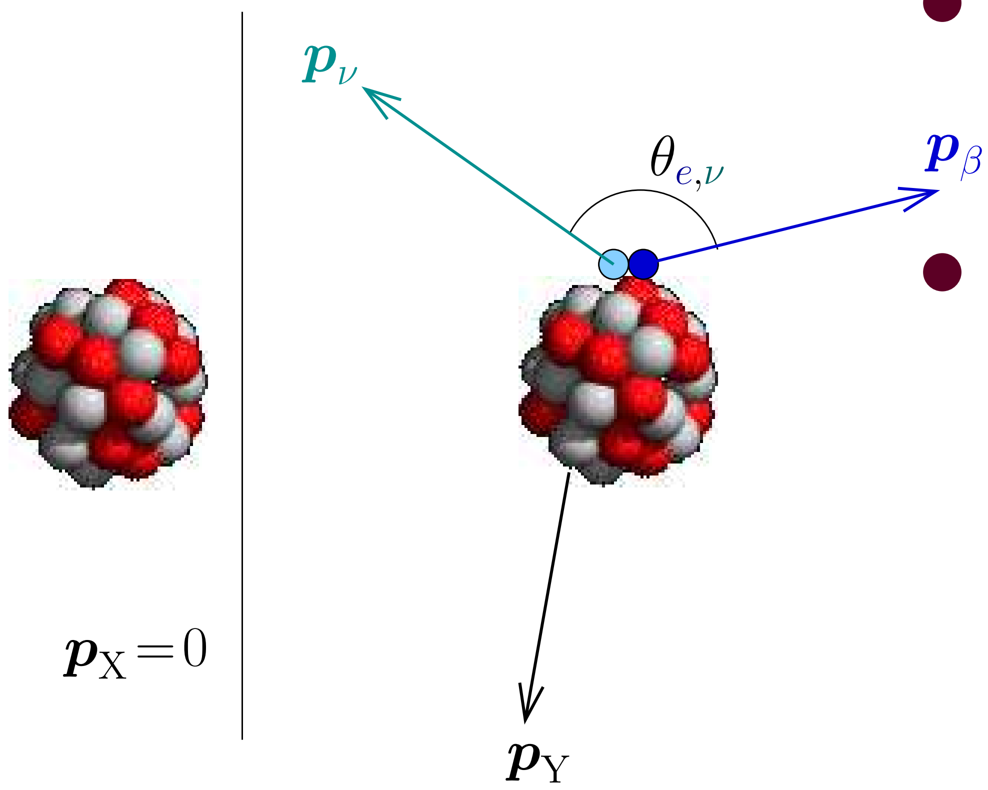
$${}^{Z}_{A}X \longrightarrow {}^{Z\mp1}_{\;\;A}Y + e^{\pm} + \nu_e$$



- perform a β decay experiment on short-lived isotopes

The Gameplan:

$${}^{Z}_{A}X \longrightarrow {}^{Z\mp 1}_{\quad A}Y + e^{\pm} + \nu_e$$



- perform a β decay experiment on short-lived isotopes
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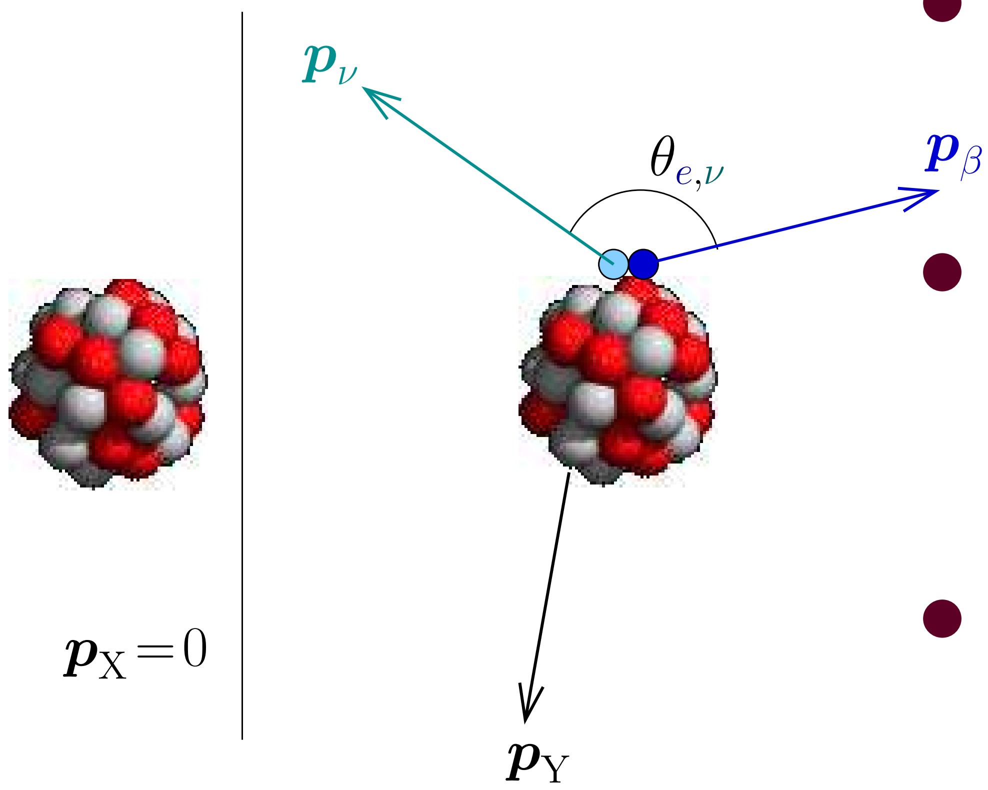
The Gameplan:

$${}^{Z}_{A}X \longrightarrow {}^{Z\mp1}{}_{A}Y + e^{\pm} + \nu_e$$



- perform a β decay experiment on short-lived isotopes
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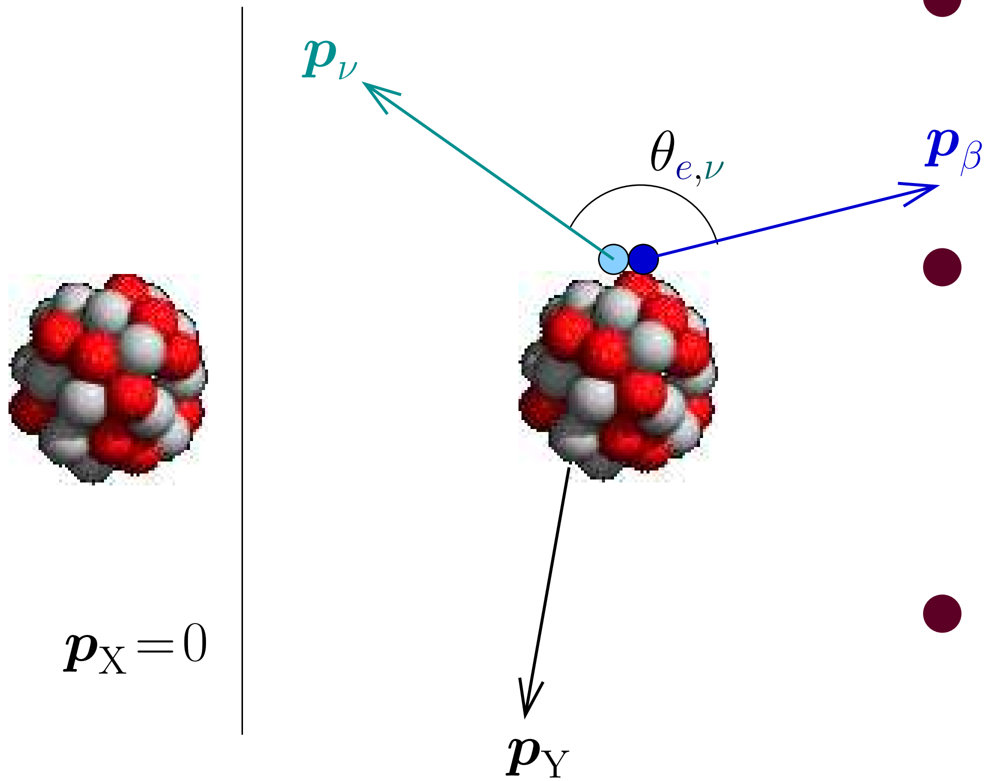
The Gameplan:

$$ {}^{Z}_{A}X \longrightarrow {}^{Z\mp1}{}_{A}Y + e^{\pm} + \nu_e $$



- perform a β decay experiment on short-lived isotopes
- make a precision measurement of the angular correlation parameters
- compare the SM predictions to observations
- look for deviations as an indication of new physics

Wu’s experiment

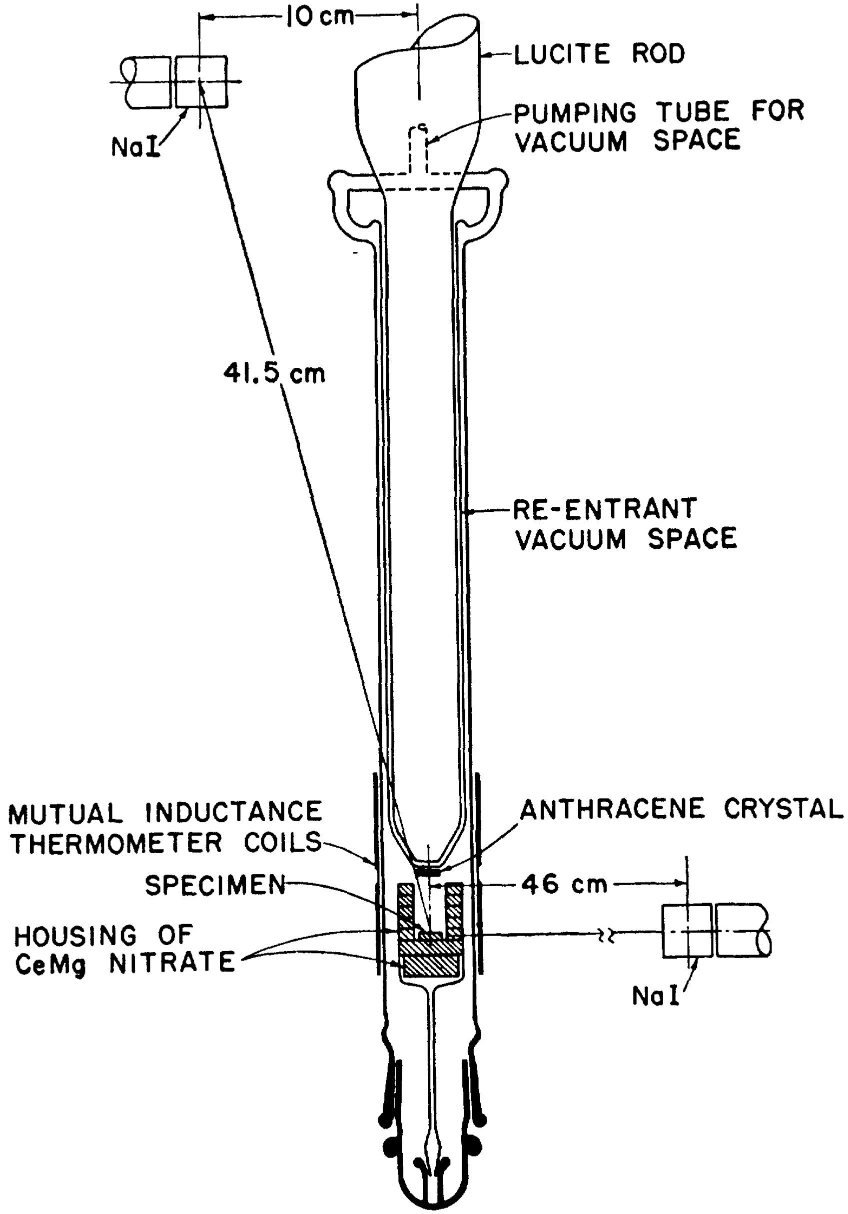
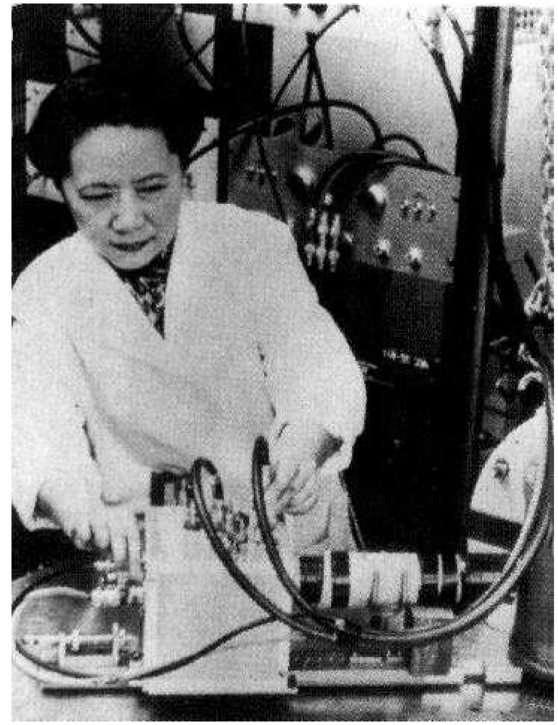
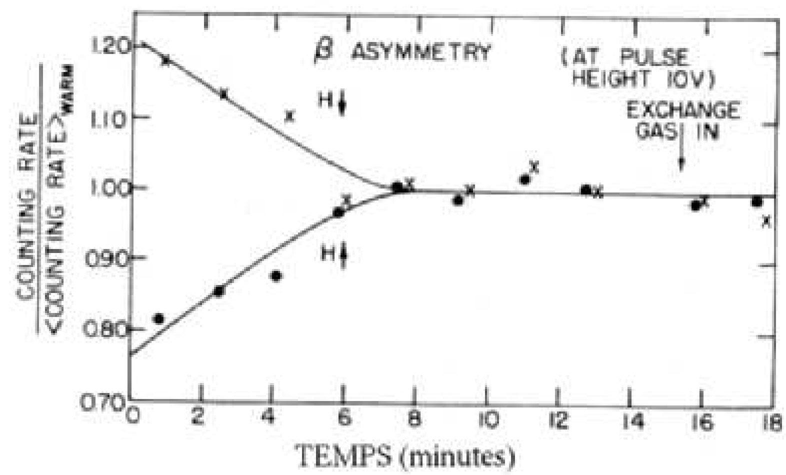


FIG. 1. Schematic drawing of the lower part of the cryostat.





Wu's experiment

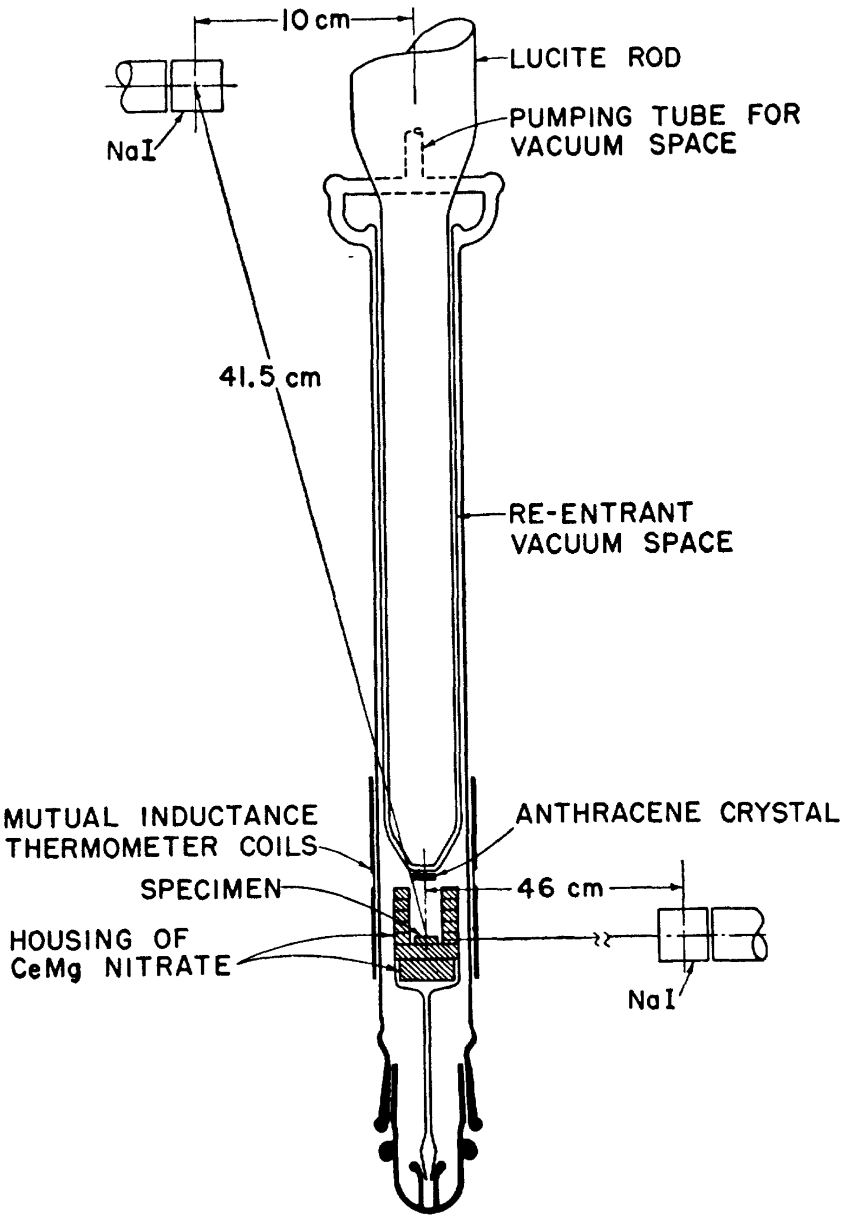
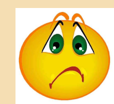
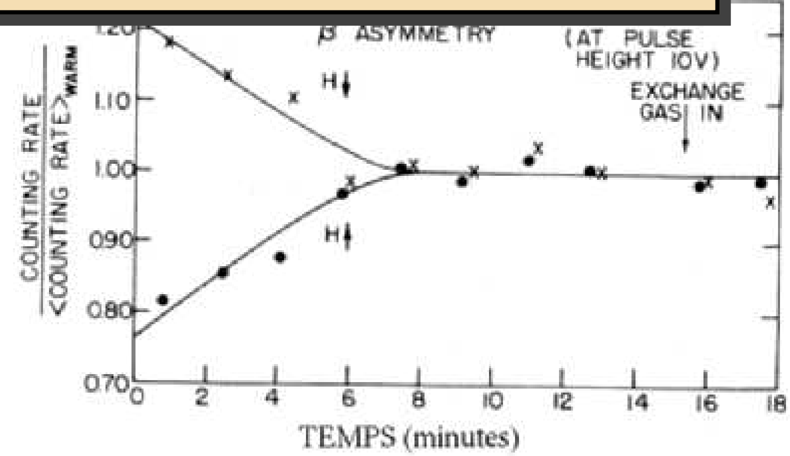


FIG. 1. Schematic drawing of the lower part of the cryostat.

