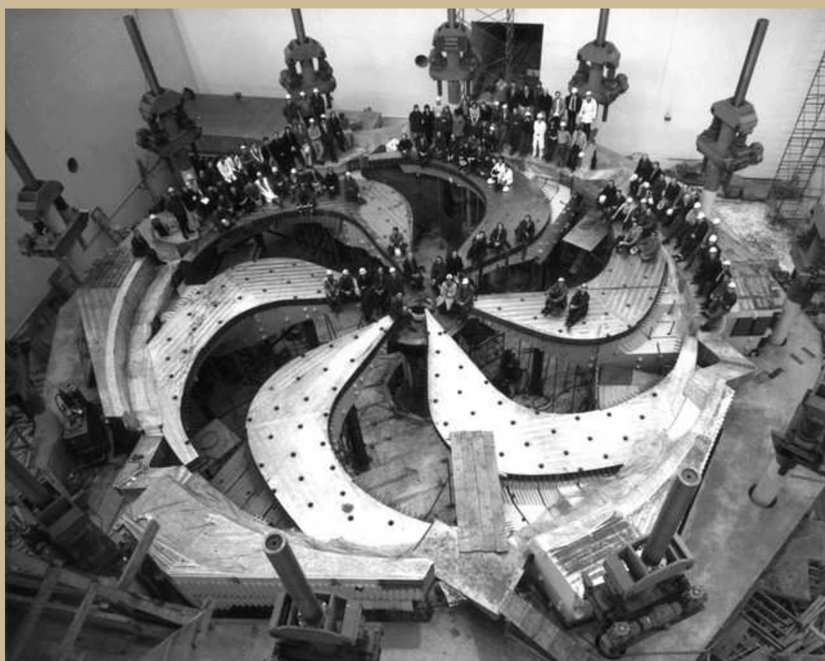
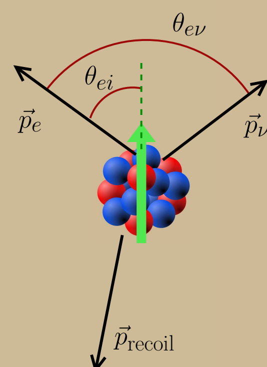
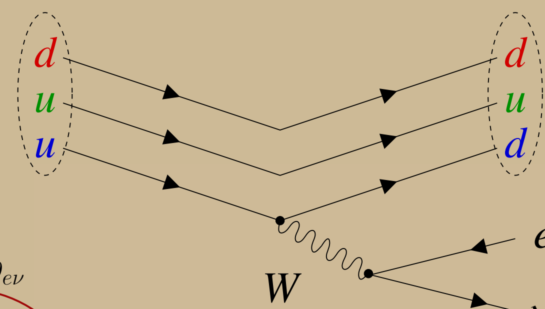
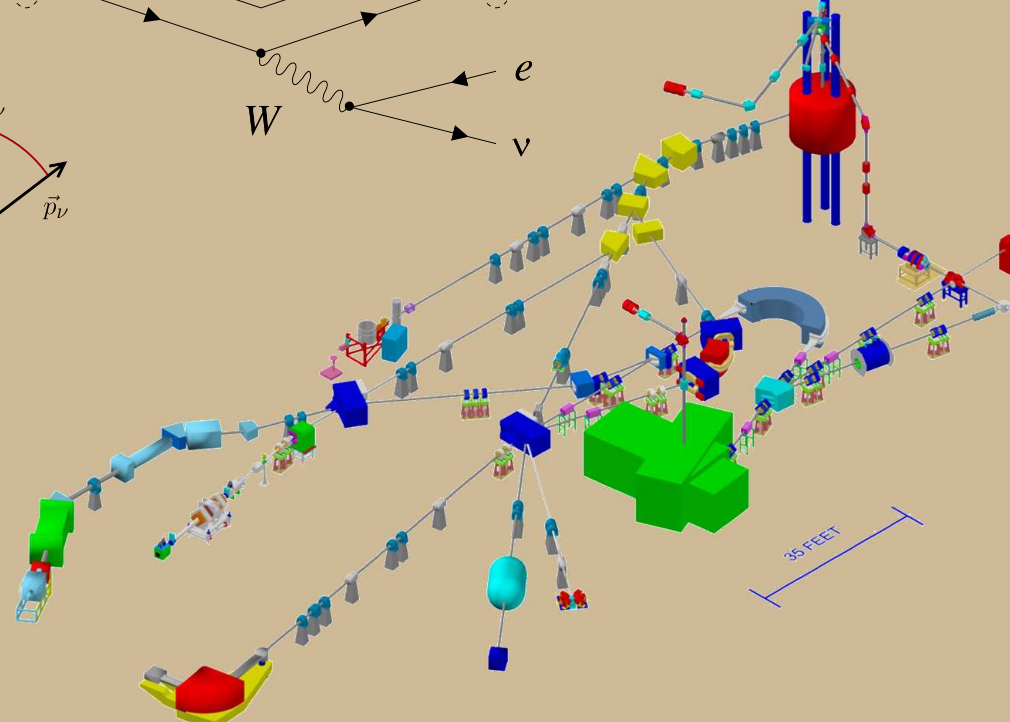
Fundamentally *Cool* Physics with Trapped Atoms and Ions









Dan Melconian

April 23, 2017

Overview

1. Fundamental symmetries

- what is our **current understanding**?
- how do we test what lies **beyond**?

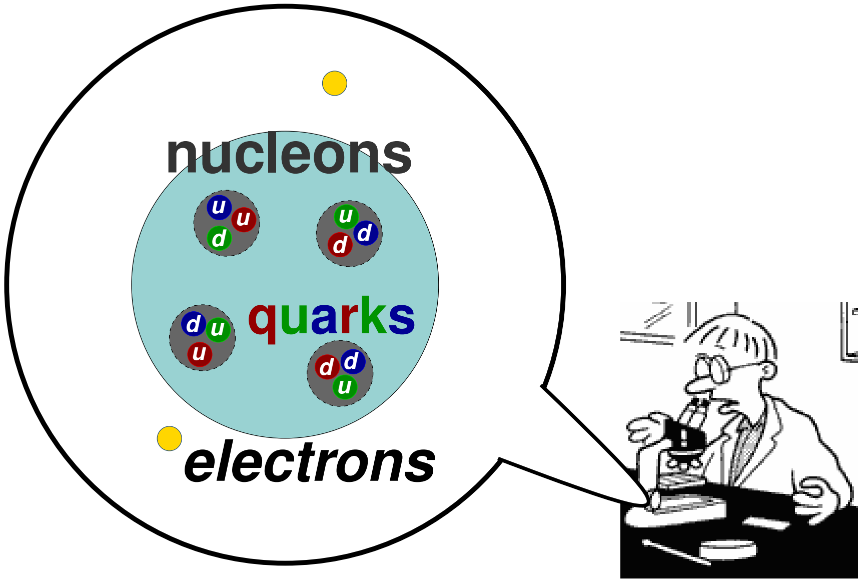
2. TAMU Penning Trap

- **physics** of superallowed β decay
- **ion trapping** of proton-rich nuclei at T-REX

3. TRIUMF Neutral Atom Trap

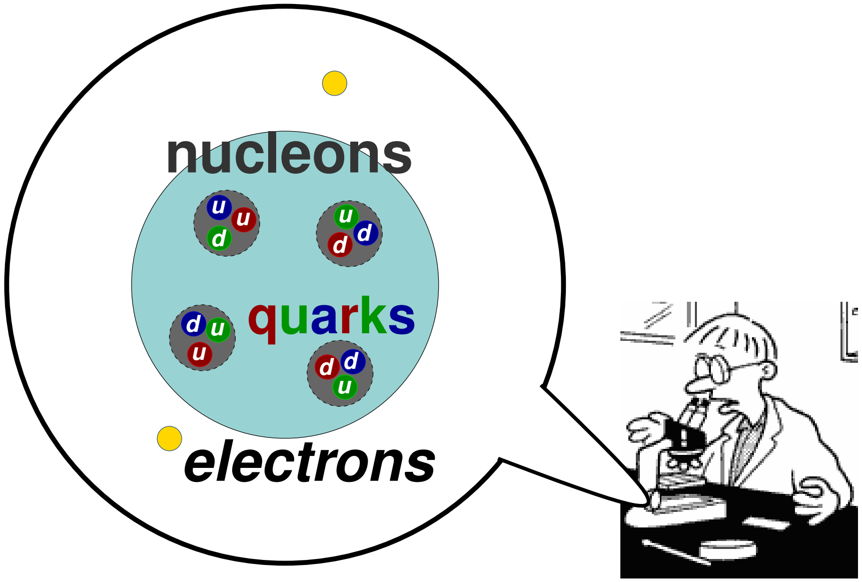
- angular correlations of **polarized ^{37}K**
- **recent results**

Scope of fundamental physics



the atom

from the very smallest scales . . .



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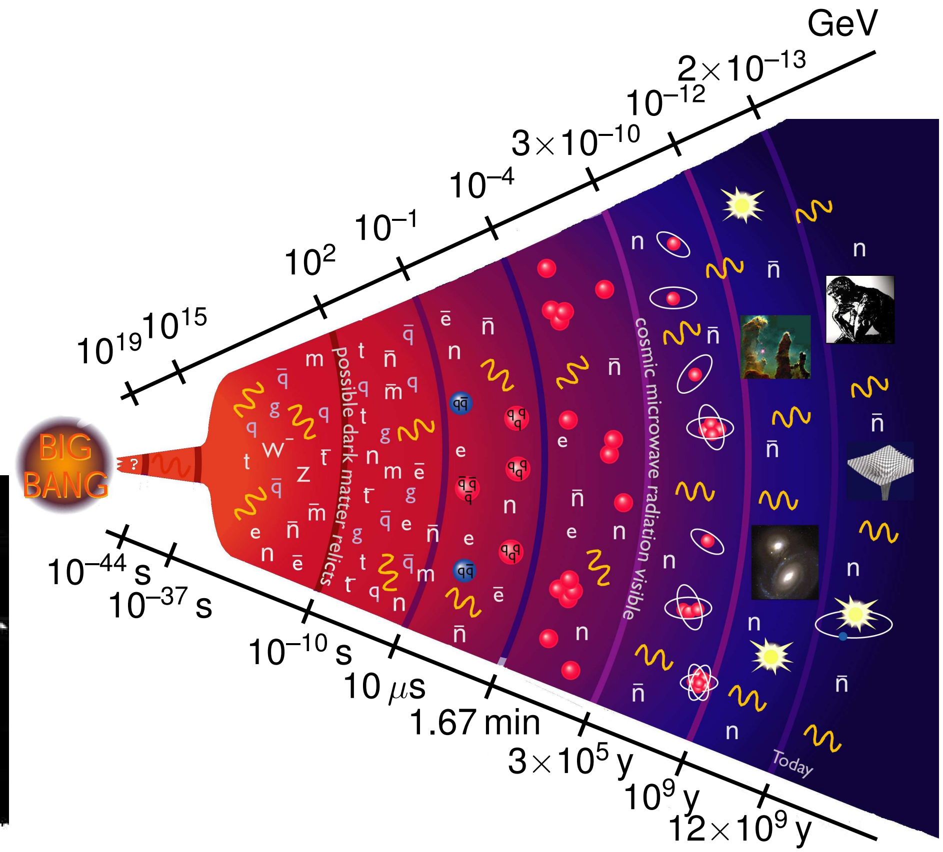