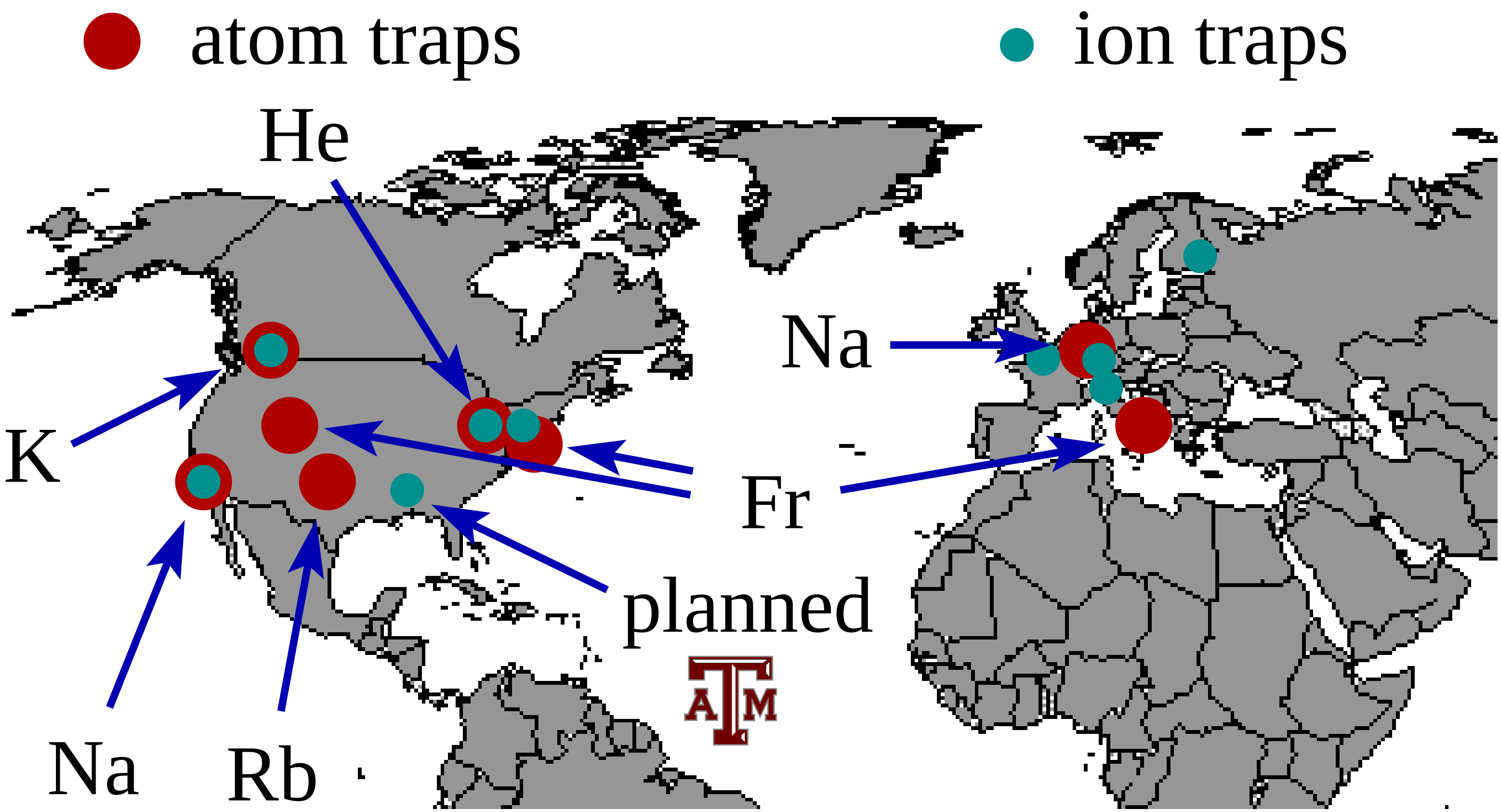
- so much scattering!
- low polarization
- short relaxation time
- poor sample purity
- pain to flip spin
- need long $t_{1/2}$





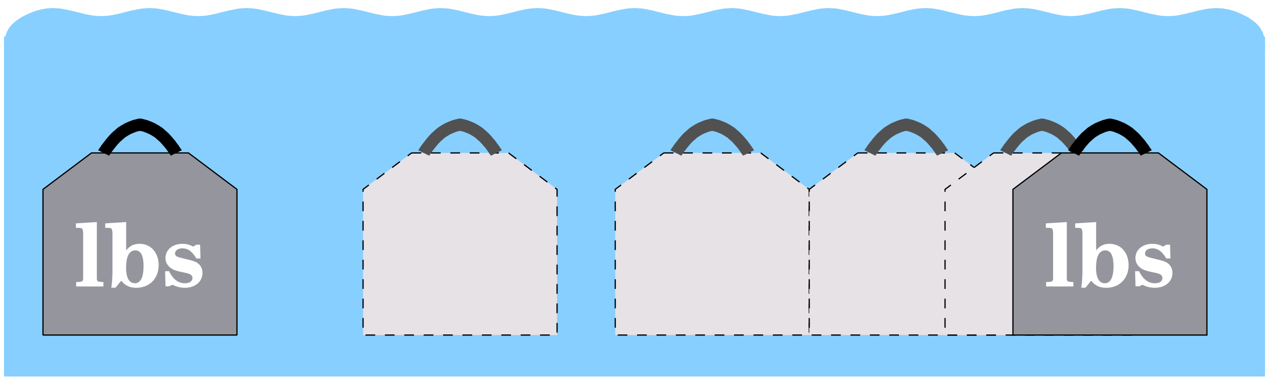
Traps around the world

Many groups around the world realize the potential of using traps for precision weak interaction studies



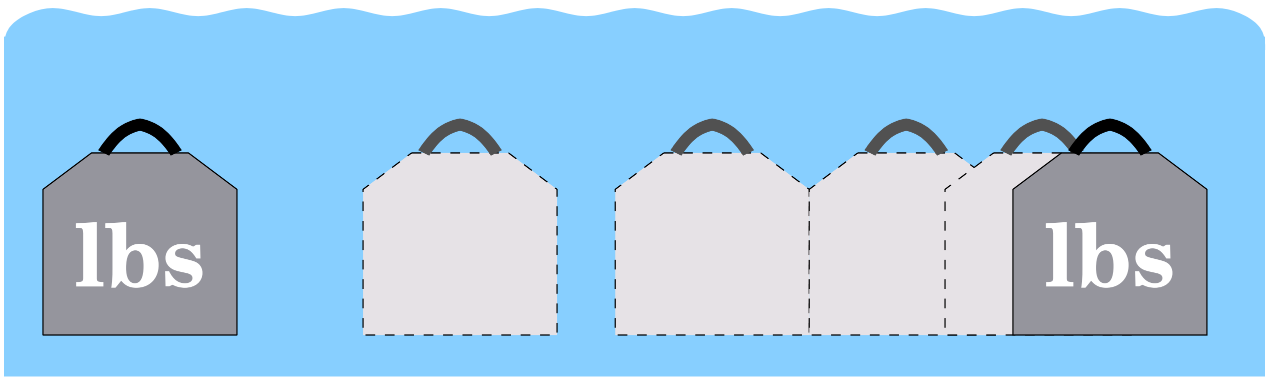
Neutral Atom Traps

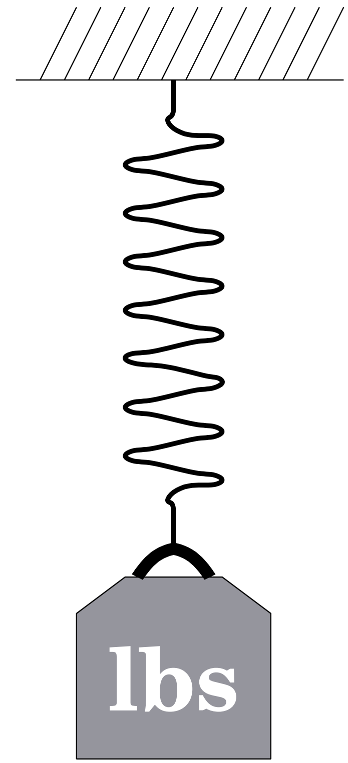
Any type of trap requires a velocity-dependent force to cool an object



Neutral Atom Traps

Any type of trap requires a velocity-dependent force to cool an object . . . as well as a position-dependent force that defines $x = 0$





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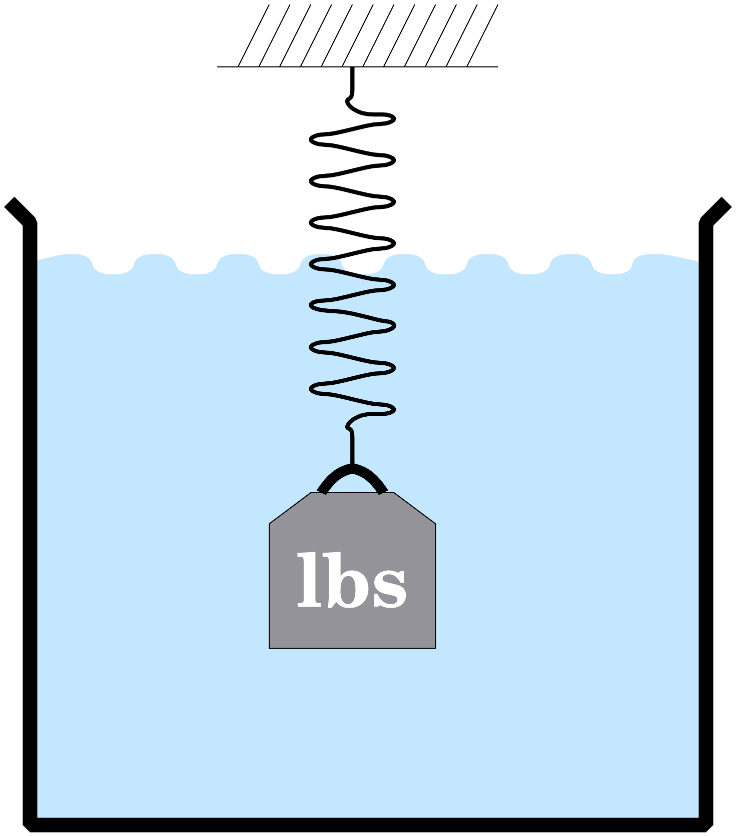


Laser light

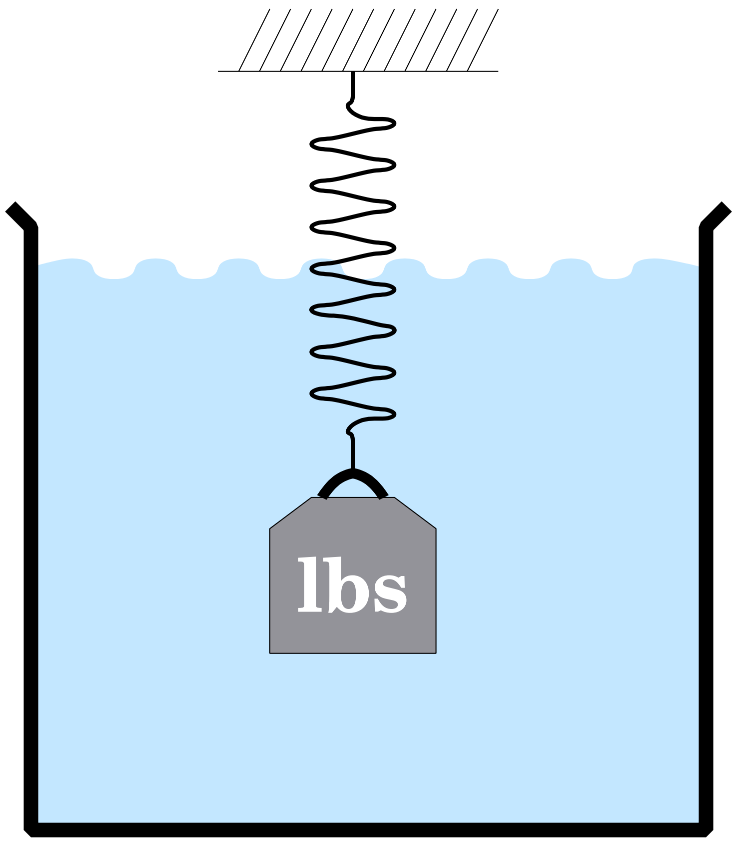
$\longrightarrow$ velocity-dependent force

Zeeman effect

$\longrightarrow$ position-dependent force

Neutral Atom Traps

Any type of trap requires a velocity-dependent force to cool an object . . . as well as a position-dependent force that defines $x = 0$



Laser light

$\longrightarrow$ velocity-dependent force

Zeeman effect

$\longrightarrow$ position-dependent force

$\Longrightarrow$ atom trap $=$ damped harmonic oscillator $\Longleftarrow$

Atom-Photon Interactions

How can light seriously affect a thermal atom?

vs.

$$\hbar c \cdot \frac{2\pi}{\lambda} = (197.3 \text{ MeV fm})(\tfrac{6.28}{770 \text{ nm}})$$
$$= 1.6 \times 10^{-6} \text{ MeV}$$

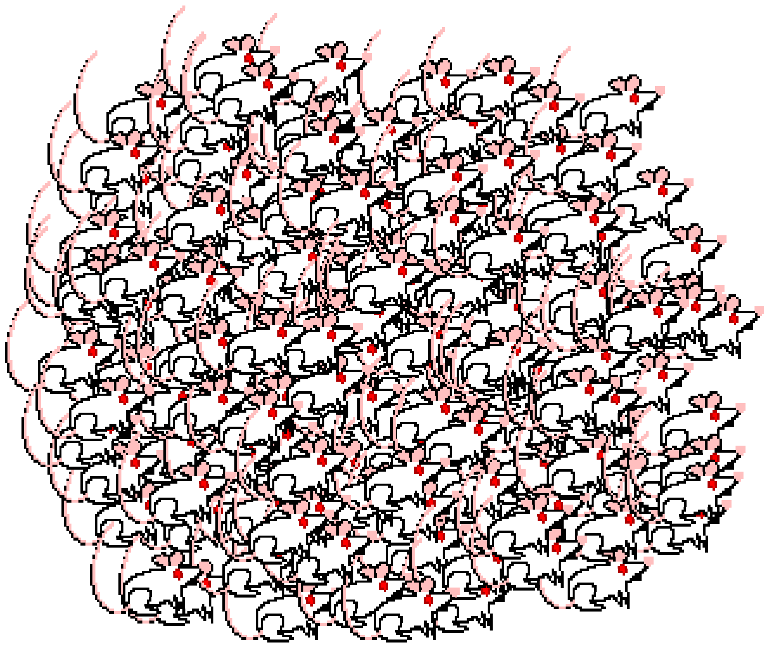
$$\Rightarrow \boxed{\hbar \boldsymbol{k} \sim 1.6 \text{ eV/c}}$$

$$\tfrac{1}{2} M v^2 = k_B T$$
$$M\boldsymbol{v} = \Big[2(40 \times 10^6 \text{ keV/c}^2)(8.62 \times 10^{-8} \text{ keV/K})(295 \text{ K})\Big]^{1/2}$$

$$\Rightarrow \boxed{M\boldsymbol{v} \sim 45 \text{ keV/c}}$$

Atom-Photon Interactions

Cycling Transitions!



vs.

$$\hbar\boldsymbol{k} \times 30,000 \approx M\boldsymbol{v}$$

However. . . .

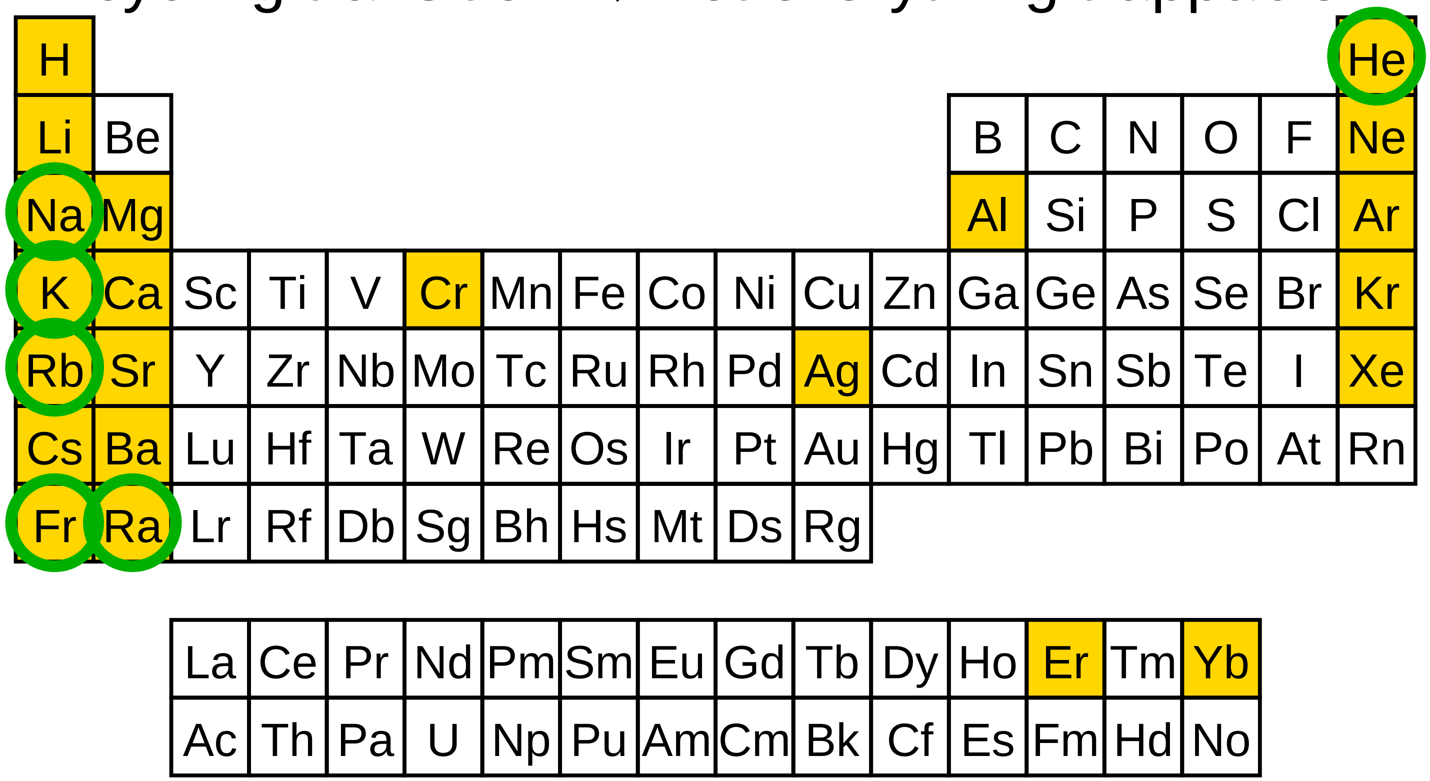
cycling transition $\Rightarrow$ not everything trappable

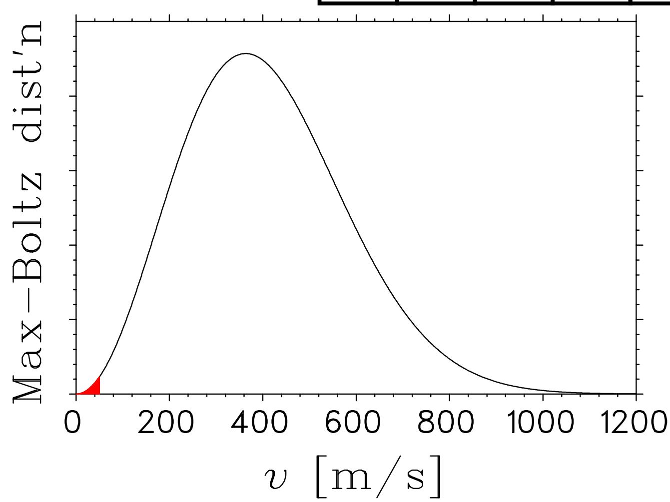
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg							

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Hd	No

However. . . .

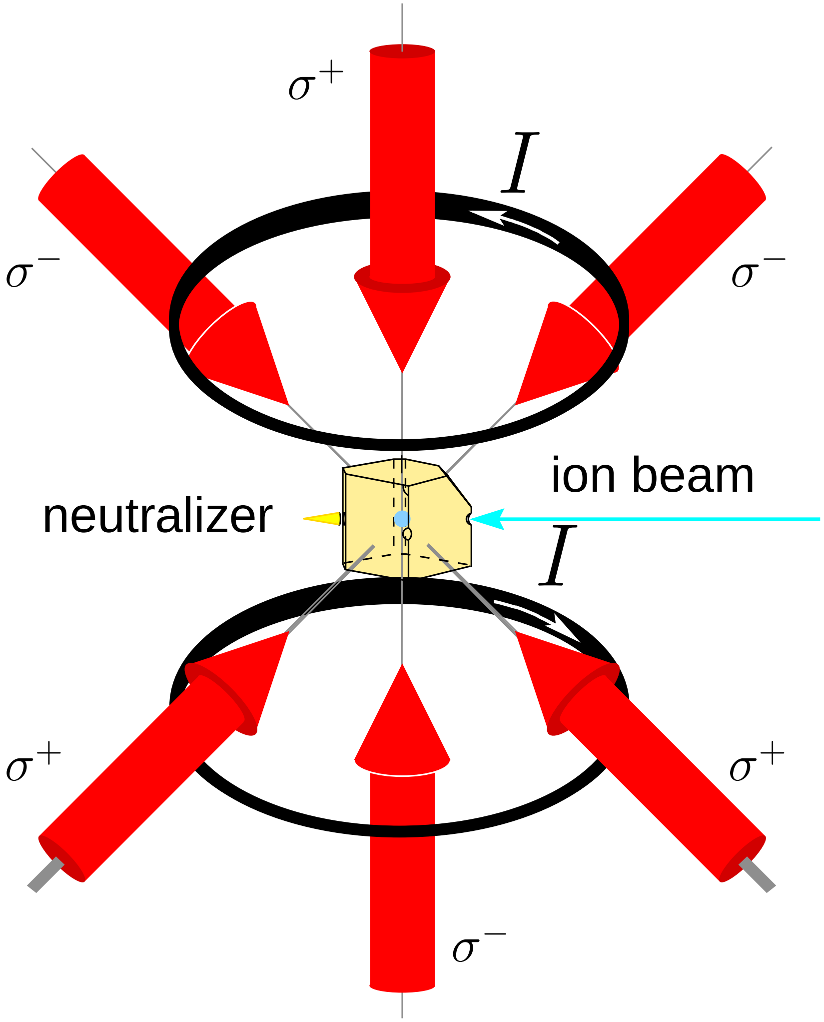
cycling transition ⇒ not everything trappable





and ***still*** the trap is shallow. . .

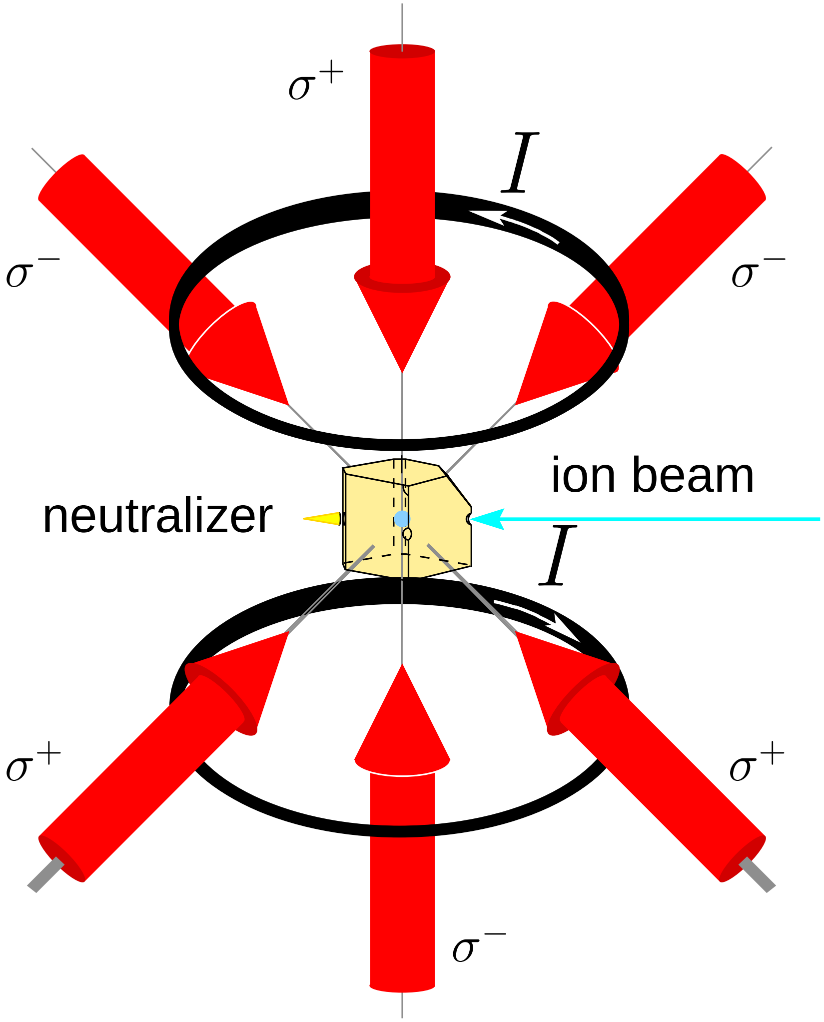
Still, gotta love it!!



Raab PRL **59** (1987)

- iso*merically* selective!

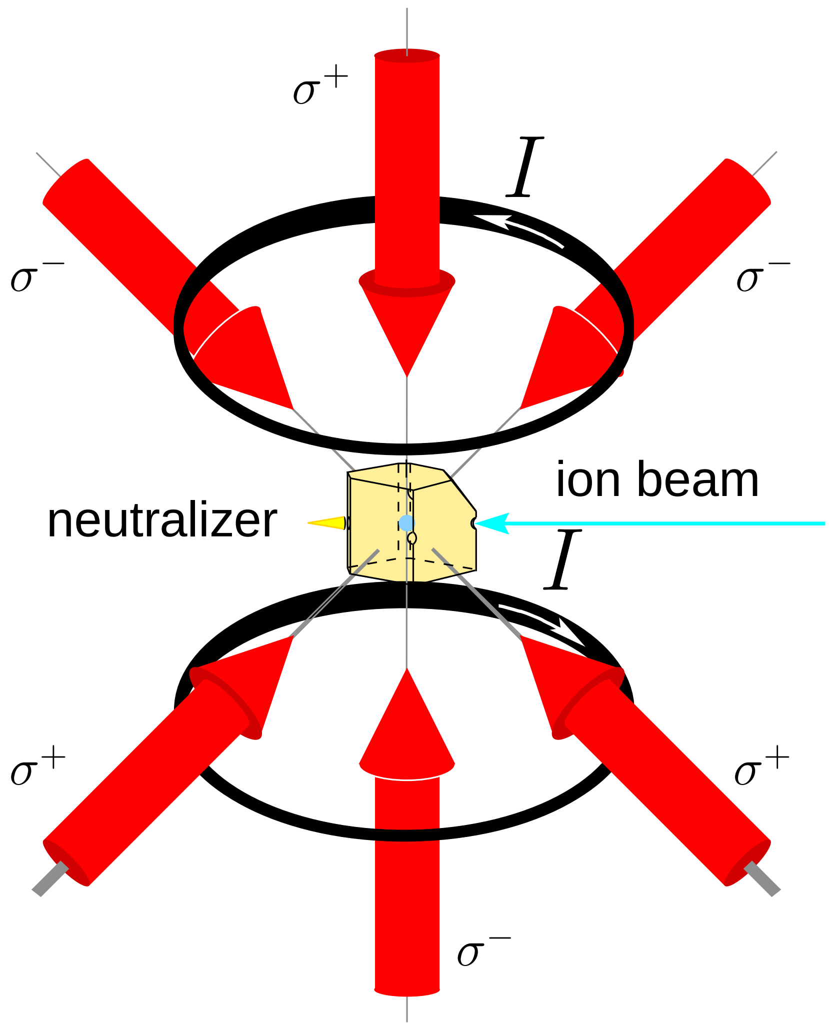
Still, gotta love it!!



Raab PRL **59** (1987)

- iso*merically* selective!
- point-like source!
  ($\lesssim 1$ mm^3 FWHM)

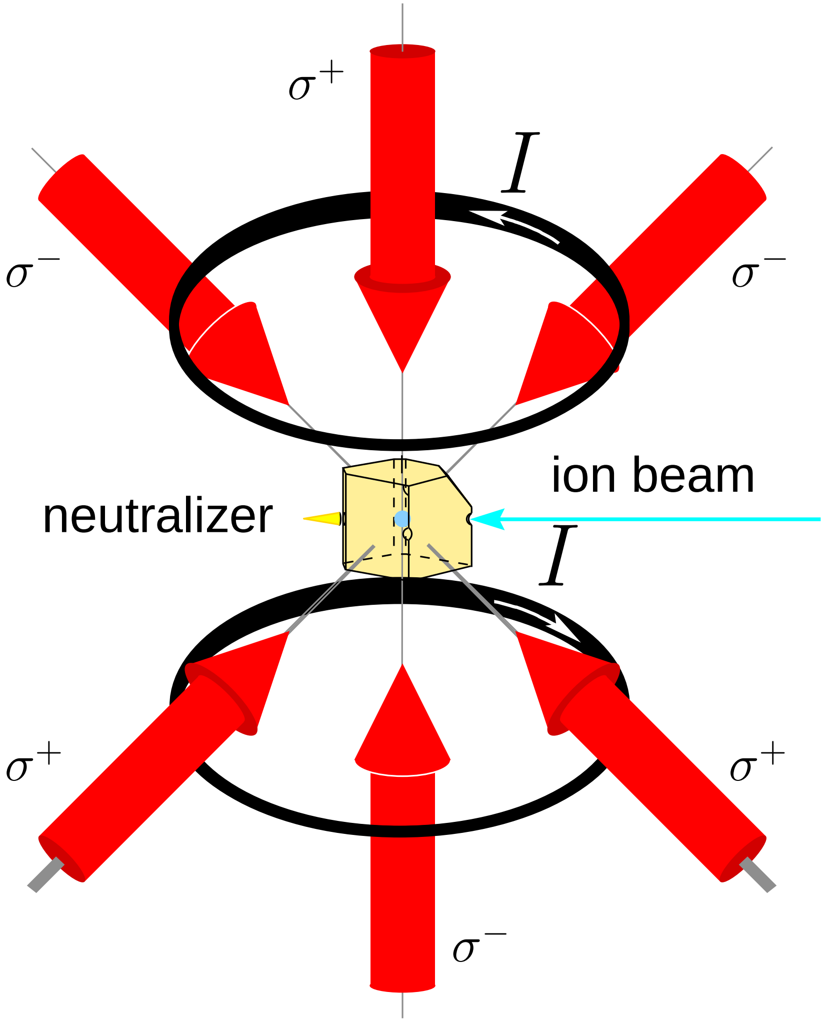
Still, gotta love it!!



Raab PRL **59** (1987)

- iso*merically* selective!
- point-like source! ($\lesssim 1$ mm^3 FWHM)
- cold atoms! ($\lesssim 1$ mK)

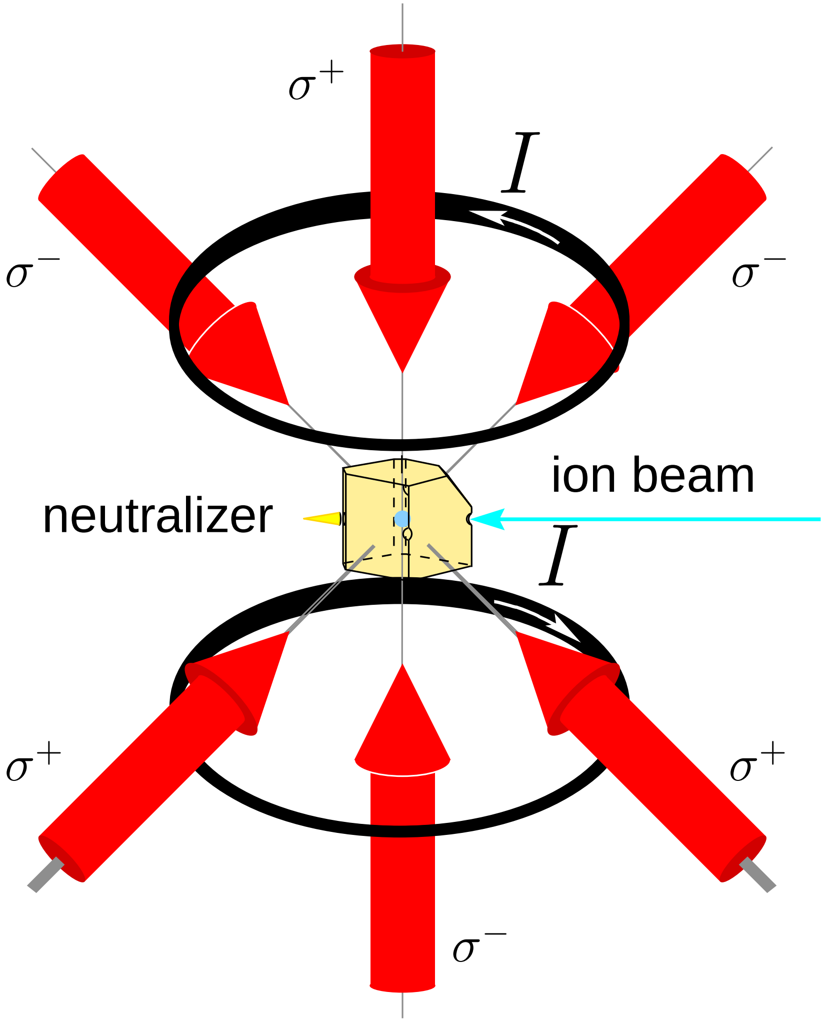
Still, gotta love it!!



Raab PRL **59** (1987)

- iso*merically* selective!
- point-like source! ($\lesssim 1$ mm^3 FWHM)
- cold atoms! ($\lesssim 1$ mK)
- backing-free source!

Still, gotta love it!!