. . . to the very **largest**

The Standard Model

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

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and there are other symmetries too:

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

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- **12 elementary particles**, **4 fundamental forces**

	1st	2nd	3rd	Q	mediator	force
leptons	$\begin{pmatrix}\nu_e \\ e\end{pmatrix}$	$\begin{pmatrix}\nu_\mu \\ \mu\end{pmatrix}$	$\begin{pmatrix}\nu_\tau \\ \tau\end{pmatrix}$	0 -1	g	strong
					$W^\pm$, Z°	weak
quarks	$\begin{pmatrix}u \\ d\end{pmatrix}$	$\begin{pmatrix}c \\ s\end{pmatrix}$	$\begin{pmatrix}t \\ b\end{pmatrix}$	$+2/3$ $-1/3$	γ	EM

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

The ***new*** **Standard Model**

- **quantum** + **special rel** $\Rightarrow$ **quantum field theory**
- Noether's theorem: symmetry $\Leftrightarrow$ conservation law
- **12 elementary particles**, **4 fundamental forces** and **1 Higgs boson**

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

$\rightsquigarrow$ and now **the Higgs!**

✔ is a **renormalizable** theory

✔ GSW $\Rightarrow$ **unified** the **weak** force with **electromagnetism**

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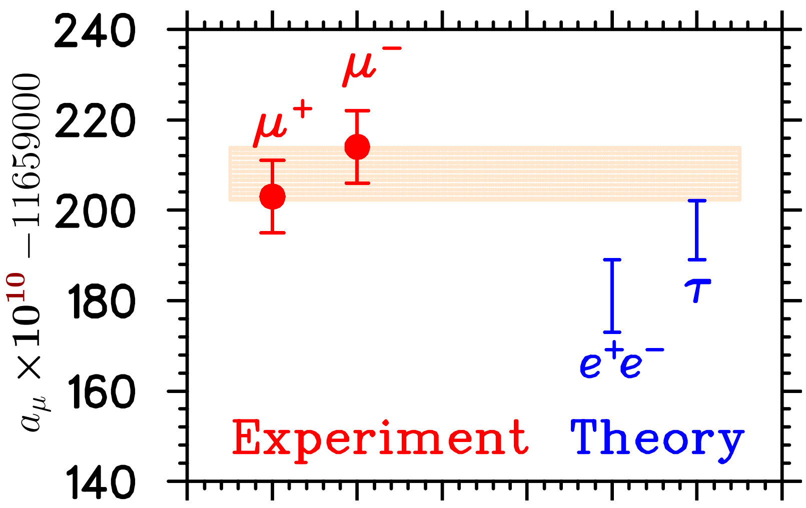

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± 1 **part-per-*million*!!**

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

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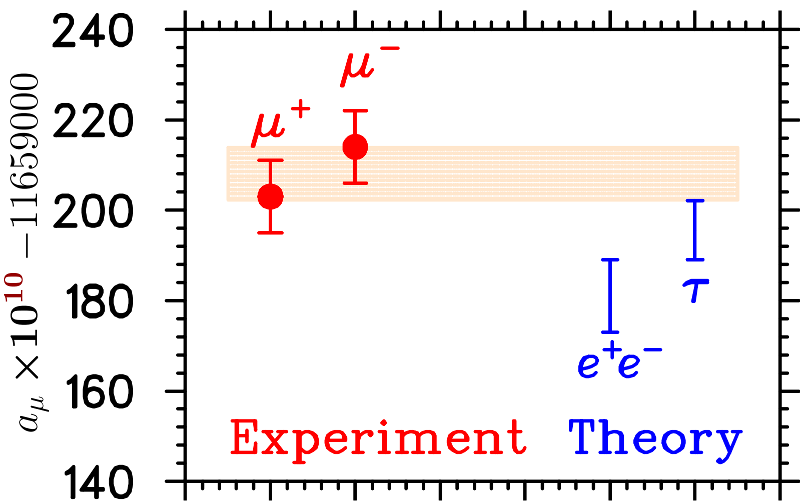

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Wow . . . this is

the most precisely tested theory ever conceived!

But there are still questions . . .

- **parameters values**: does our “ultimate” theory *really* need **25** arbitrary constants? Do they **change** with time?
- **dark matter**: SM physics makes up **less than 5%** 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**? Mass **hierarchy**?
- **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?
- **gravity**: of course can’t forget about a **quantum** description of **gravity**!

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

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often they are **interdisciplinary**

(which makes it extra *fun*!)

How does high-energy physics test the SM?

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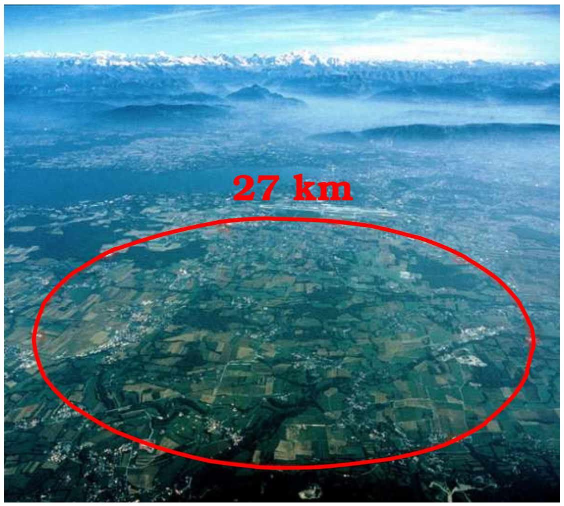
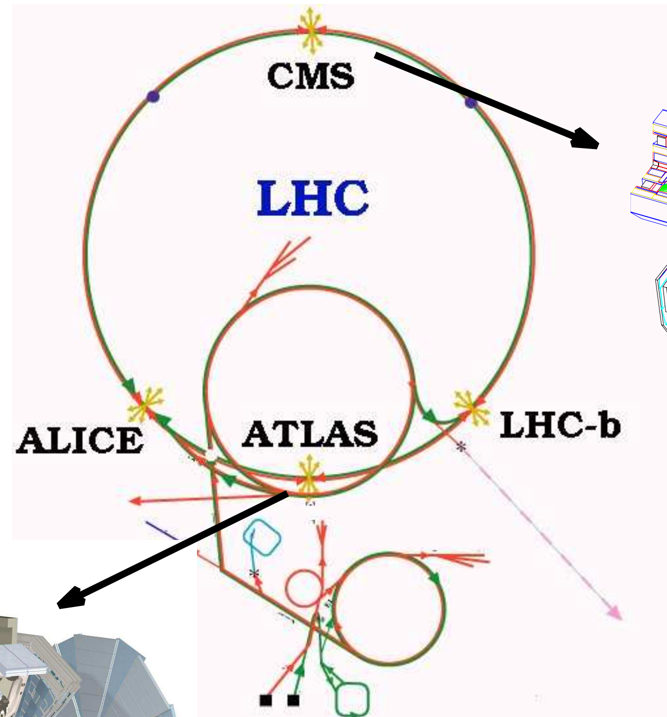
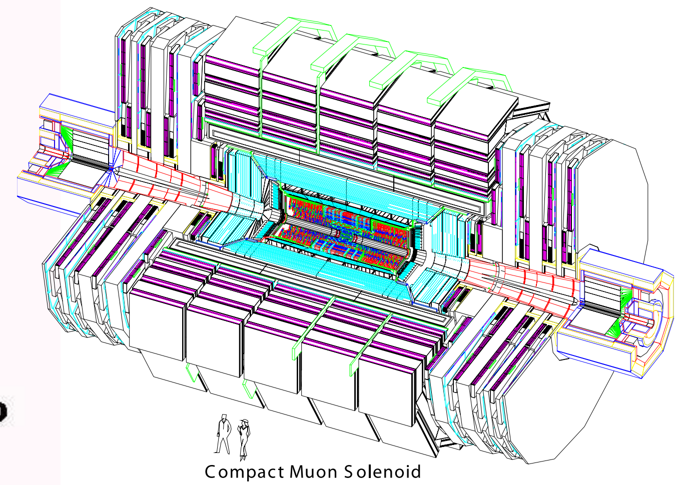
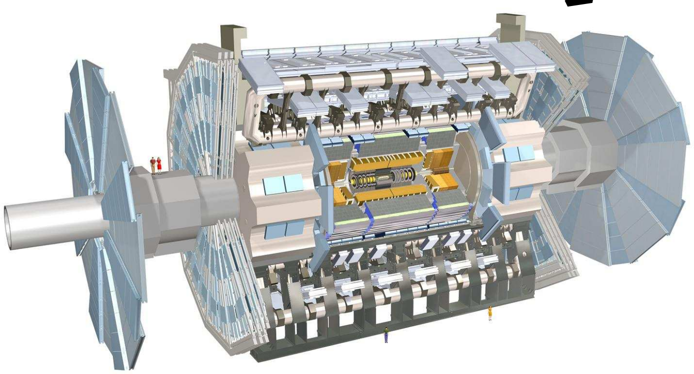
direct search of particles









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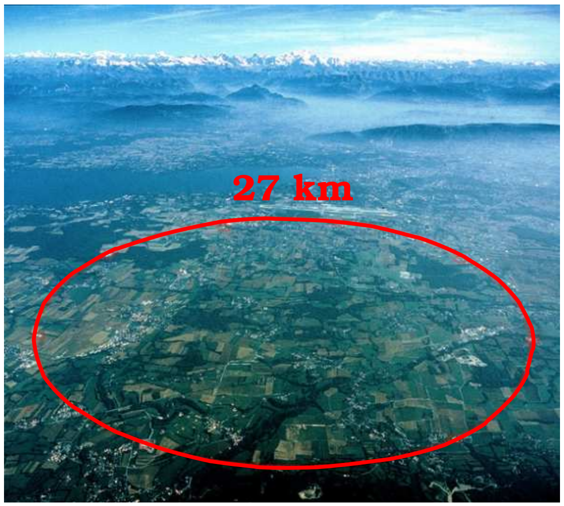