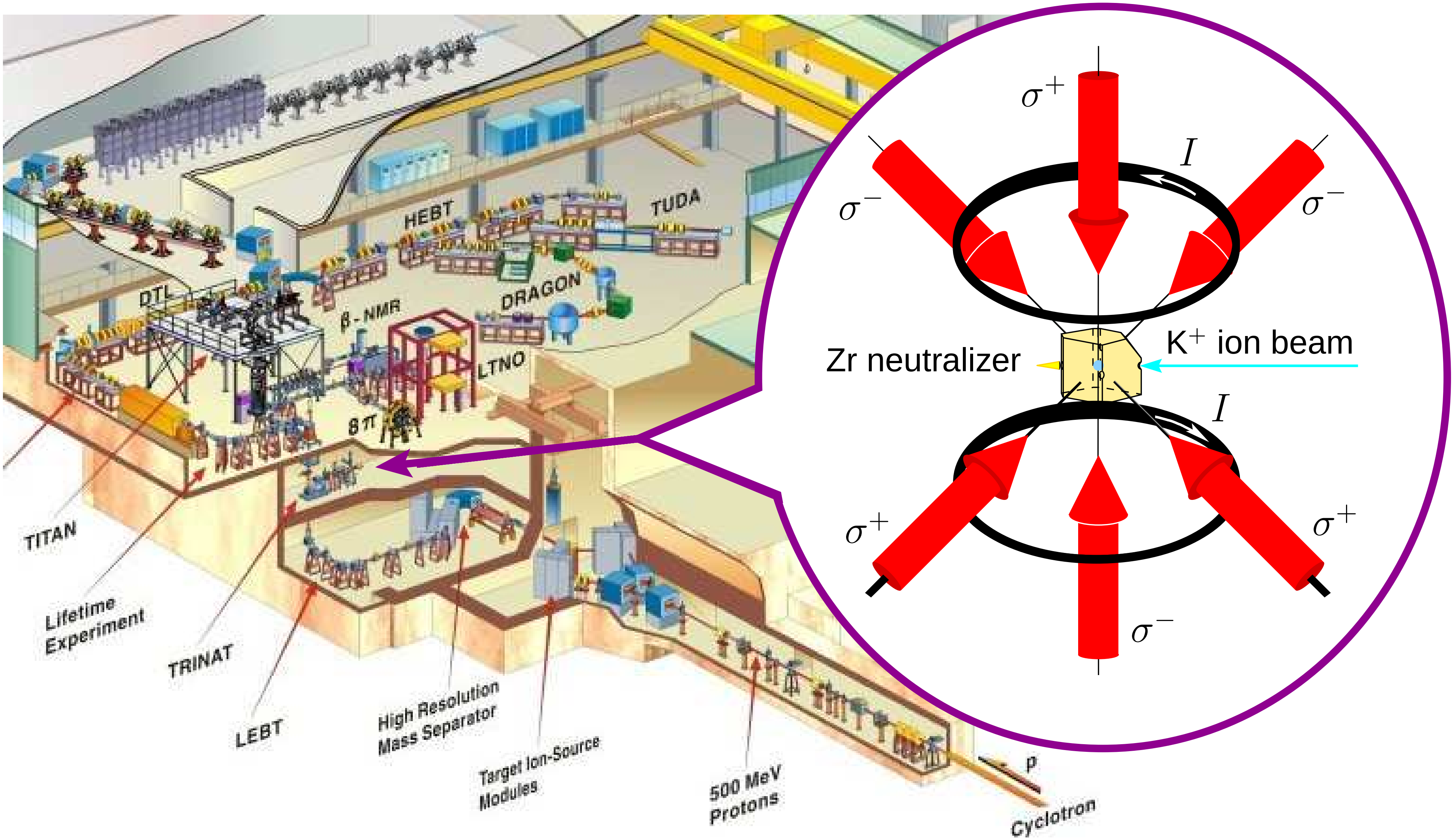


- iso*merically* selective!
- point-like source! ($\lesssim 1$ mm^3 FWHM)
- cold atoms! ($\lesssim 1$ mK)
- backing-free source!

Raab PRL **59** (1987)

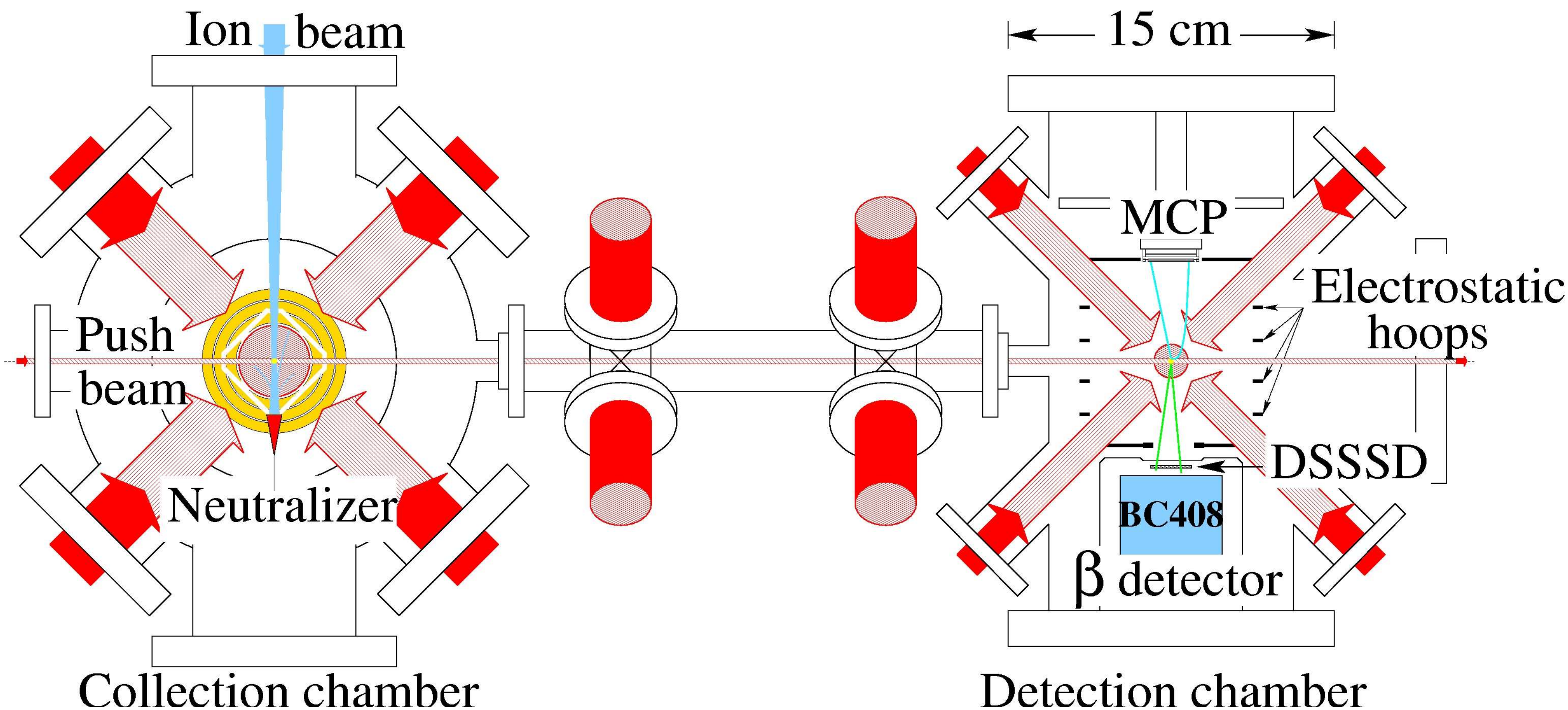
an **ideal** source of radioactives for β-decay experiments!

Coupling a MOT to ISAC-I

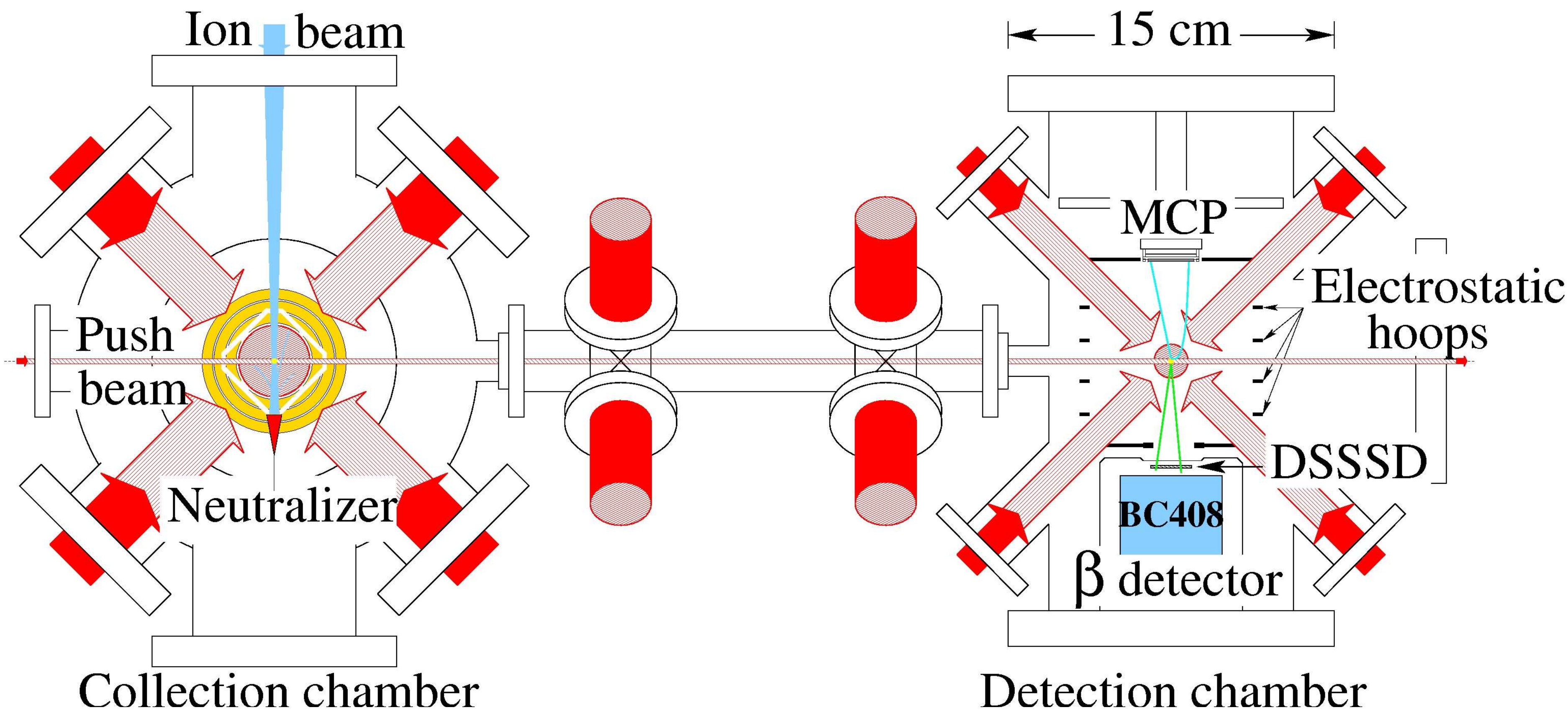


^{37}K yield with 40 μA on TiC #1: 6×10^7/s

Double-MOT system



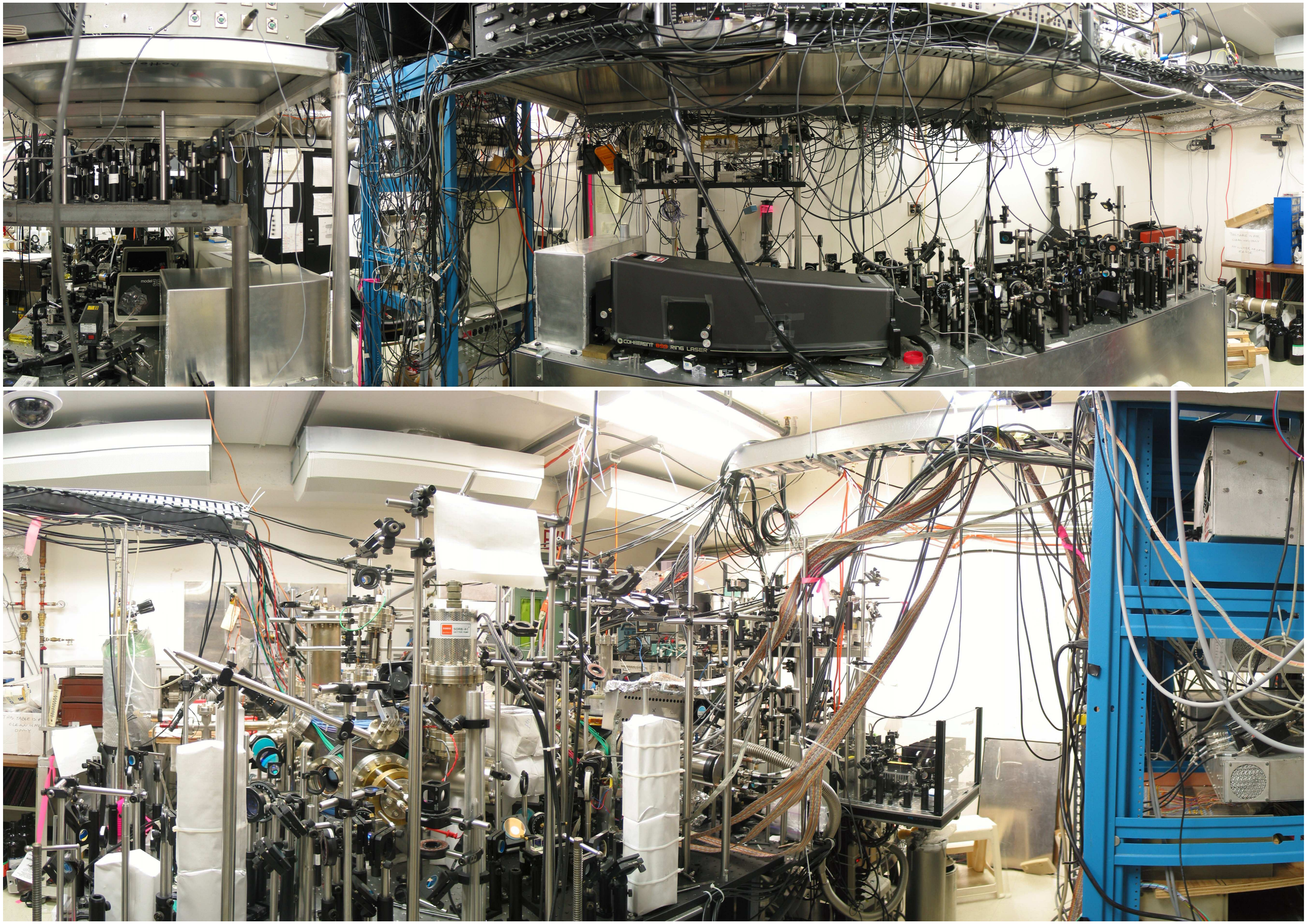
Double-MOT system



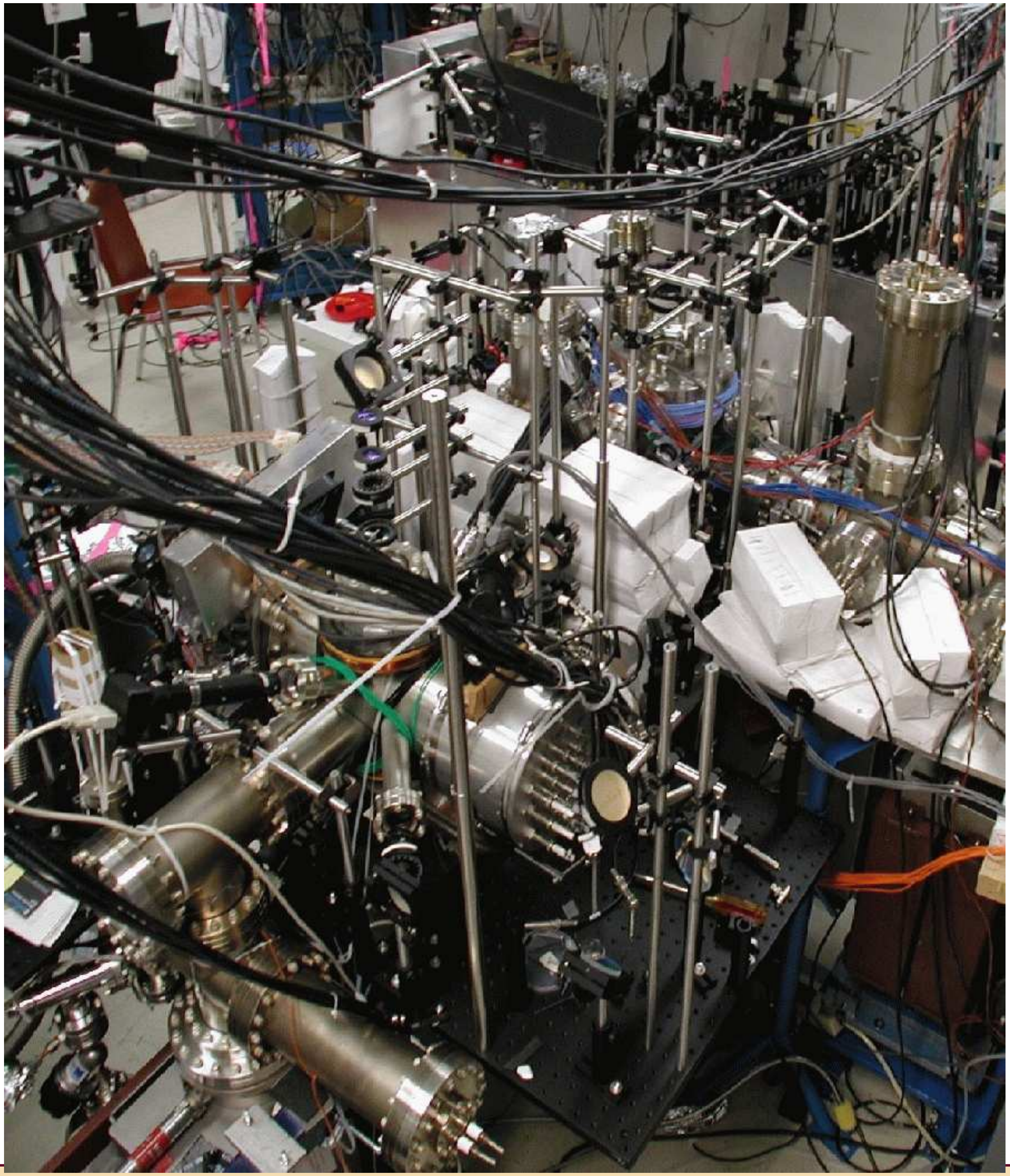
Traps provide a backing-free, cold ($\lesssim 1$ mK), localized ($\lesssim 1\,\mathrm{mm}^3$) source of short-lived radioactive atoms

Detect $\boldsymbol{p}_\beta$ *and* $\boldsymbol{p}_{\rm recoil}$ $\Rightarrow$ deduce $\boldsymbol{p}_\nu$!