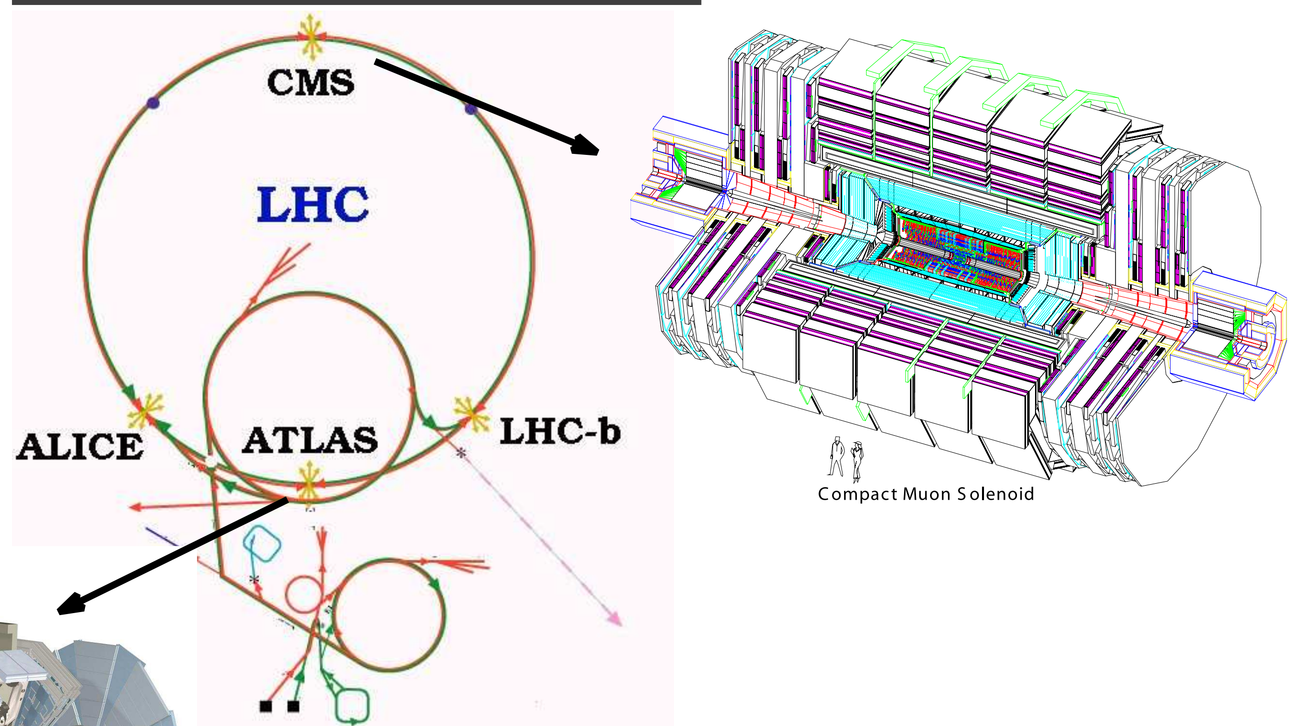

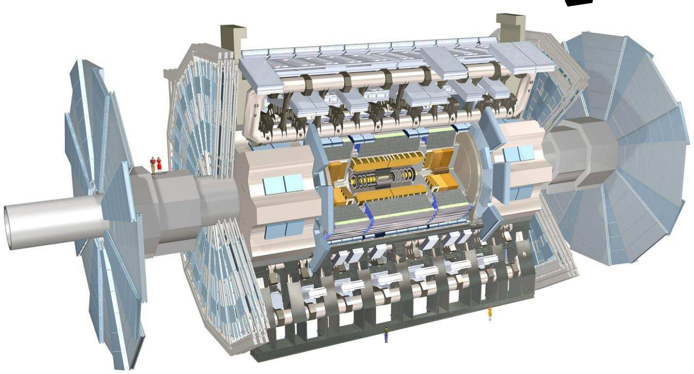

- large multi-national collabs
- *billion* $ price-tags

How does nuclear physics test the SM?

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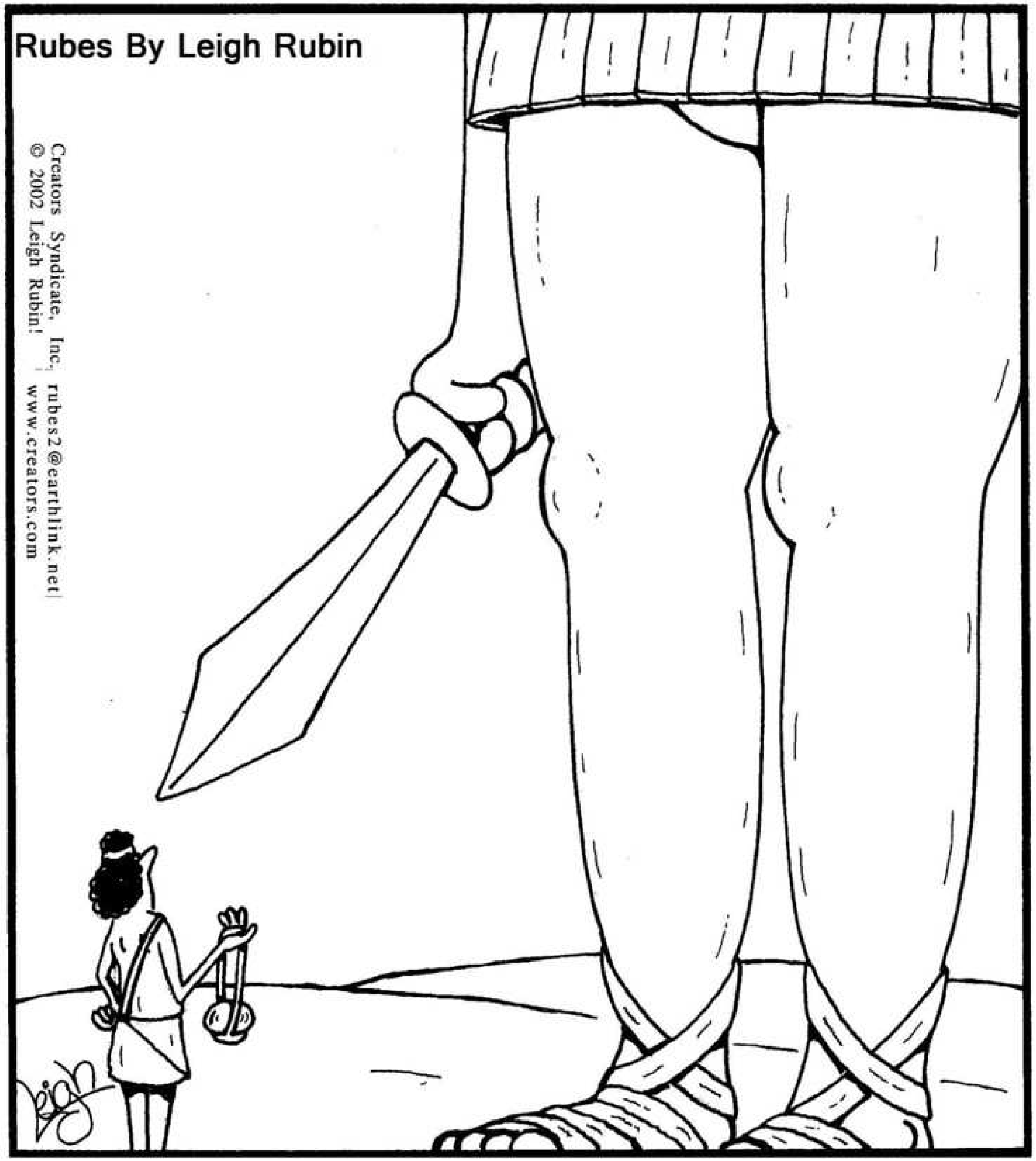
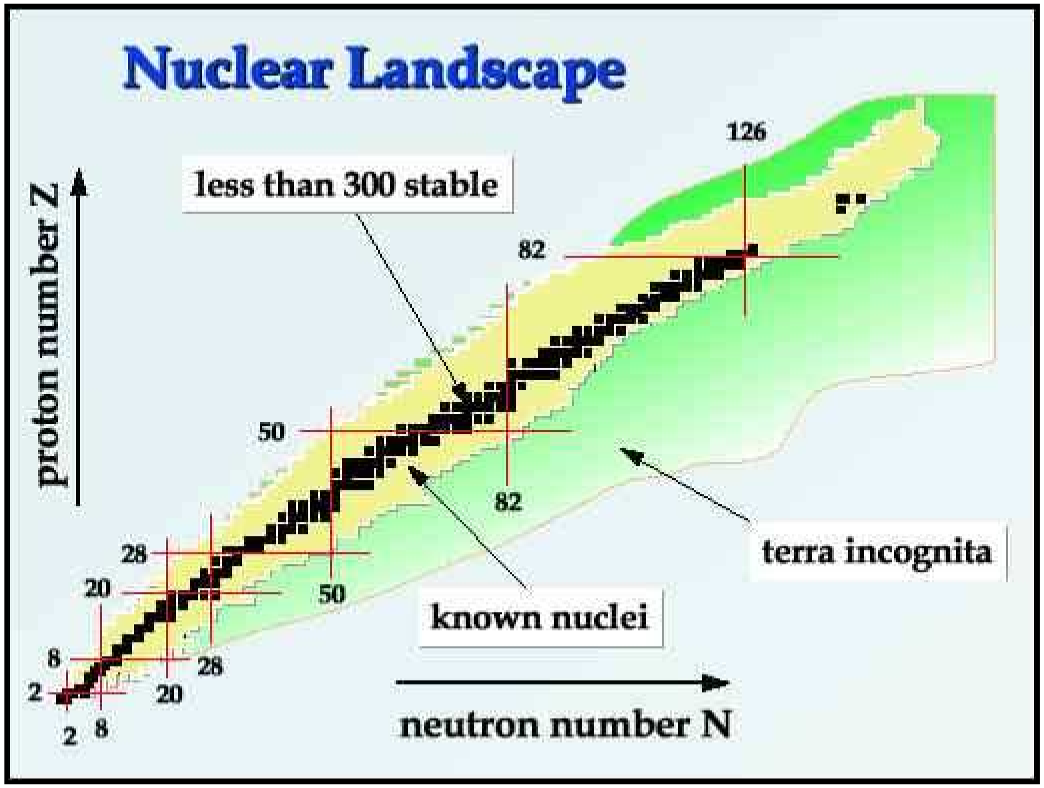


Overcoming temptation, David opted against the obvious, unsportsmanlike cheap shot.