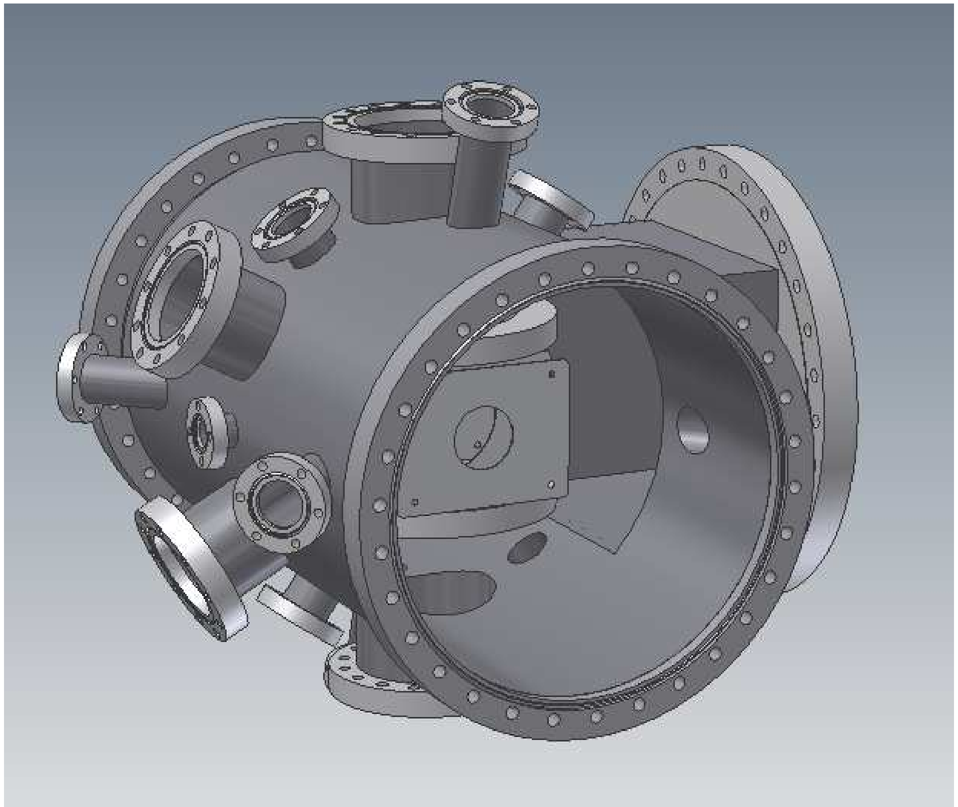
The TRINAT lab

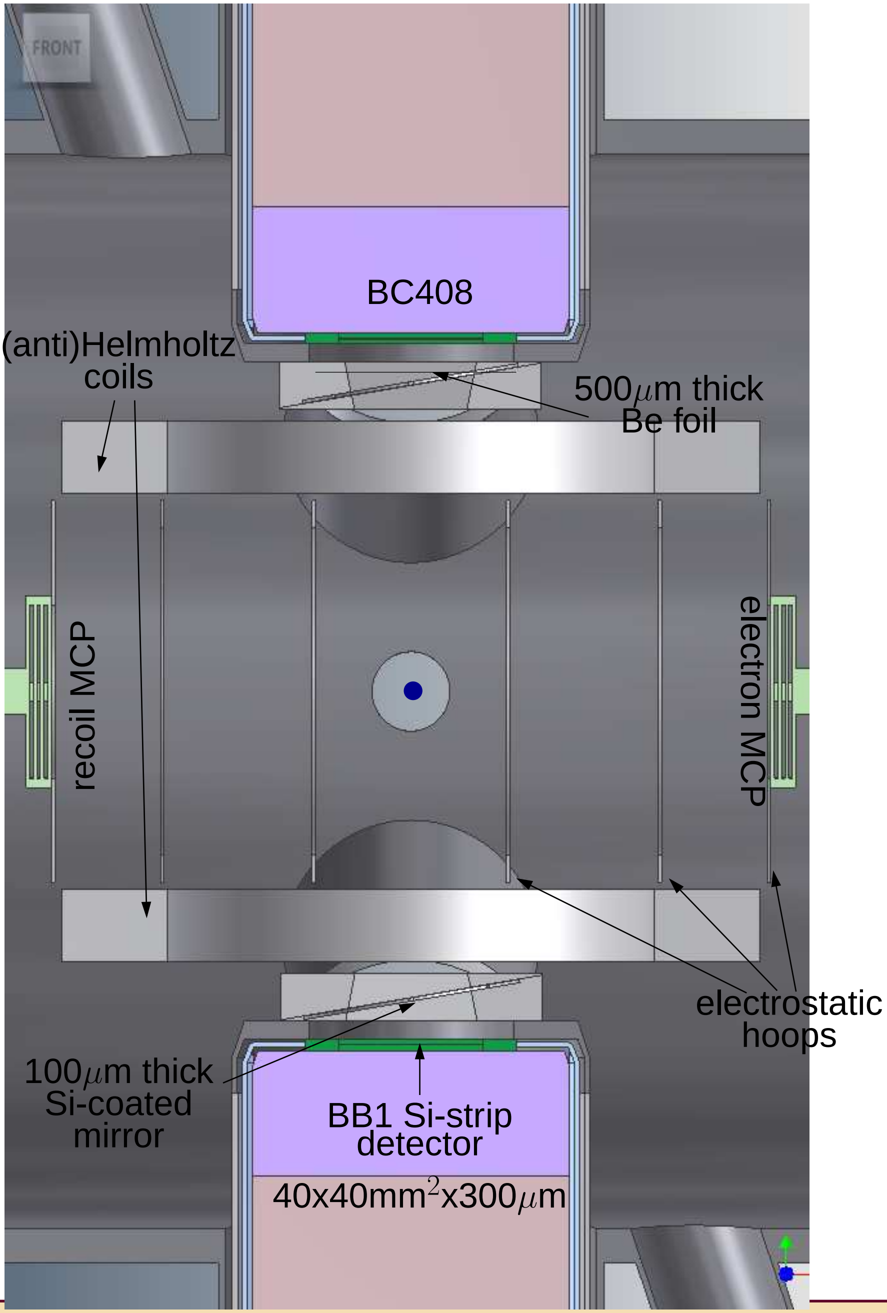


The TRINAT lab



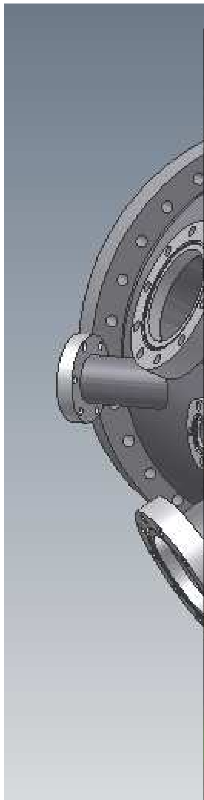
The new chamber

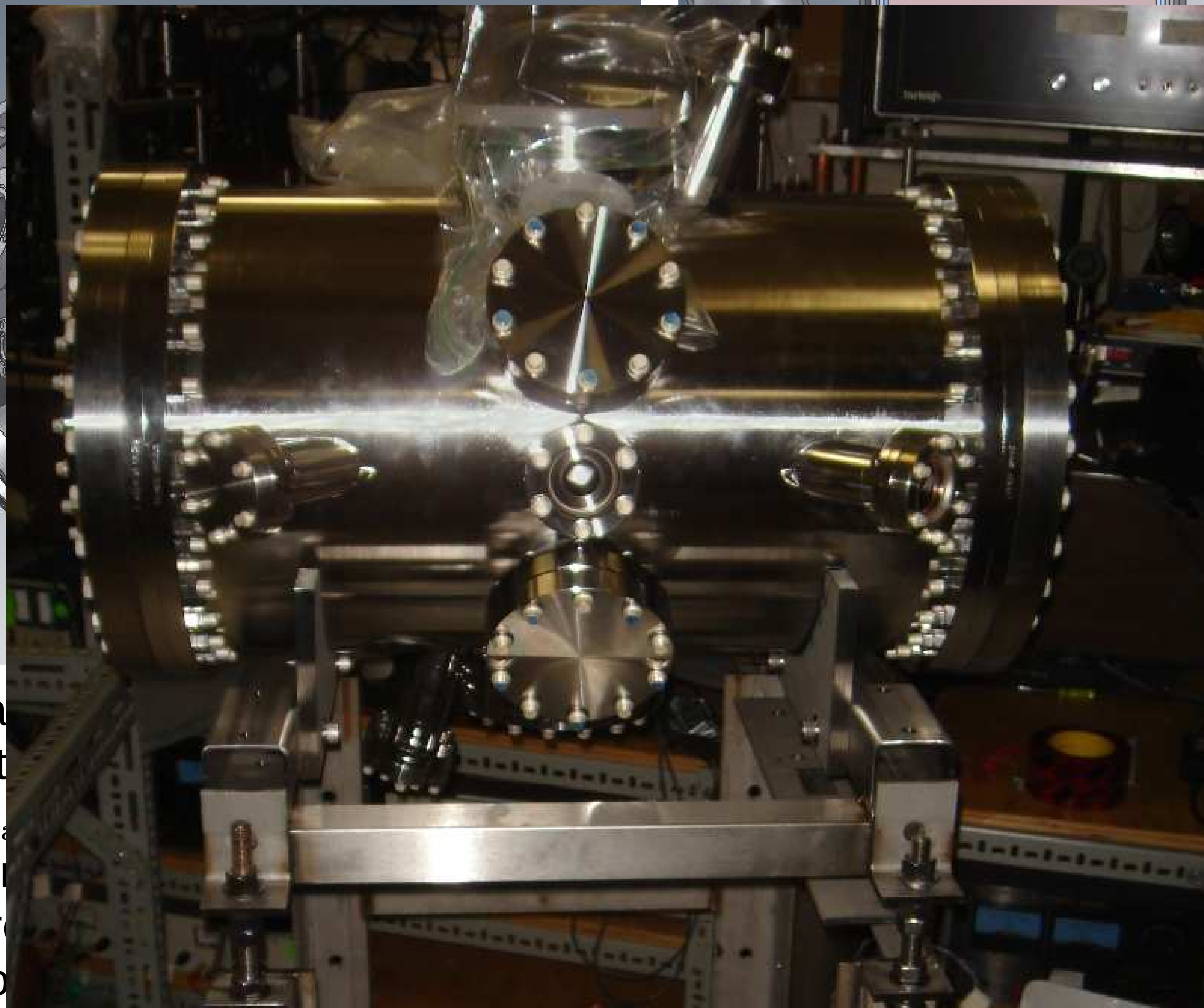


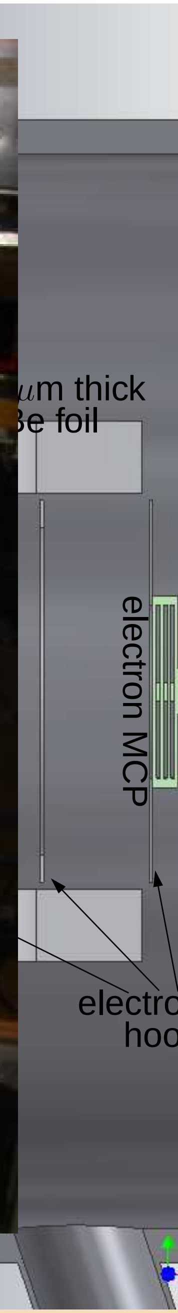


- Shake-off e^- detection
- Better control of OP beams
- $B_{\text{quad}} \rightarrow B_{\text{OP}}$ quickly: AC-MOT (Harvery & Murray, PRL **101** (2008))
- Increased β/recoil solid angles
- Stronger E-field
- ...

The new chamber

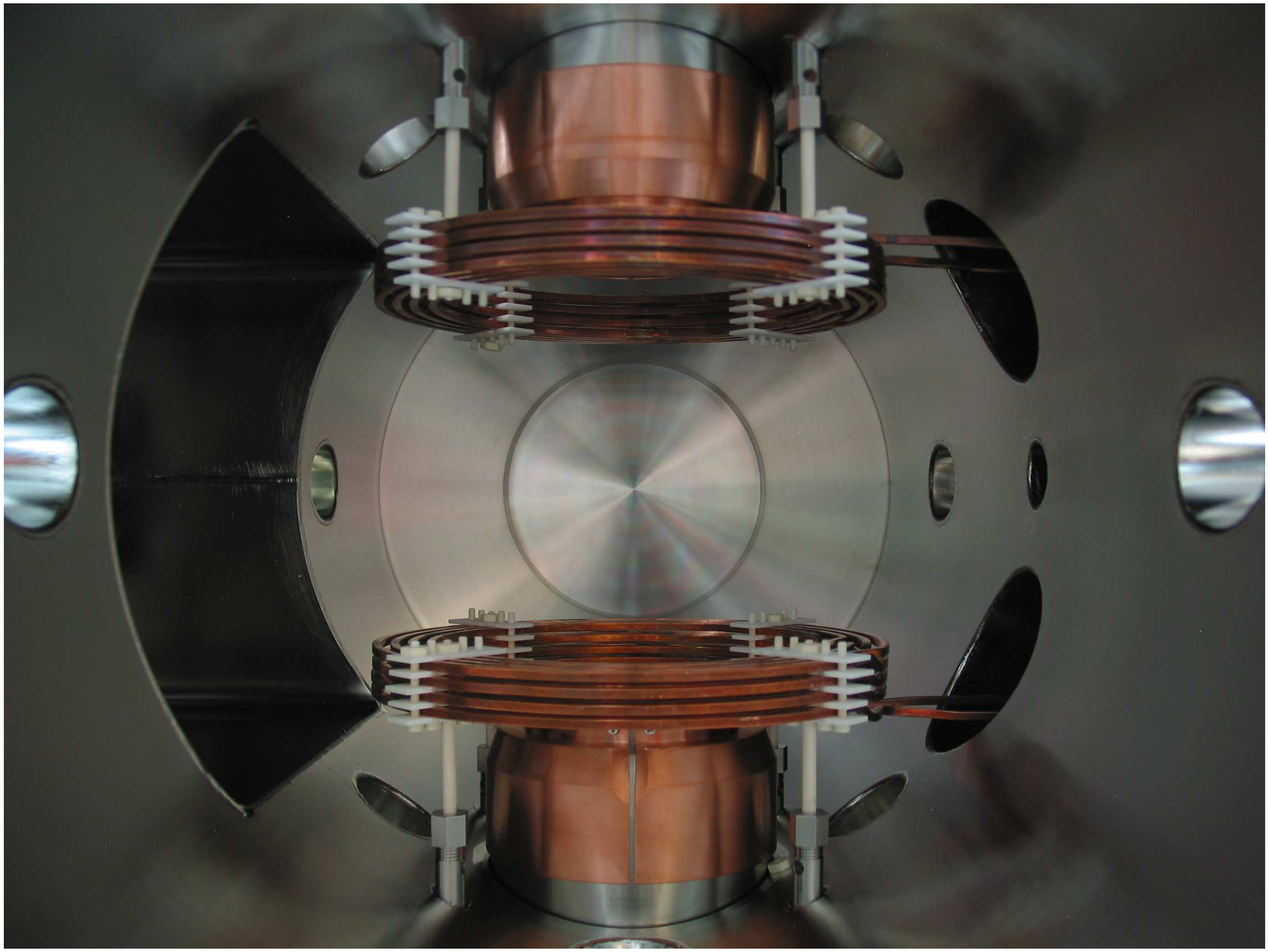




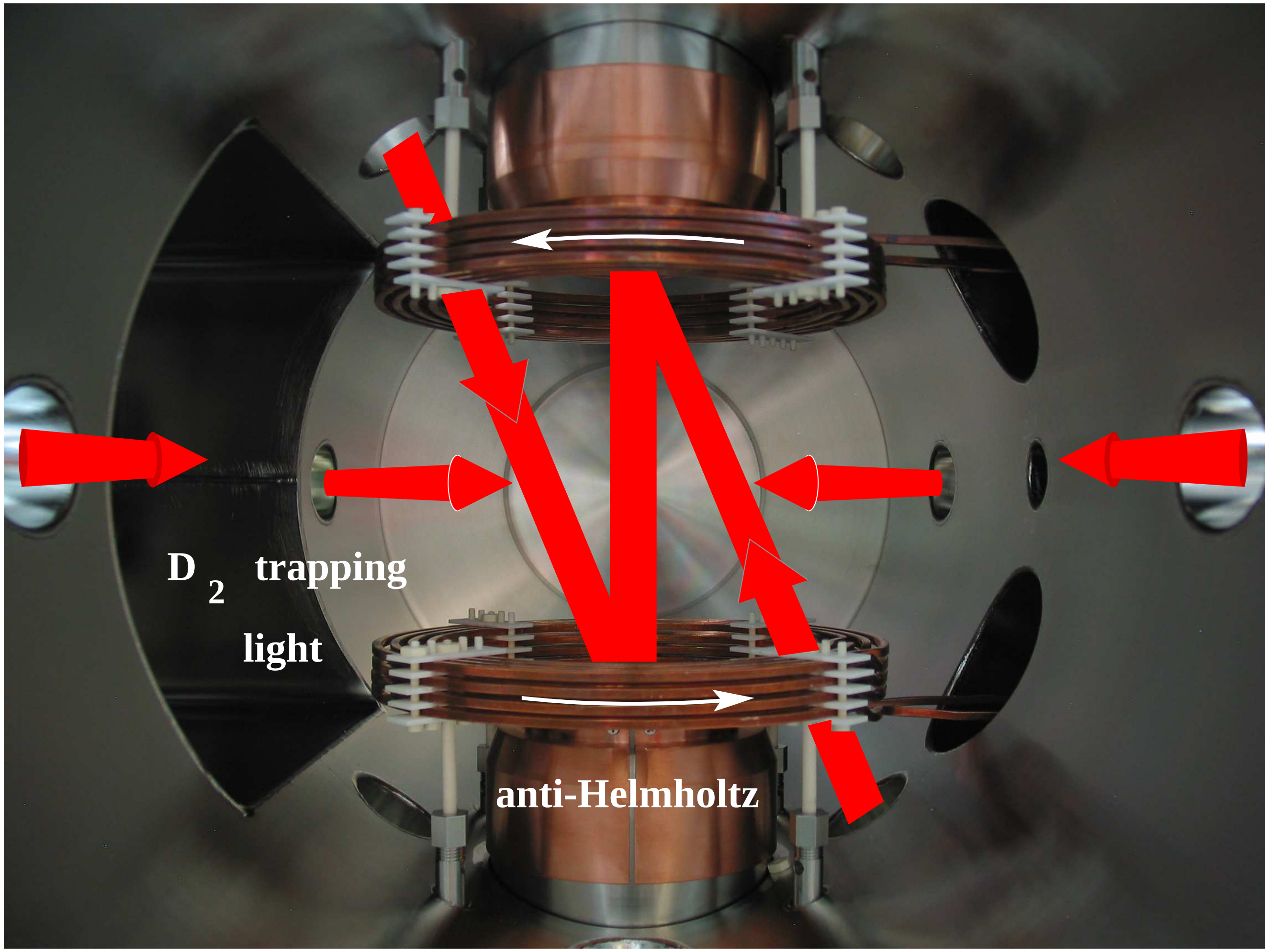


- Sha
- Bett
- B_{qua}
  (Har
- Incr
- Stro
- . . .