How does nuclear physics test the SM?

nuclear physics: radioactive ion beam facilities

indirect search via precision measurements



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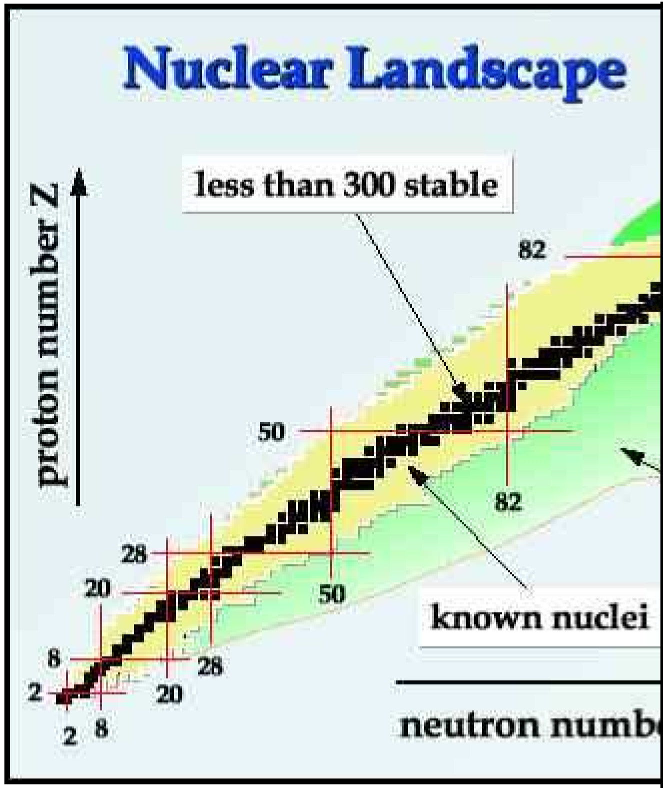

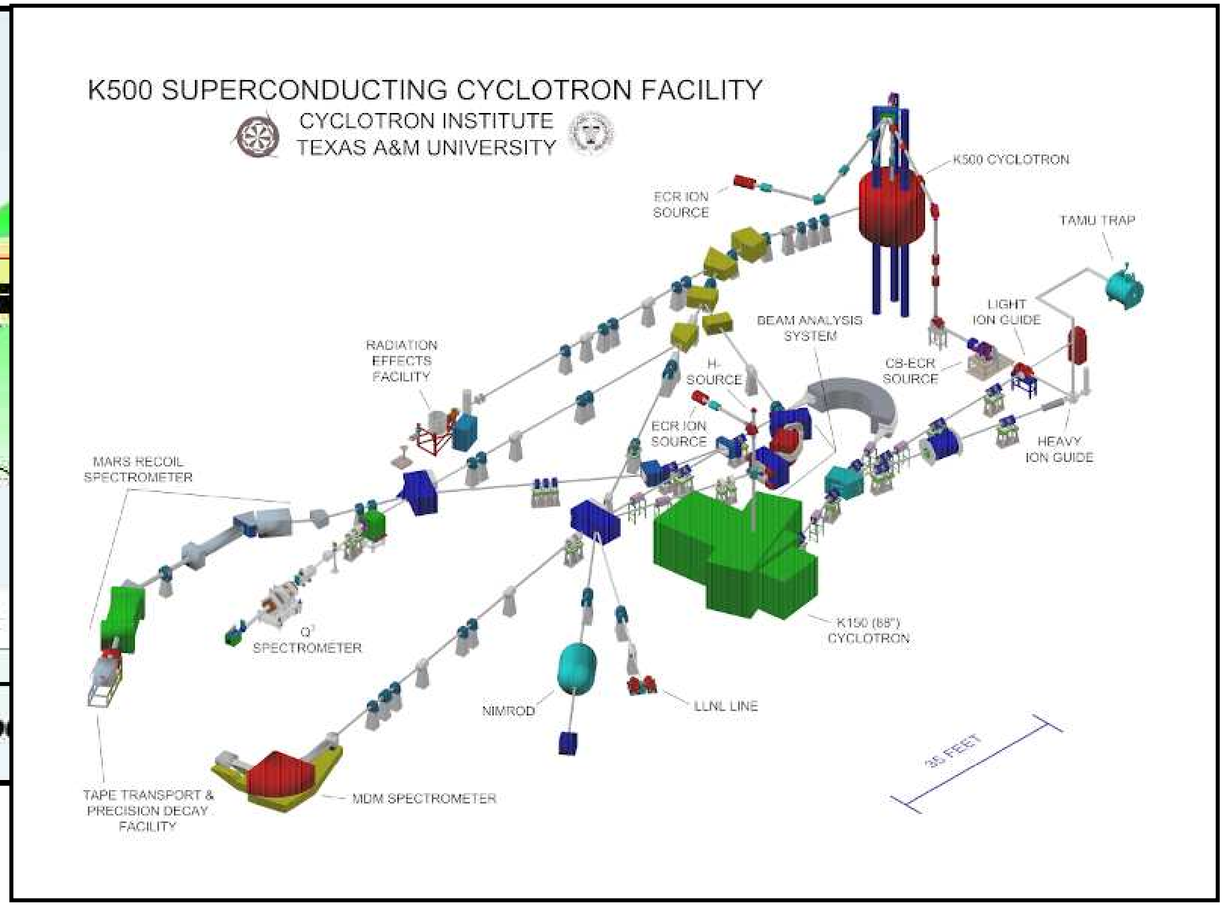

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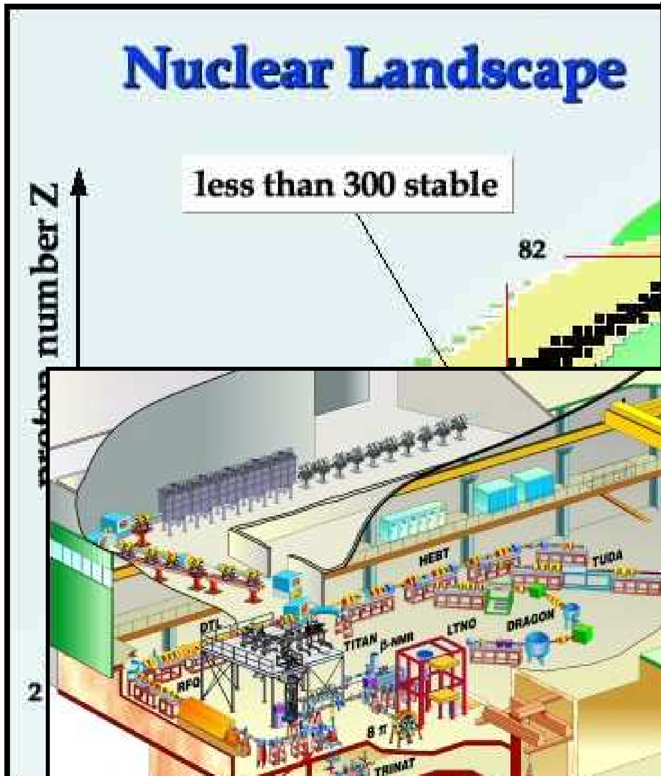

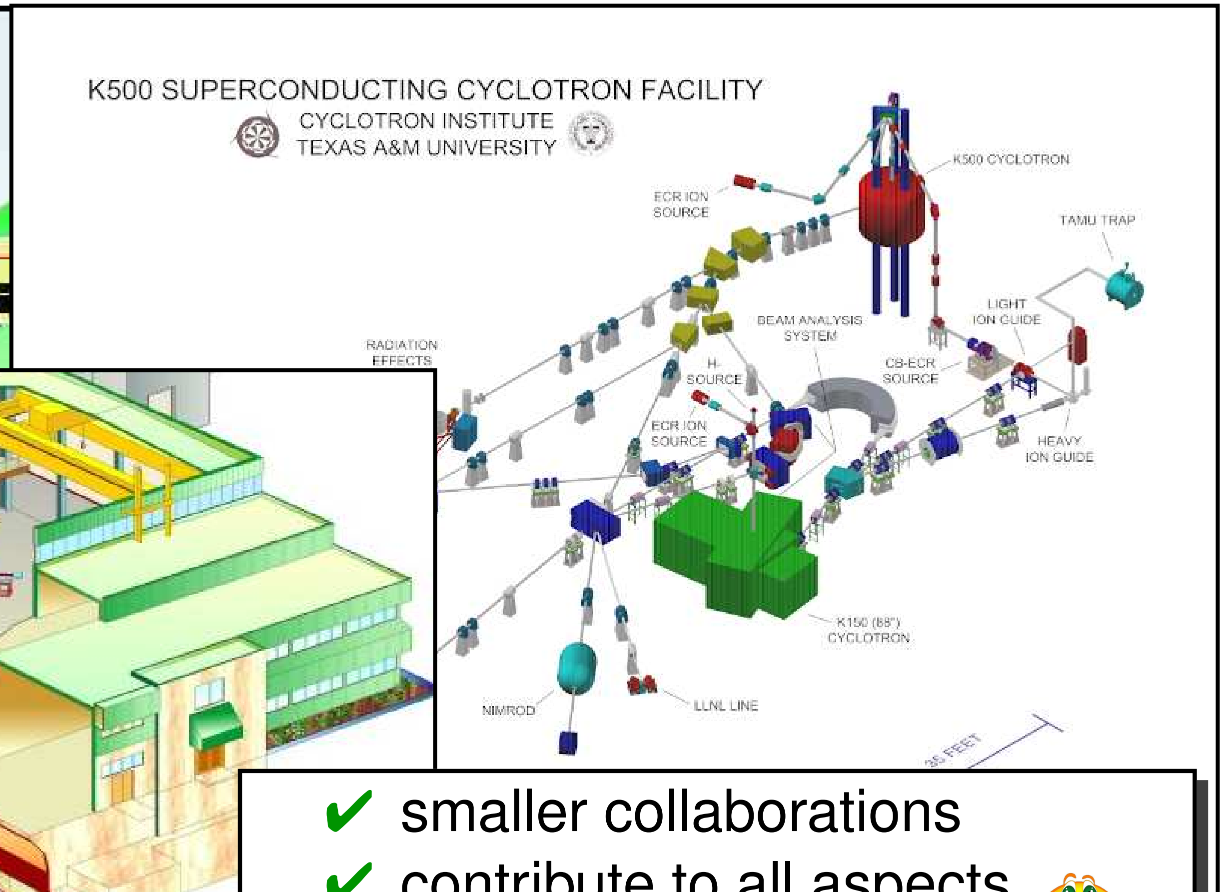

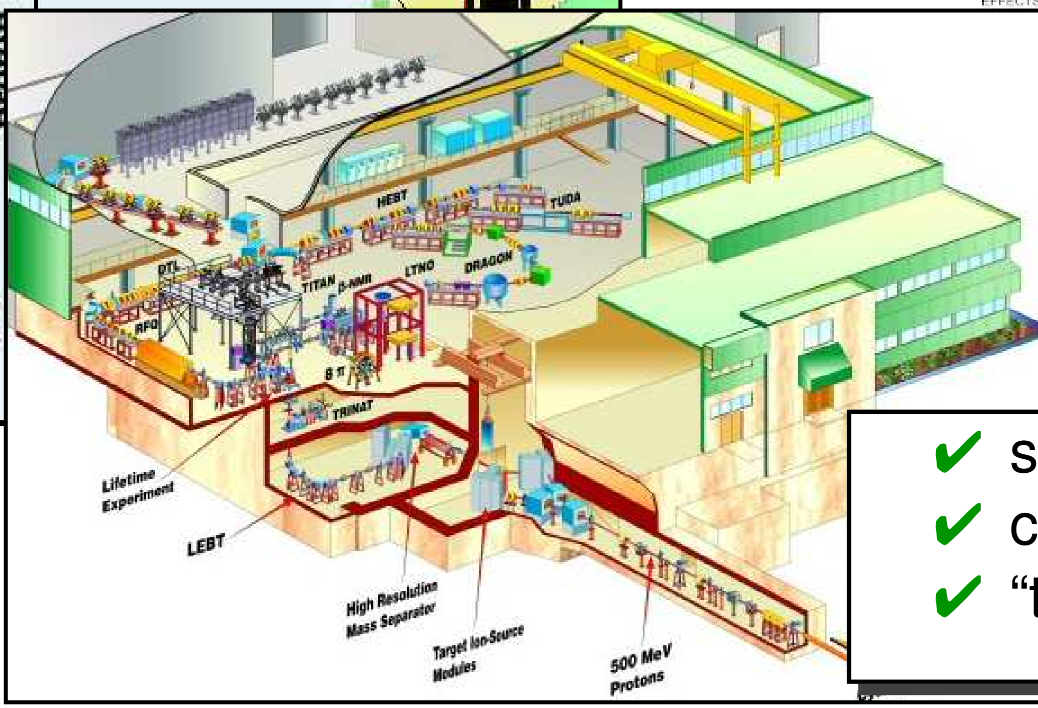

- ✔ smaller collaborations
- ✔ contribute to all aspects
- ✔ “table-top” physics

How specifically do I plan to test the SM?

- Begin by looking at the rate for β decay

$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \overbrace{\frac{G_F^2 |\boldsymbol{V_{ud}}|^2}{(2\pi)^5} p_e E_e (A_\circ - E_e)^2}^{\text{basic decay rate}}$$

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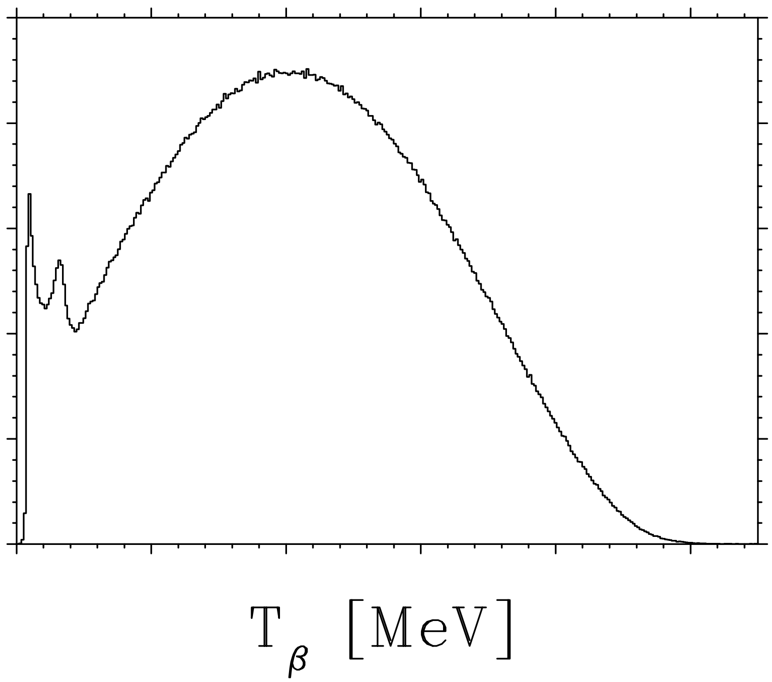

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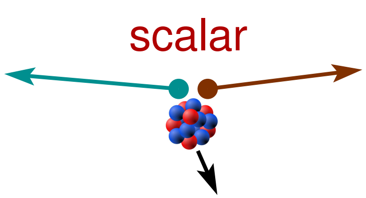
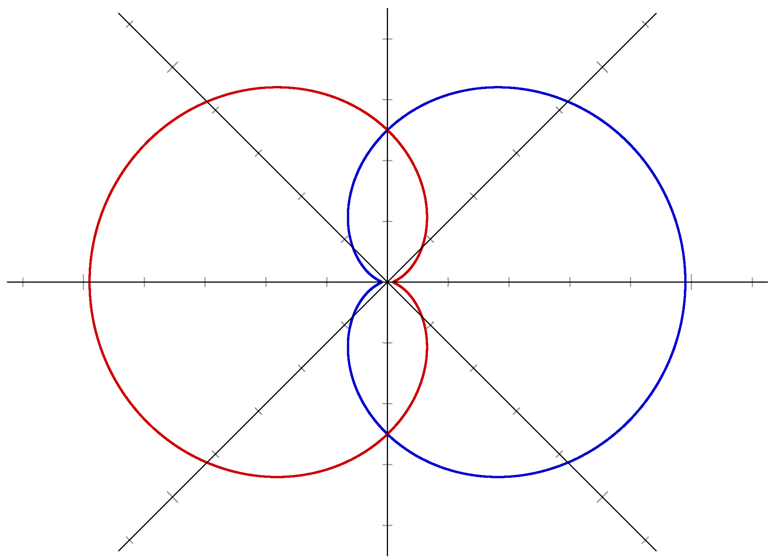
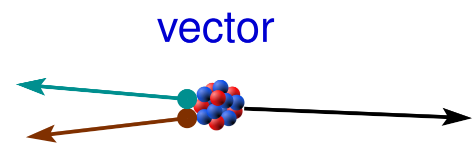


$$a_{\beta\nu} = \frac{-|C_S|^2 - |C_S'|^2}{|C_S|^2 + |C_S'|^2}$$





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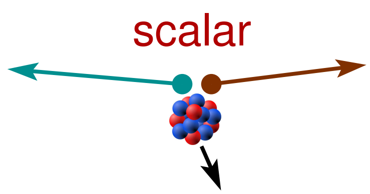

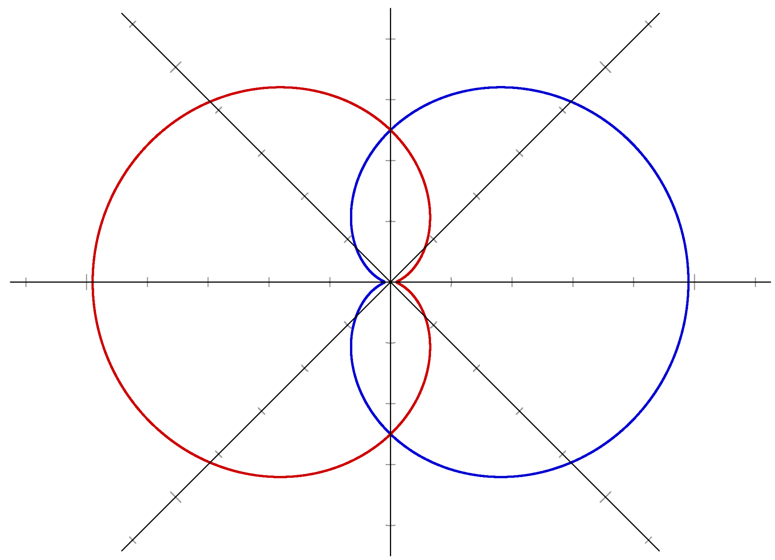

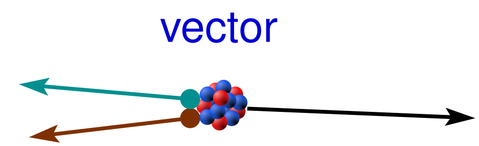

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This correlation is quadratic in the couplings…not as sensitive as the Fierz parameter, which is linear:

$$b_F = \frac{-2\Re e(C_S^* C_V + C_S'^* C_V')}{|C_V|^2 + |C_V'|^2 + |C_S|^2 + |C_S'|^2} = 0??$$

see González-Alonso and Naviliat-Čunčić, PRC **94**, 035503 (2016)

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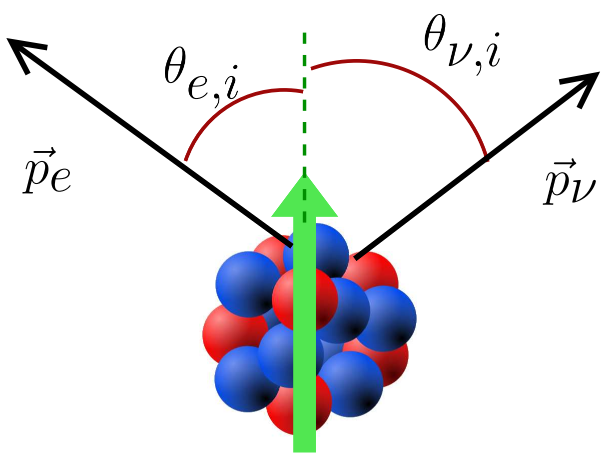
$$\left. + \frac{\langle \vec{I} \rangle}{I} \cdot \left[\underbrace{A_\beta \frac{\vec{p}_e}{E_e}}_{\beta \text{ asym}} + \underbrace{B_\nu \frac{\vec{p}_\nu}{E_\nu}}_{\nu \text{ asym}} + \underbrace{D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}}_{T-\text{violating}} \right] + \ldots \right)$$



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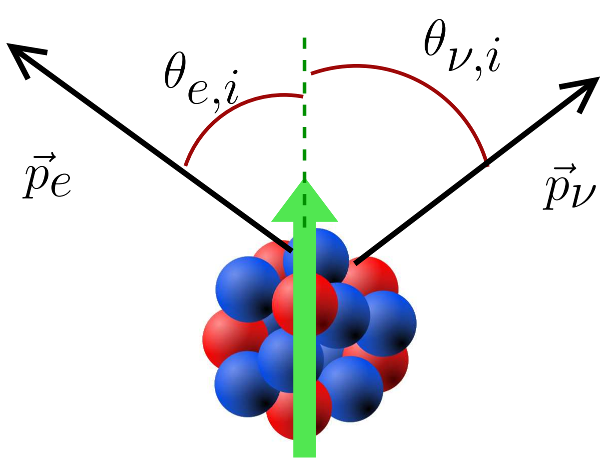

E.g. $A_\beta = \frac{-2\rho}{1+\rho^2} \left[(1-xy)\sqrt{\frac{3(1+x^2)}{5(1+y^2)}} - \frac{\rho(1-y^2)}{5(1+y^2)} \right]$

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

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

are right-handed current parameters that are zero in the SM, and $\rho \equiv \frac{C_A M_{GT}}{C_V M_F}$

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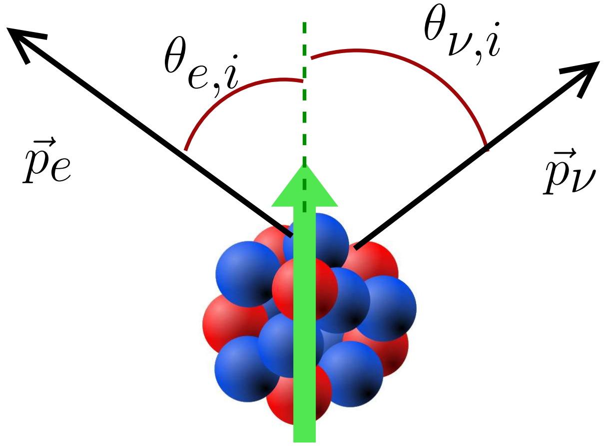
$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \overbrace{\frac{G_F^2|V_{ud}|^2}{(2\pi)^5} p_e E_e (A_\circ - E_e)^2 \xi}^{\text{basic decay rate}} \left(1 + \ldots\right)$$

basic decay rate, $\beta-\nu$ correlation, Fierz term, β asym, ν asym, $T-$violating

β-decay parameters depend on the currents mediating the weak interaction

$\Rightarrow$ sensitive to **new physics** $\Leftarrow$



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

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

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

are right-handed current parameters that are zero in the SM, and $\rho \equiv \frac{C_A M_{GT}}{C_V M_F}$

How specifically do I plan to test the SM?