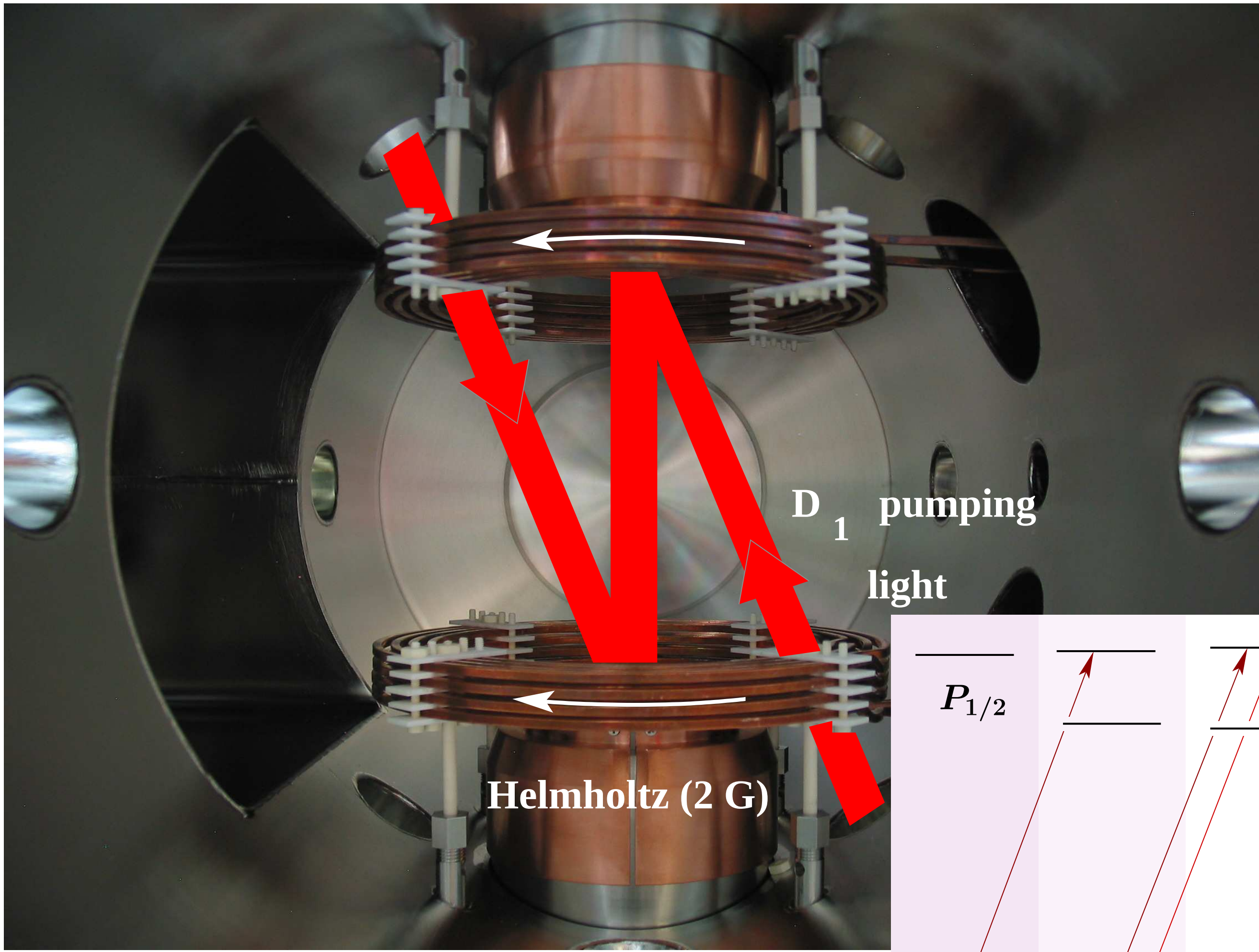
Outline of polarized experiment

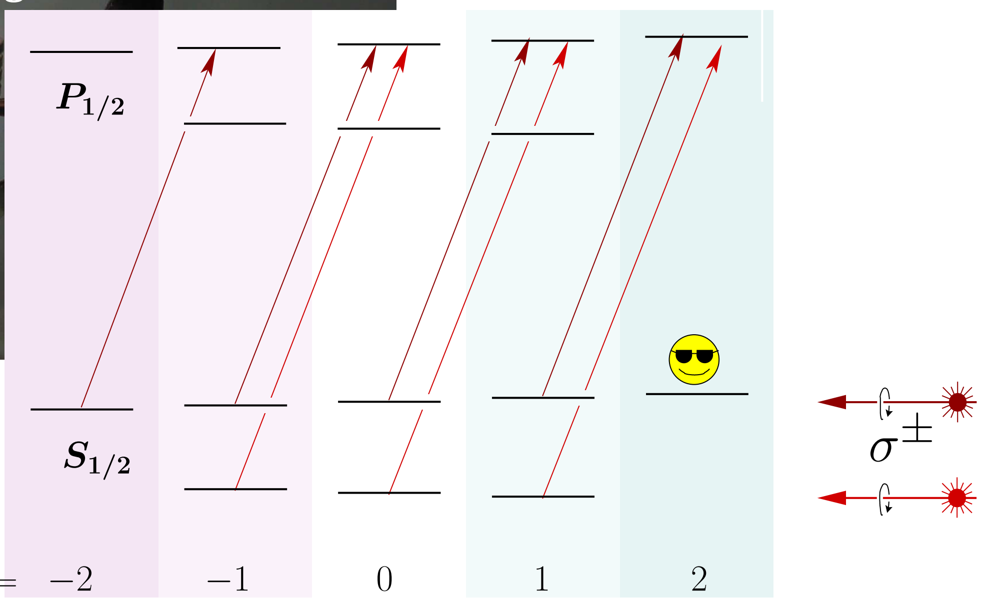


Outline of polarized experiment



Outline of polarized experiment



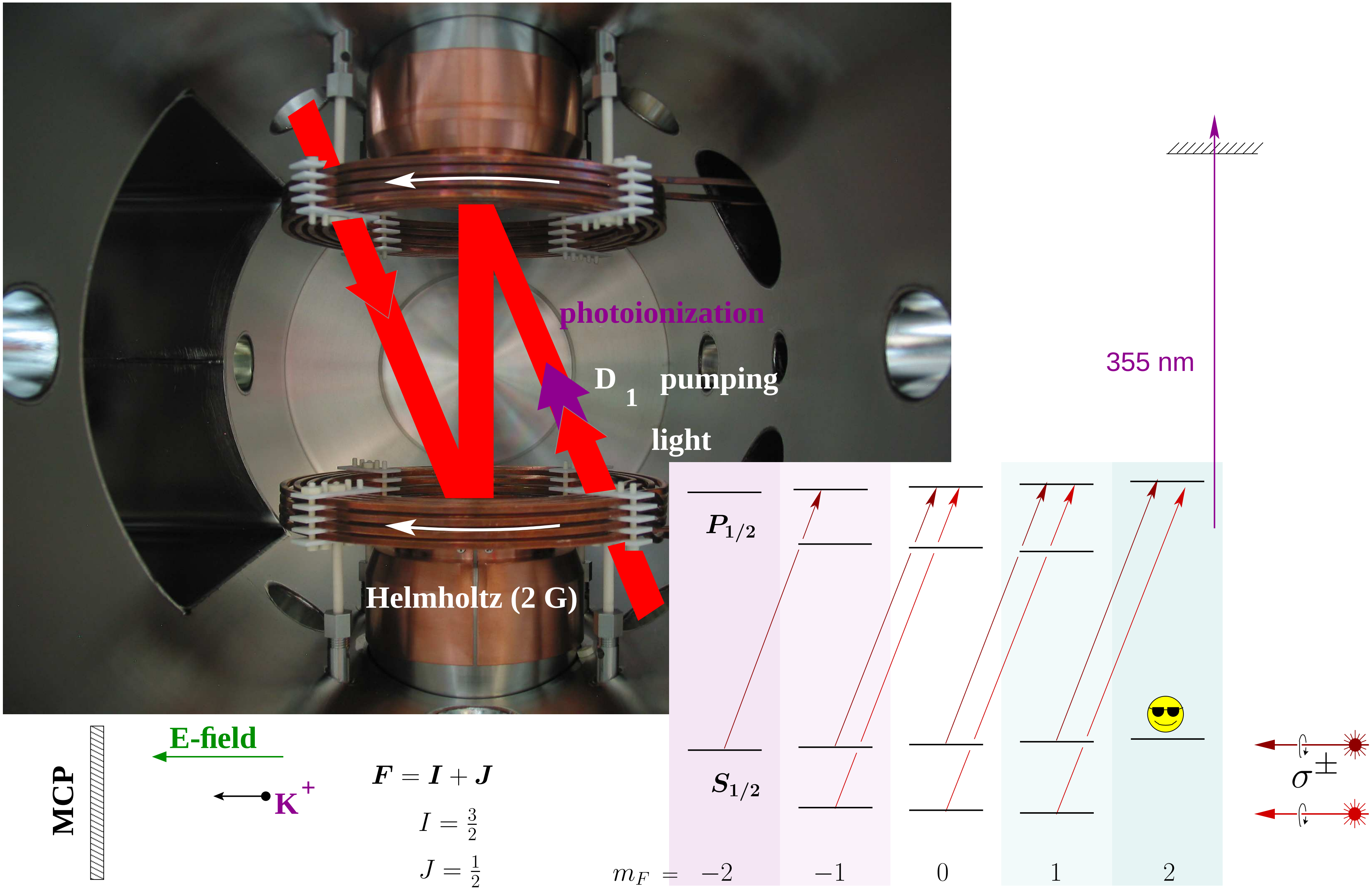


$$\boldsymbol{F} = \boldsymbol{I} + \boldsymbol{J}$$

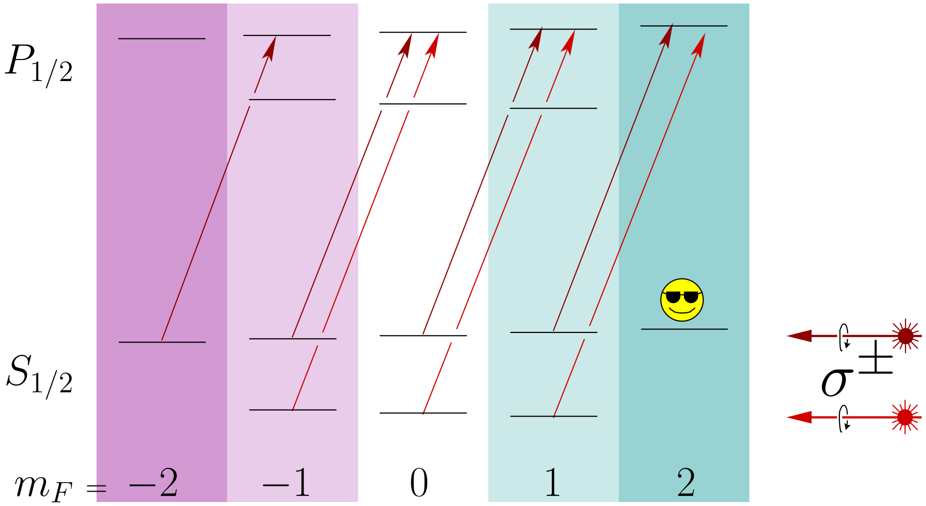
$$I = \tfrac{3}{2}$$

$$J = \tfrac{1}{2}$$

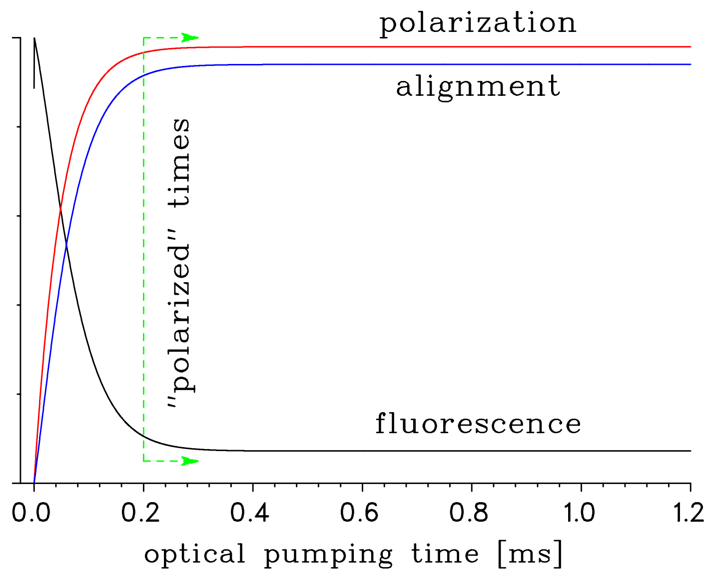
Outline of polarized experiment

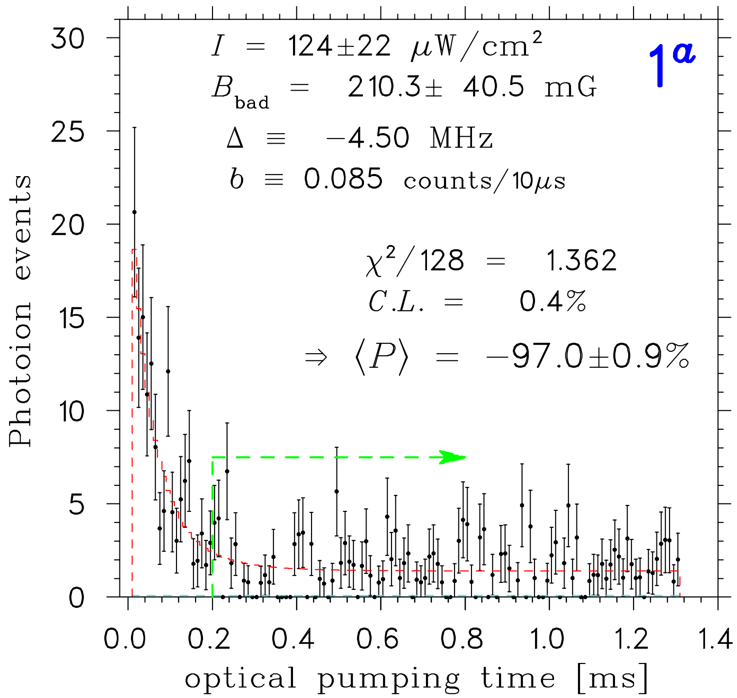


Atomic measurement of P



deduce P based on a model of the excited state populations:





$$\Rightarrow P_{\text{nucl}} = 96.74 \pm 0.53^{+0.19}_{-0.73}$$

Atomic measurement of P

$P_{1/2}$

$S_{1/2}$

$m_F =$

e

PRL **101,** 173201 (2008) PHYSICAL REVIEW LETTERS week ending 24 OCTOBER 2008

for MOT currents rapidly switched to zero, the induced eddy currents continue to produce **B** fields until they too reduce to zero.

In practice the **B** field due to the MOT takes ~10 ms to reduce to $<10^{-7}$ T, this time depending on the proximity of conductors to the coils, their shape, and resistivity. During this time, a large fraction of trapped atoms escape, resulting in a cold atom density that rapidly falls to zero. Losses can be reduced by leaving the cooling lasers on to create an optical molasses (if this does not interfere with the experiment); however, the loss problems remain. The comparatively long time taken for the **B** field to decay also reduces data accumulation rates, since the repetition rate is then only ~50 Hz.