- Expand to the often-quoted **angular distribution** of the decay:
  (Jackson, Treiman and Wyld, Phys Rev **106** and Nucl Phys **4**, 1957)

$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \overbrace{\frac{G_F^2 |V_{ud}|^2}{(2\pi)^5} p_e E_e (A_\circ - E_e)^2 \xi}^{\text{basic decay rate}} \Bigg(1 + \overbrace{\cdots}^{\beta-\nu \text{ correlation}} \overbrace{\cdots}^{\text{Fierz term}} \cdots \underbrace{\cdots}_{\beta \text{ asym}} \underbrace{\cdots}_{\nu \text{ asym}} \underbrace{\cdots E_e E_\nu}_{T-\text{violating}} \Bigg] + \cdots \Bigg)$$

β-decay parameters depend on the currents mediating the weak interaction

$\Rightarrow$ sensitive to **new physics** $\Leftarrow$

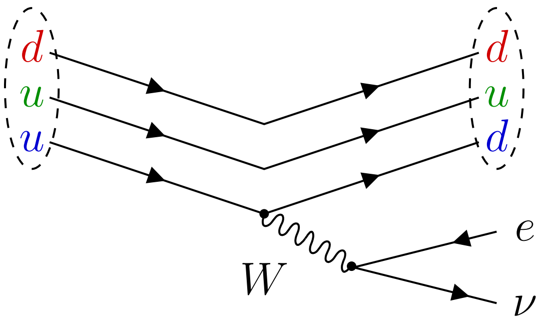
$\vec{p}_e$ θ

Goal must be $\lesssim$ **0.1%** to complement LHC

Naviliat-Čunčić and González-Alonso, Ann. Phys. **525**, 600 (2013)
Cirigliano, González-Alonso and Graesser, JHEP **1302**, 046 (2013)
Vos, Wilschut and Timmermans, RMP **87**, 1483 (2015)

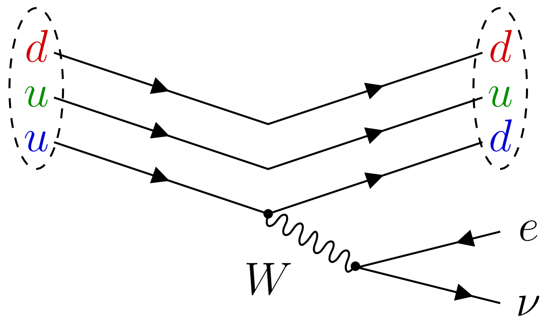
...n the SM, and $\rho \equiv \frac{C_A M_{GT}}{C_V M_F}$

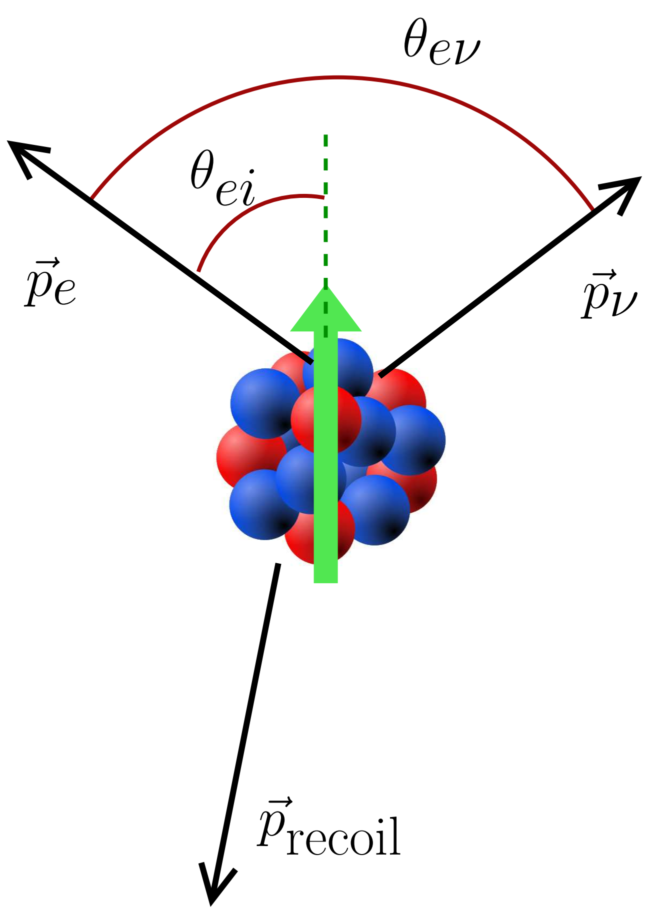
How to acheive our goal?



- perform a β decay experiment on **short-lived** isotopes

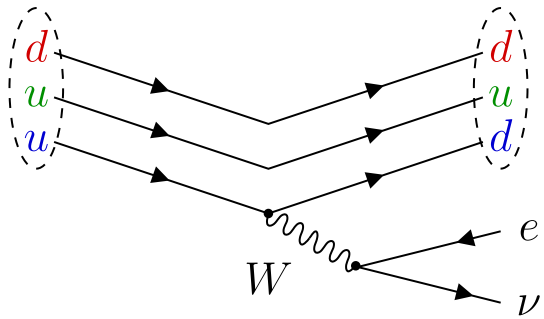
How to acheive our goal?

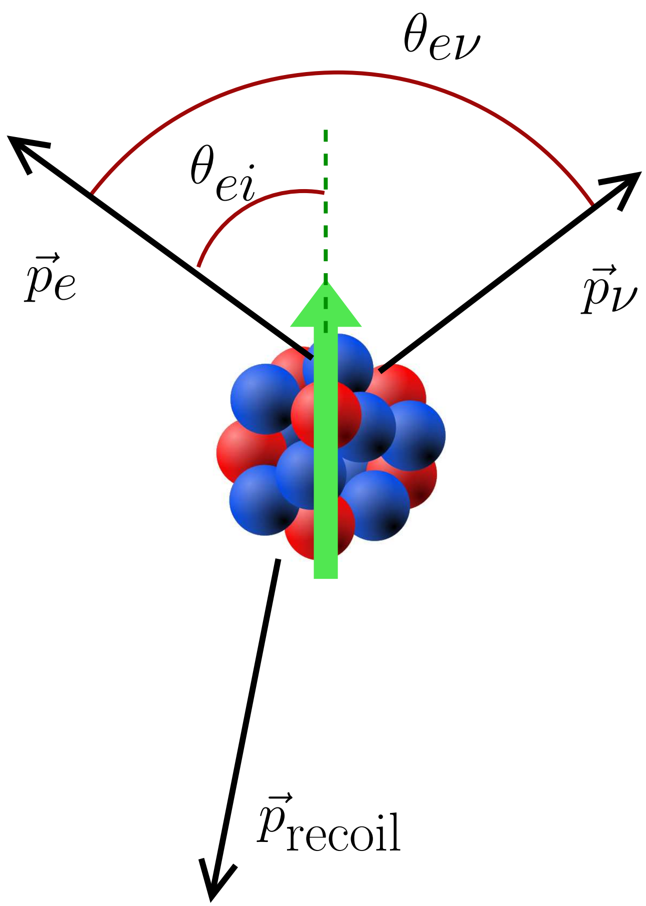




- perform a β decay experiment on **short-lived** isotopes
- make a **precision measurement** of the angular correlation parameters

How to acheive our goal?





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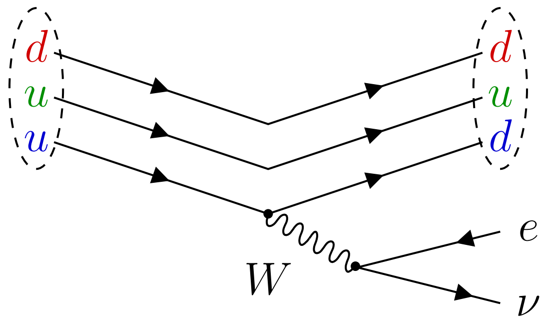
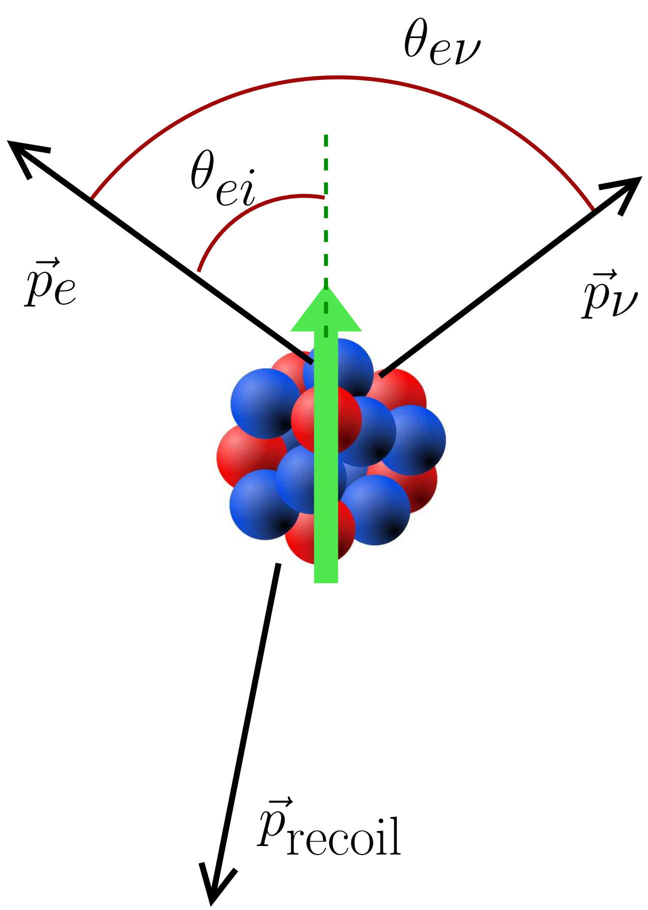
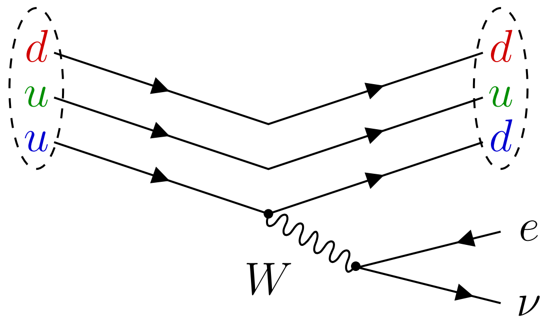




- perform a β decay experiment on **short-lived** isotopes
- make a **precision measurement** of the angular correlation parameters
- **compare** the SM predictions to observations
- look for **deviations** as an indication of **new physics**

How to acheive our goal?



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- ...the SM predictions to obser-
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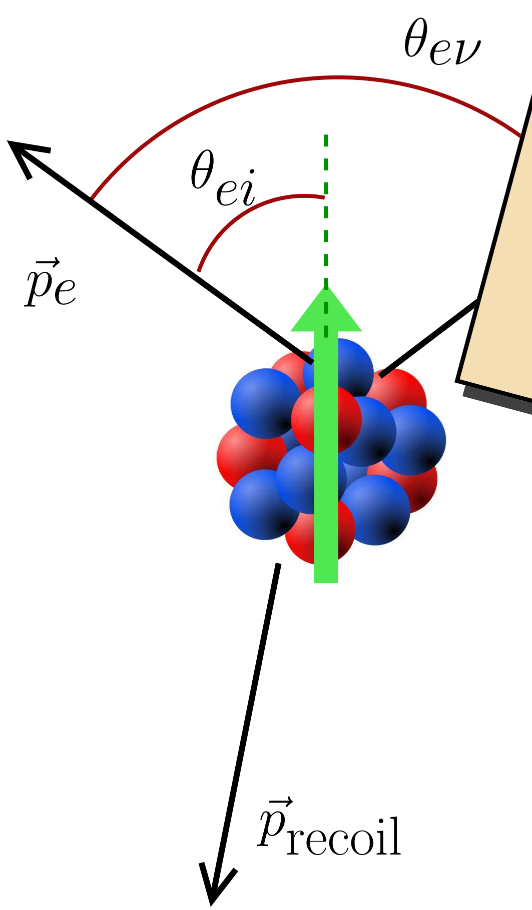


perform a nuclear measurement – often using atomic techniques – to test high-energy theories

C.S. Wu's experiment – Parity violation

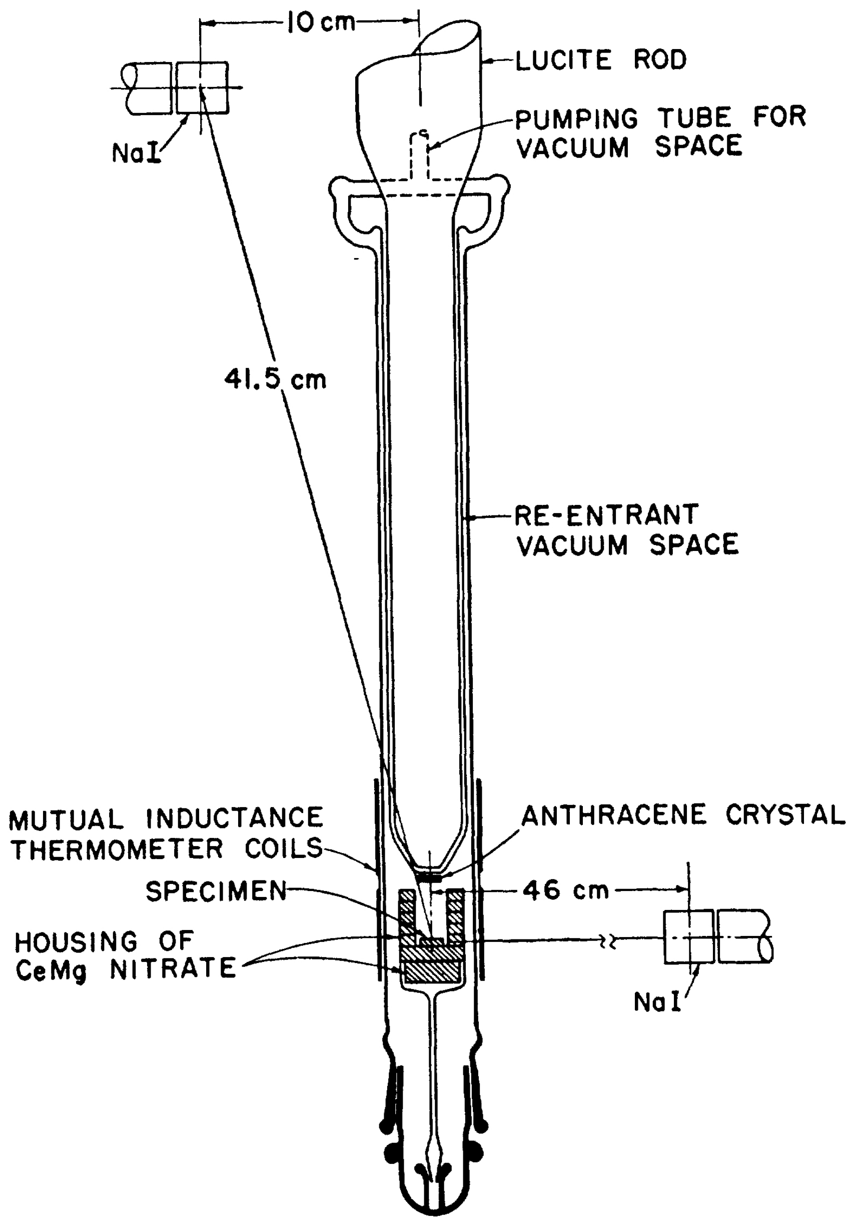
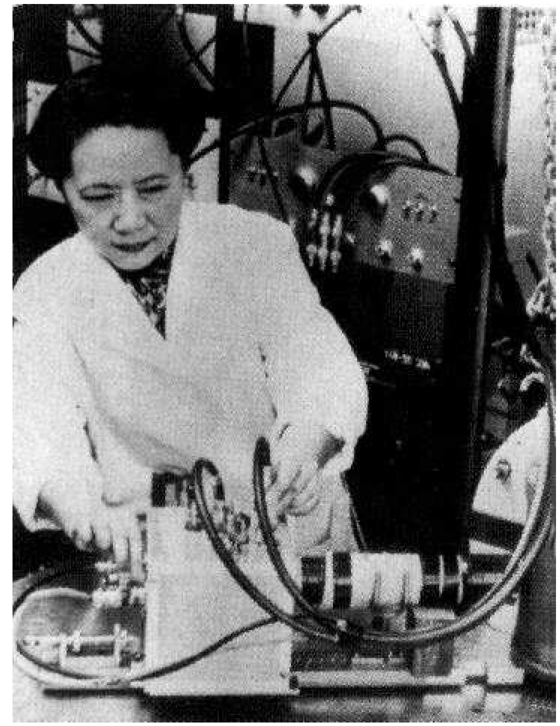
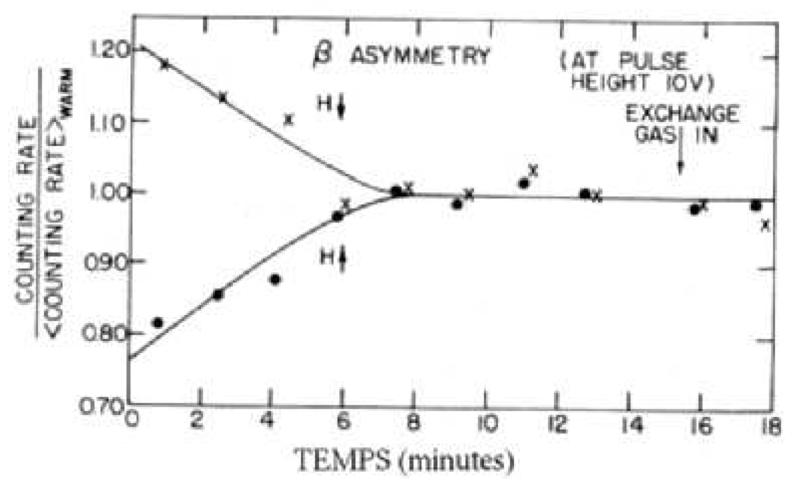


FIG. 1. Schematic drawing of the lower part of the cryostat.





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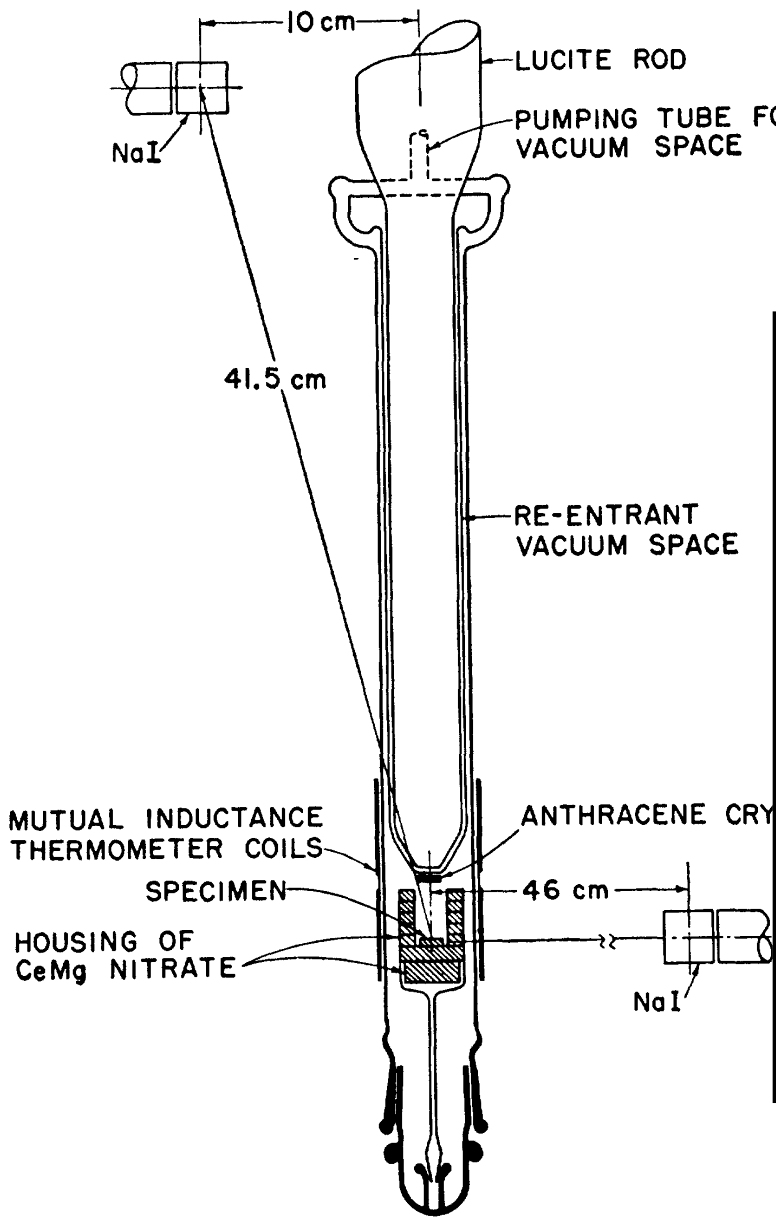
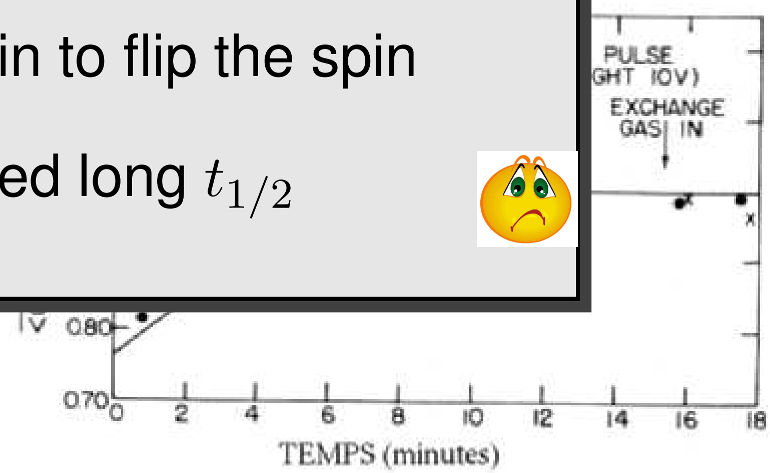