It is clearly advantageous to eliminate these constraints. Several methods have been attempted, including shaping the dc MOT driving current at switchoff to try to cancel fields due to eddy currents [10]. This technique is complicated and requires different currents when spectrometer

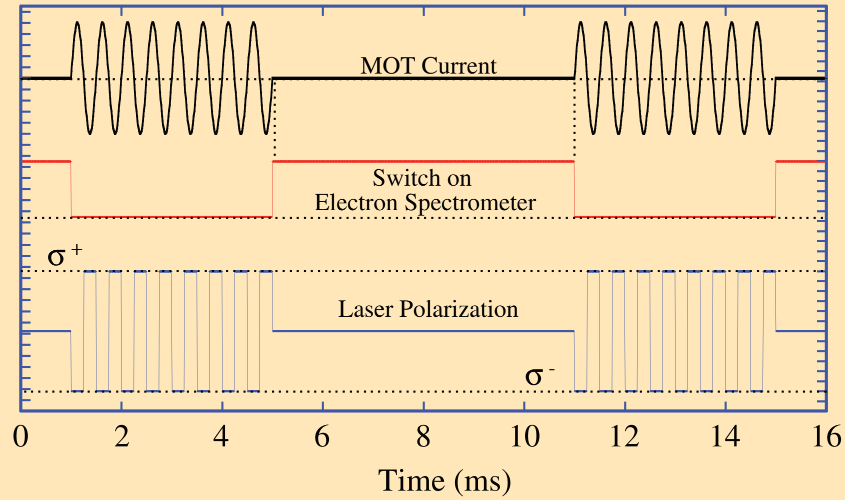
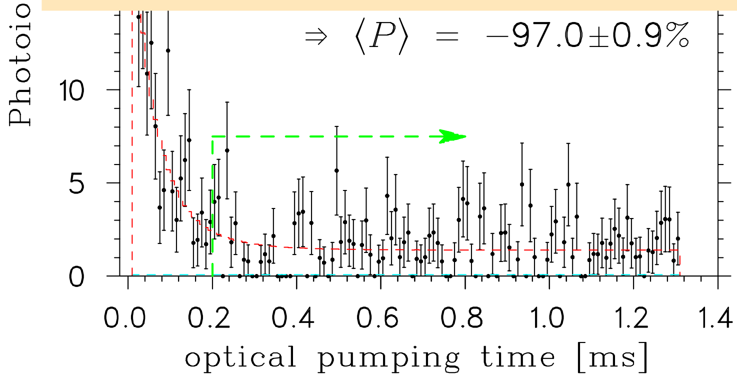
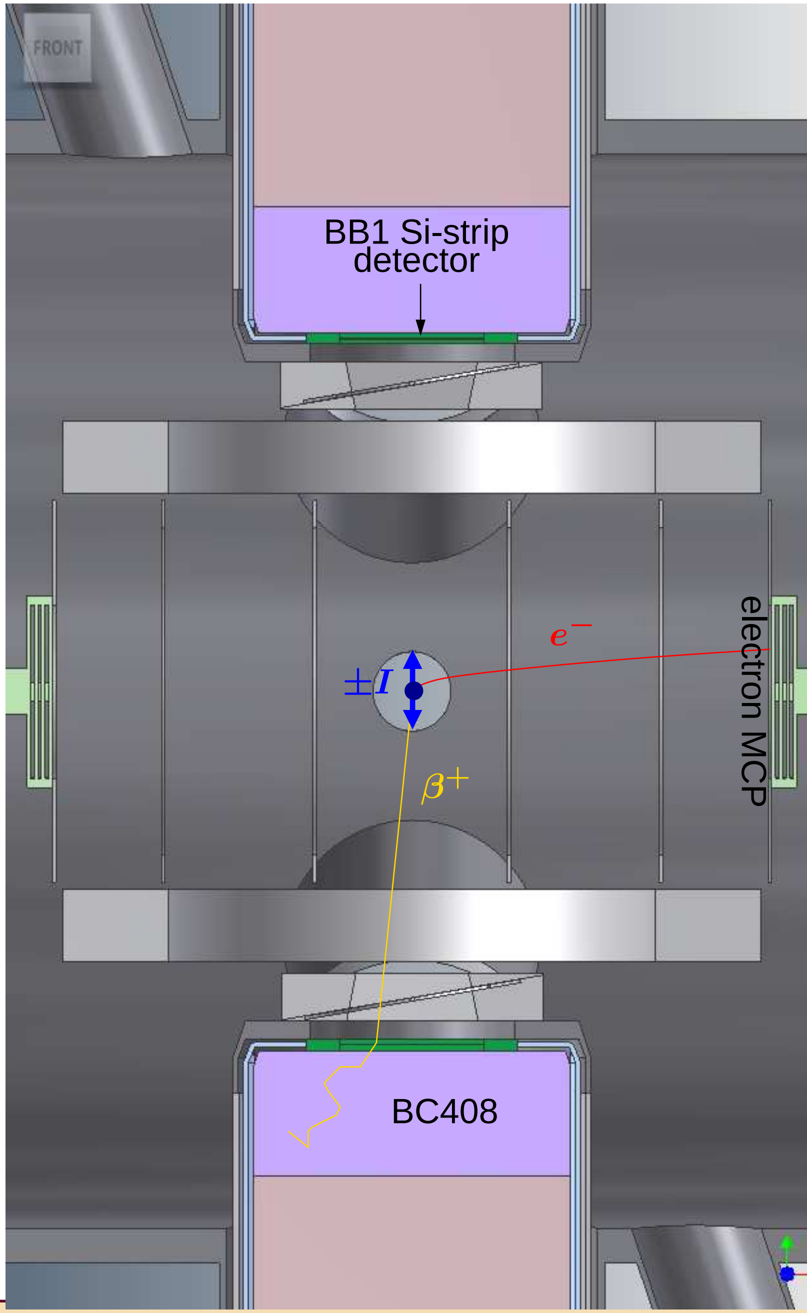


FIG. 1 (color online). The switching configuration for the ac MOT. The MOT is driven by an alternating supply, so that the net induced current in conductors surrounding the MOT coils is zero. The polarization of the six trapping laser beams is switched at the same rate as the MOT current, so as to maintain trapping. Experiments using charged particles are conducted during the time the MOT current is zero.



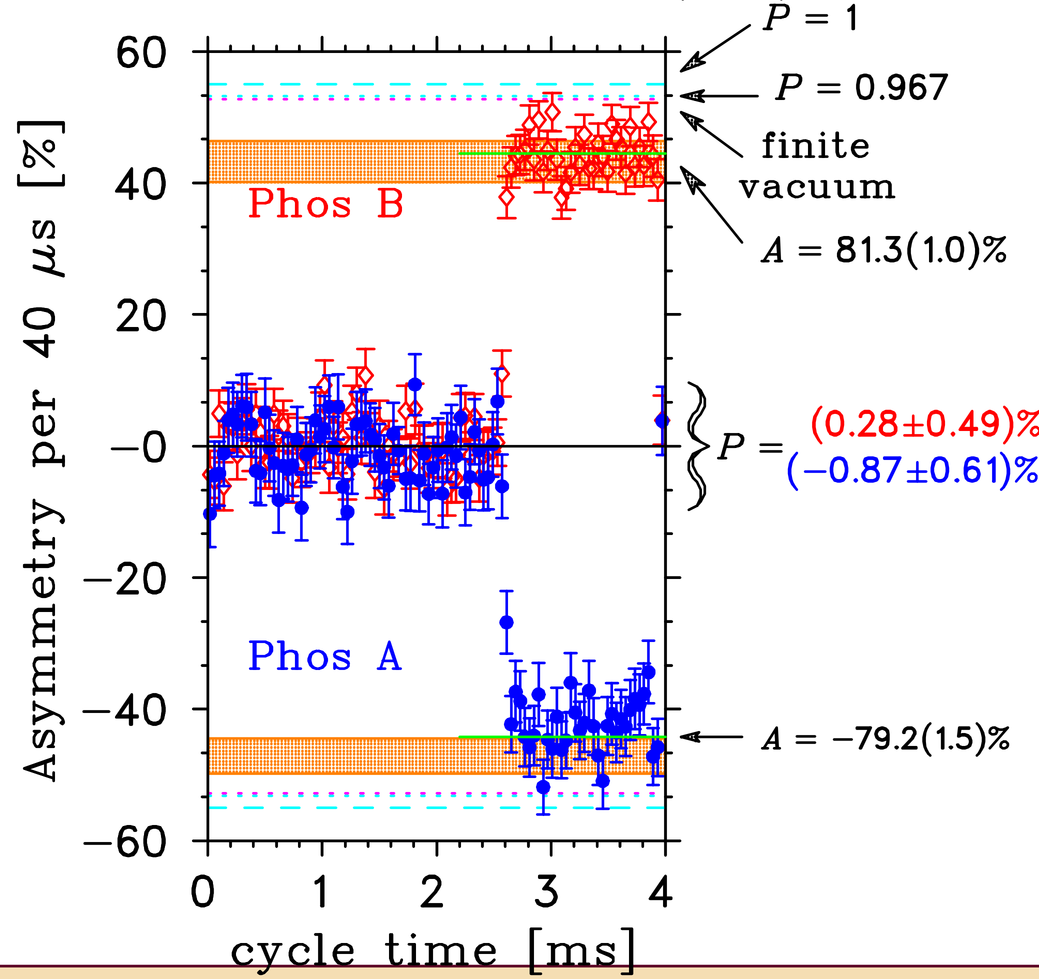
$$\Rightarrow P_{\text{nucl}} = 96.74 \pm 0.53^{+0.19}_{-0.73}$$

Measuring A_β — Fall 2012(?)



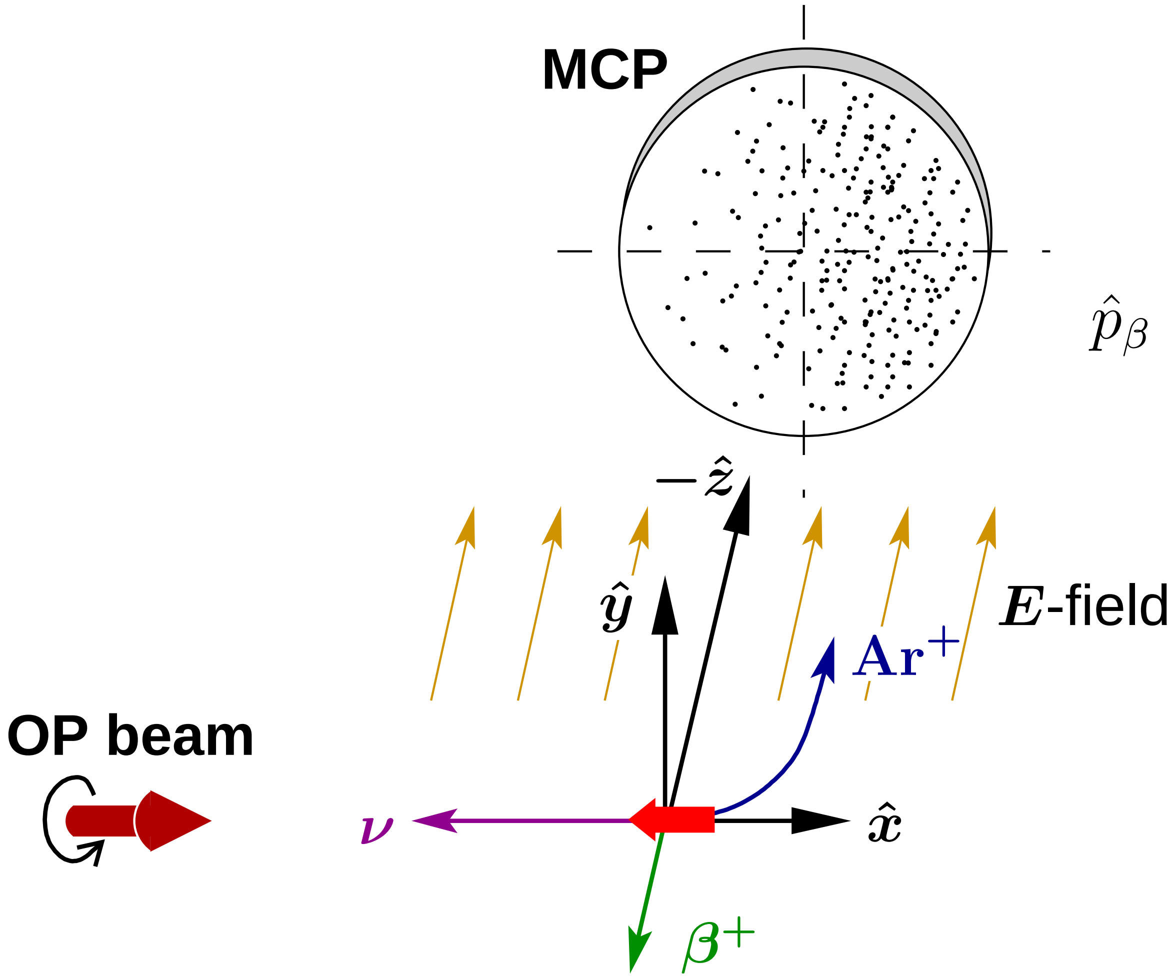
$$\text{Asymmetry} = \frac{N(\sigma^+) - N(\sigma^-)}{N(\sigma^+) - N(\sigma^-)}$$

$$\sim P A_\beta \left\langle \frac{p_e}{E_e} \right\rangle$$



Measuring B_ν (and D)

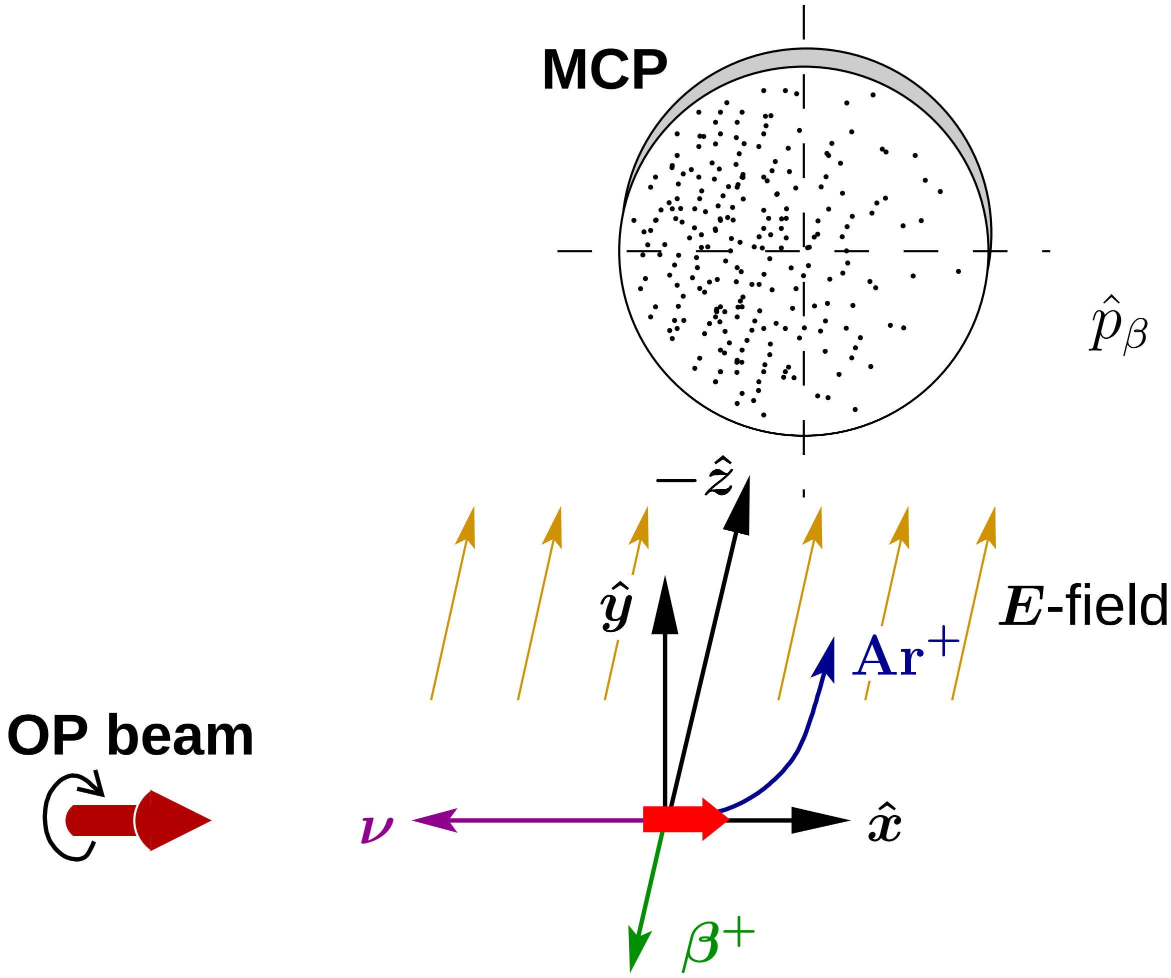
$$dW \sim \boldsymbol{P}\boldsymbol{B_\nu}\hat{p}_\nu \cdot \hat{i} + \boldsymbol{P}\boldsymbol{D}\frac{\hat{i}\cdot(\boldsymbol{p}_\beta \times \hat{p}_\nu)}{E_\beta}$$



$$\hat{p}_\beta \approx \hat{z} \quad \Rightarrow \quad \boldsymbol{p}_\nu \approx -\boldsymbol{p}_{\mathrm{Ar}}$$

Measuring B_ν (and D)

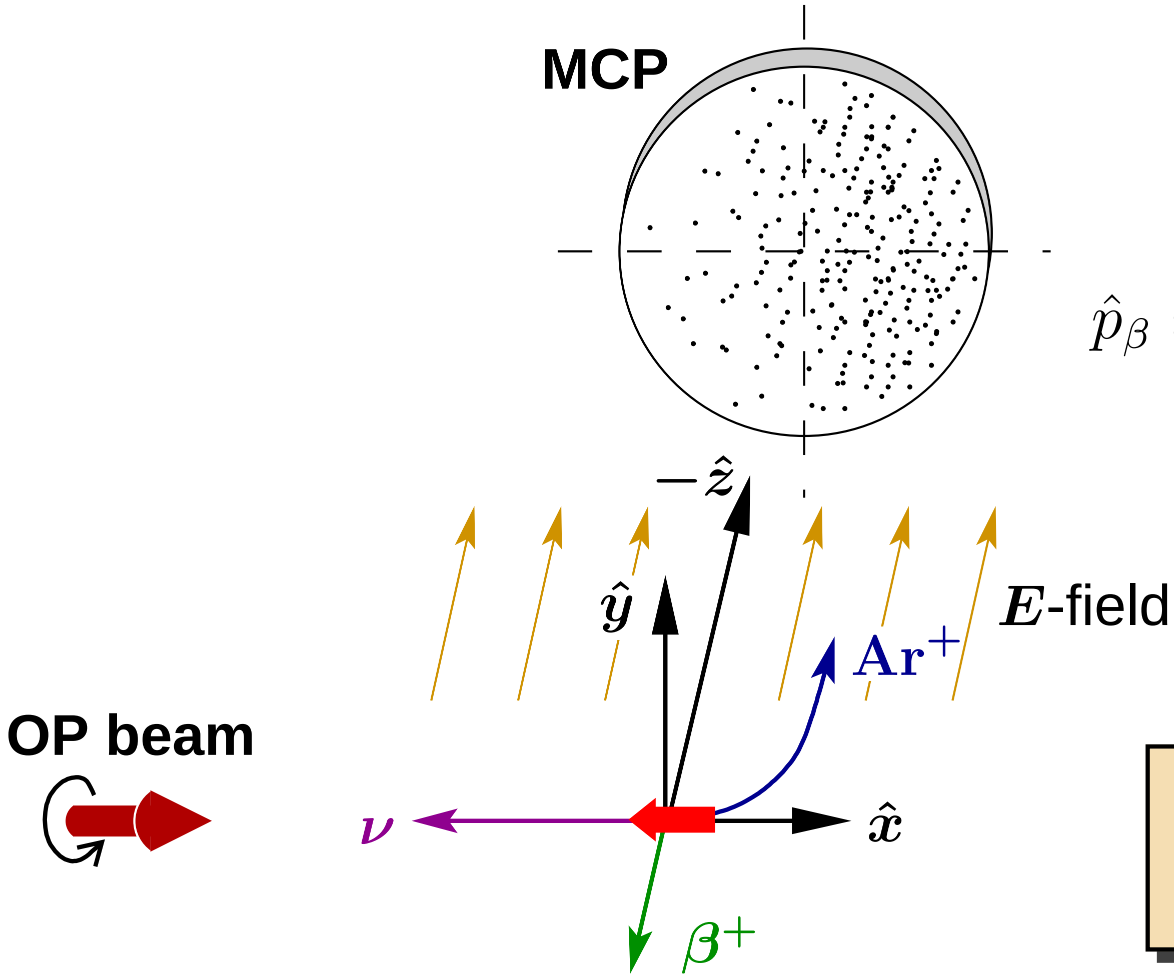
$$dW \sim \boldsymbol{P}\boldsymbol{B_\nu}\hat{p}_\nu \cdot \hat{i} + \boldsymbol{P}\boldsymbol{D}\frac{\hat{i}\cdot(\boldsymbol{p}_\beta \times \hat{p}_\nu)}{E_\beta}$$



$$\hat{p}_\beta \approx \hat{z} \quad \Rightarrow \quad \boldsymbol{p}_\nu \approx -\boldsymbol{p}_{\mathrm{Ar}}$$

Measuring B_ν (and D)

$$dW \sim PB_\nu \hat{p}_\nu \cdot \hat{i} + PD \frac{\hat{i} \cdot (\boldsymbol{p}_\beta \times \hat{p}_\nu)}{E_\beta}$$

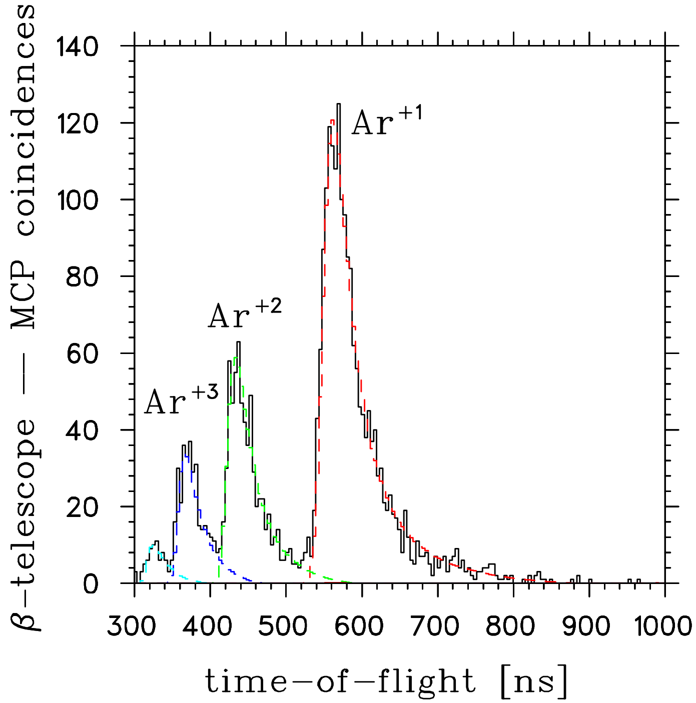


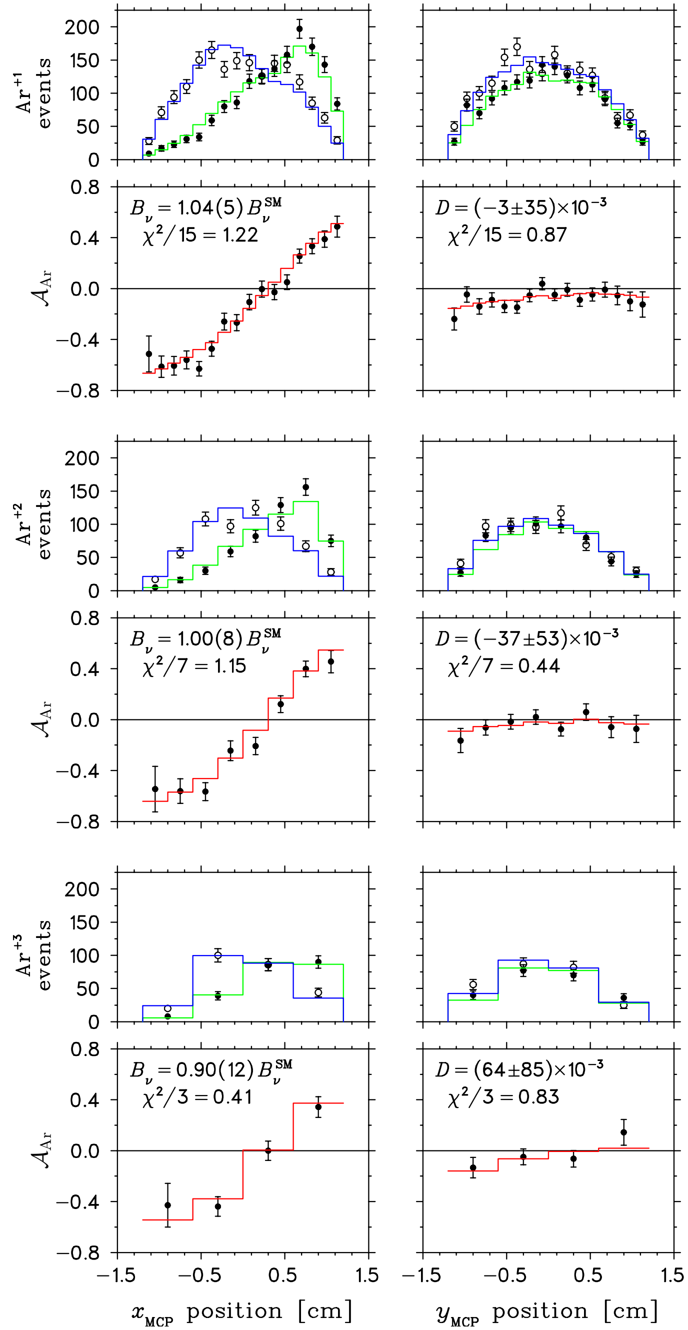
$$\hat{p}_\beta \approx \hat{z} \quad \Rightarrow \quad \boldsymbol{p}_\nu \approx -\boldsymbol{p}_{\text{Ar}}$$

$\hat{x}$ asymmetry $\sim PB_\nu$

$\hat{y}$ asymmetry $\sim PD$

The neutrino asymmetry measurement





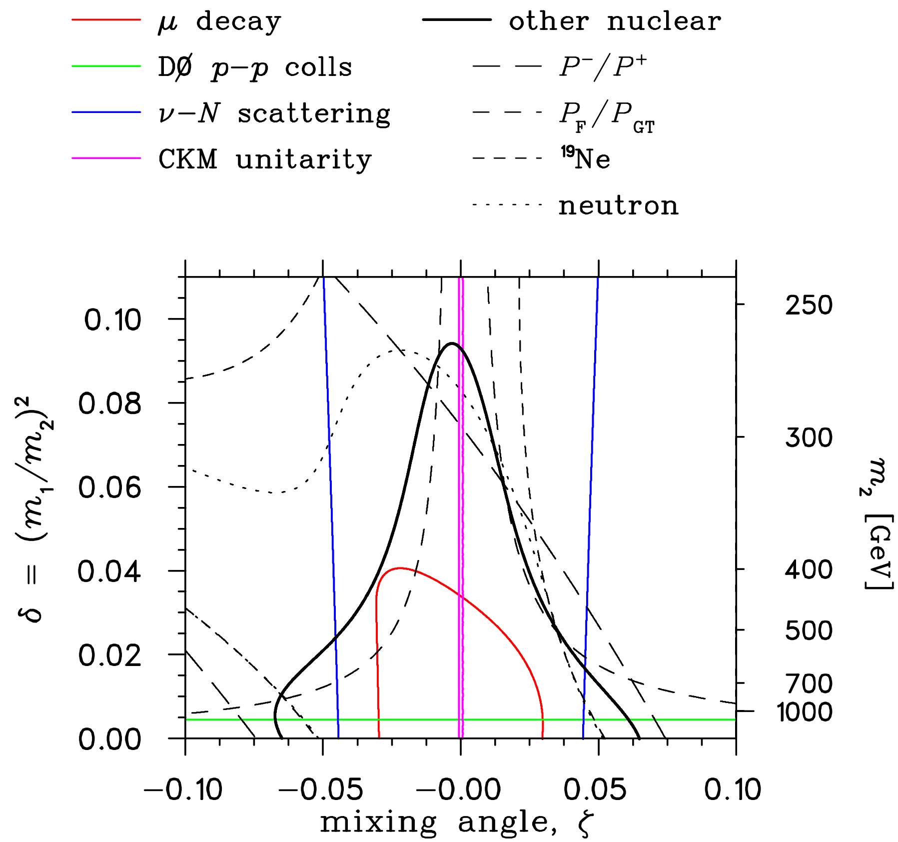
$$1^{\text{st}}: \; \langle B_\nu \rangle = (0.995 \pm \underset{(\text{stat})}{0.040}) B_\nu^{\text{SM}}$$

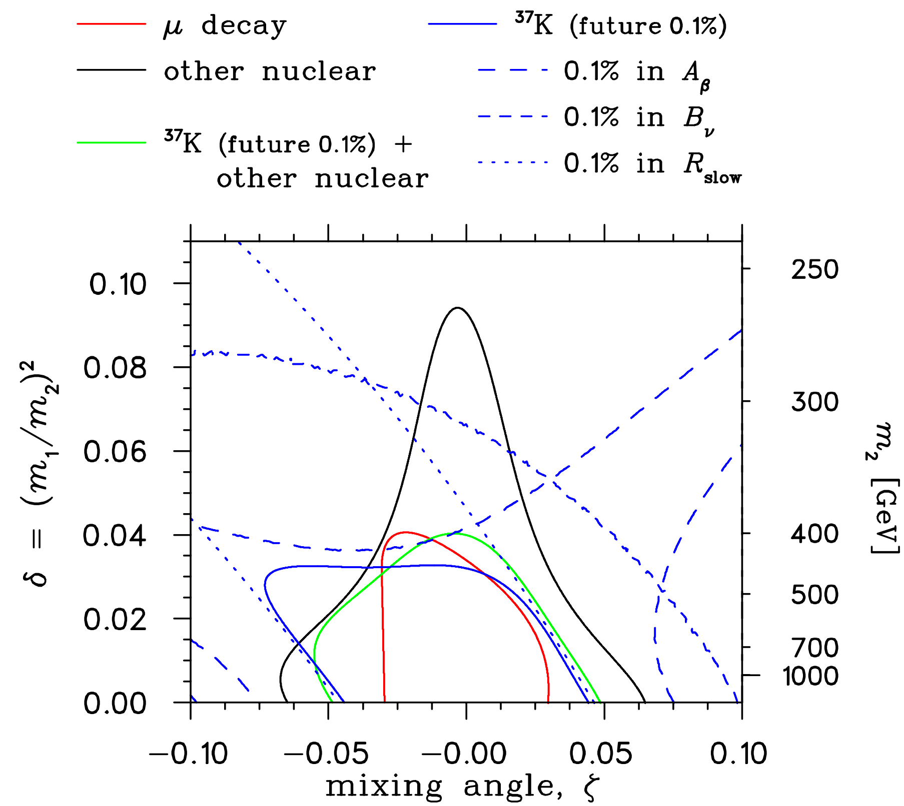
$$2^{\text{nd}}: \; \langle B_\nu \rangle = (0.975 \pm \underset{(\text{stat})}{0.031}) B_\nu^{\text{SM}}$$

$$\Rightarrow \boxed{\boldsymbol{B_\nu = 0.981(26)(17) B_\nu^{\text{SM}}}}$$

(Melconian, PLB **649** (2007) 370)

Goal, in terms of RHCs

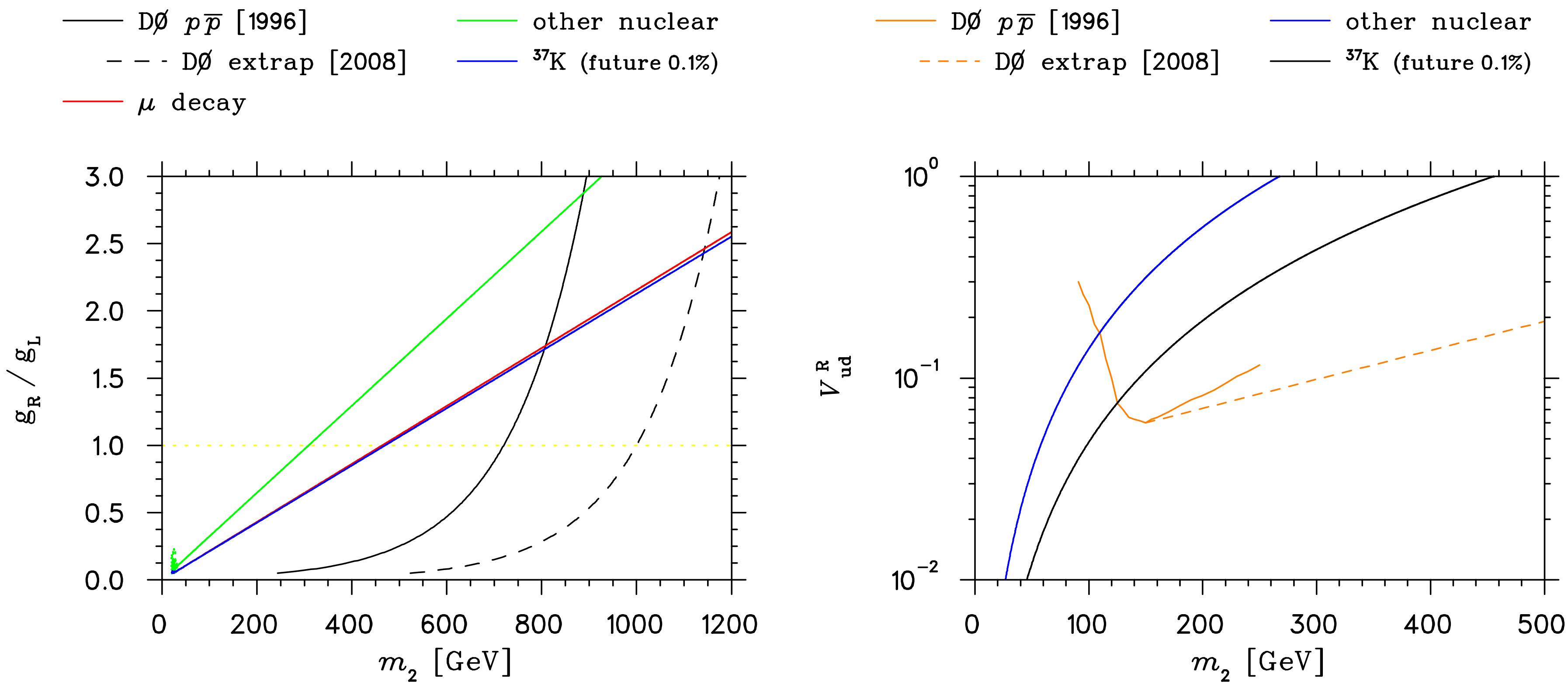




Expected limits if A_β, B_ν and $R_{\rm slow}$ all measured to 0.1%

see Profumo, Ramsey-Musolf and Tulin, PRD **75** (2007) 075017

Beyond the minimal L-R symmetric model



(adapted from Thomas *et al.*, Nucl Phys A **694**; see also Severijns, Beck and Naviliat-Cuncic, Rev Mod Phys **78** (2006))

different experiments are complementary

Summary

- SM is fantastic, but incomplete
- many exciting avenues to find more complete model
- **needed:** precision measurement of correlation parameters
- (AC-)MOT + opt. pumping = ***cool*** physics

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- many exciting avenues to find more complete model
- **needed:** precision measurement of correlation parameters
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Don’t get married five days before you’re supposed to give a talk! ;-)

Main collaborators/thanks

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