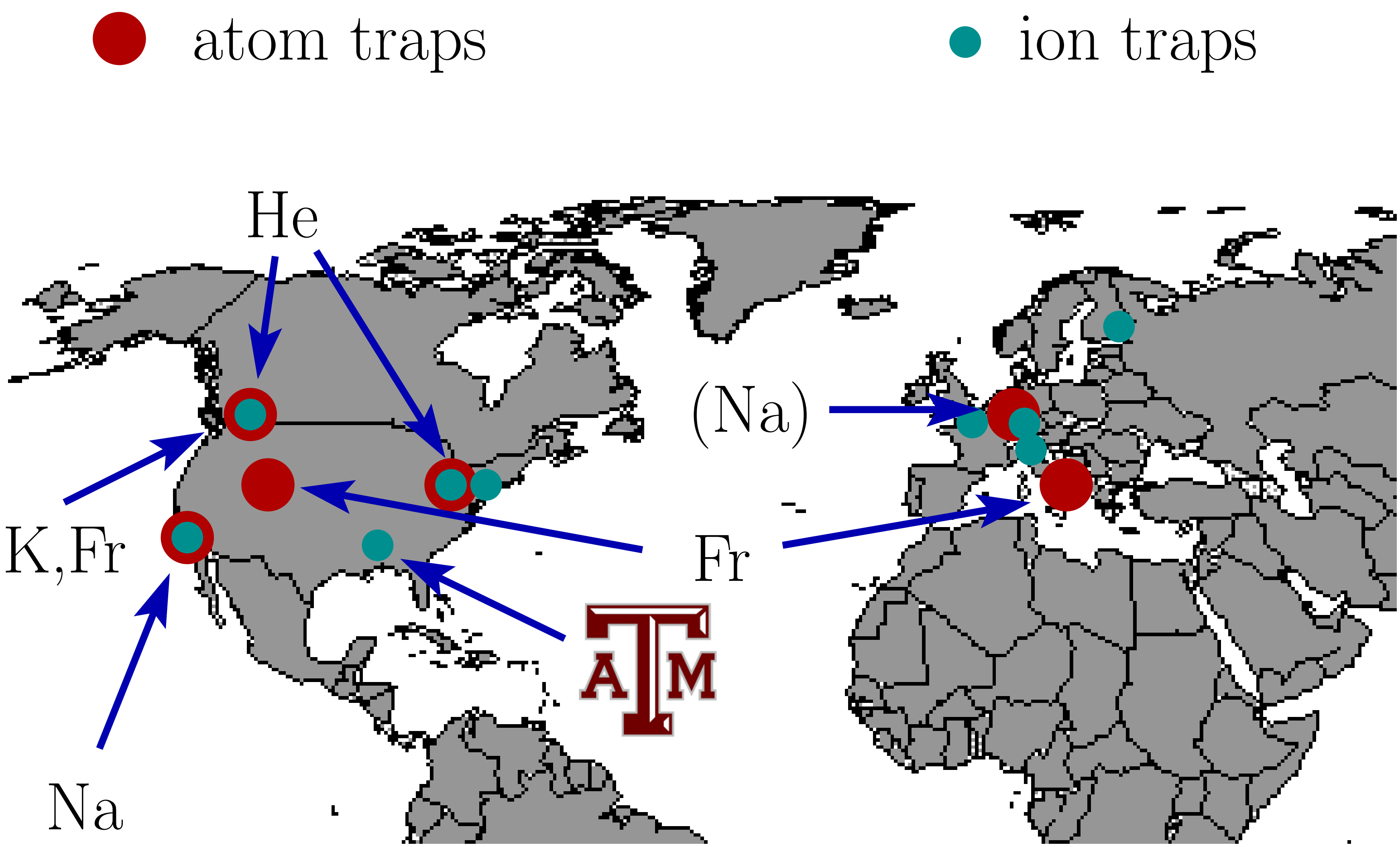
FIG. 1. Schematic drawing of the lower part of the cryostat.

- so much scattering!
- low polarization
- short relaxation time
- poor sample purity
- pain to flip the 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



Overview

1. Fundamental symmetries

- what is our **current understanding**?
- how do we test what lies **beyond**?

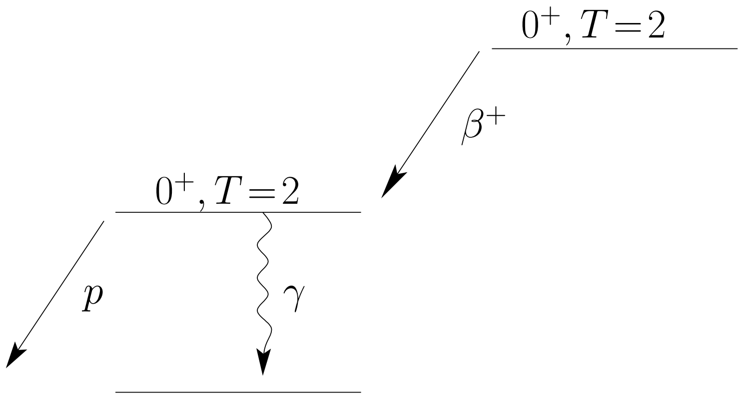
2. TAMU Penning Trap

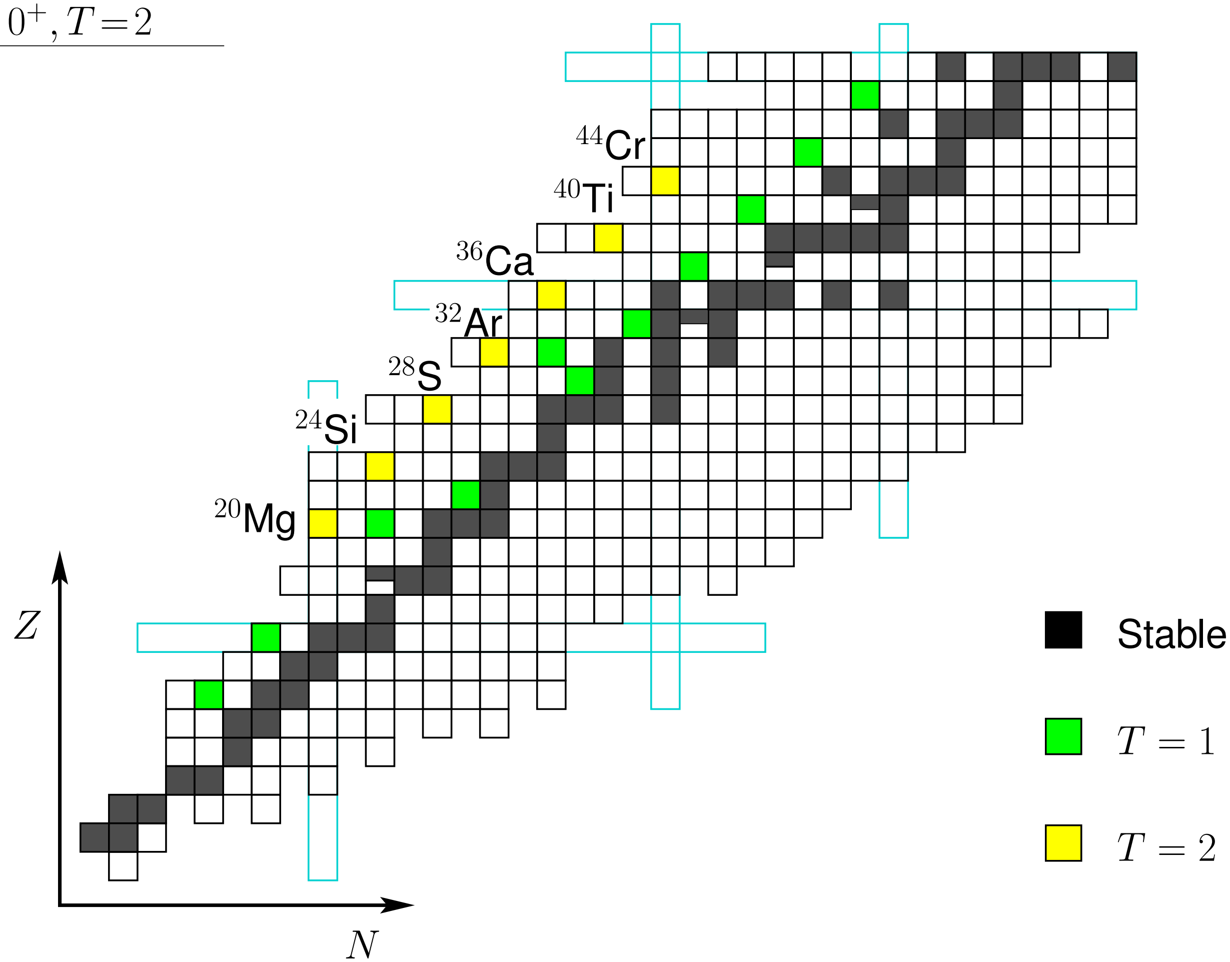
- **physics** of superallowed β decay
- **ion trapping** of proton-rich nuclei at T-REX

3. TRIUMF Neutral Atom Trap

- angular correlations of **polarized ^{37}K**
- **recent results**

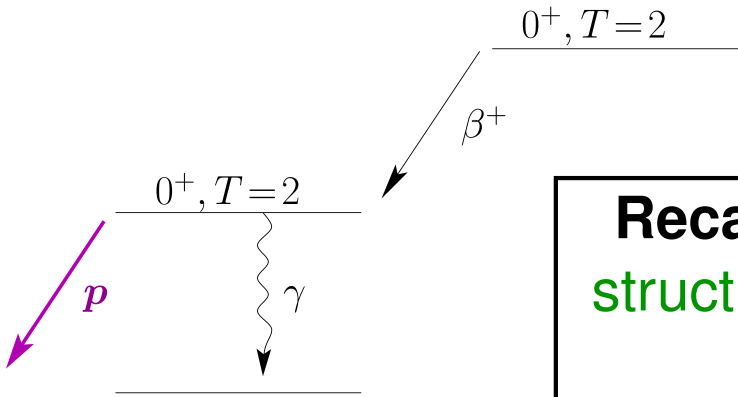
$T = 2$ superallowed decays

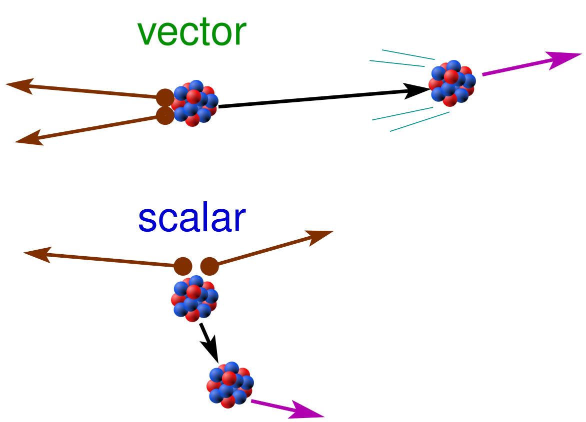


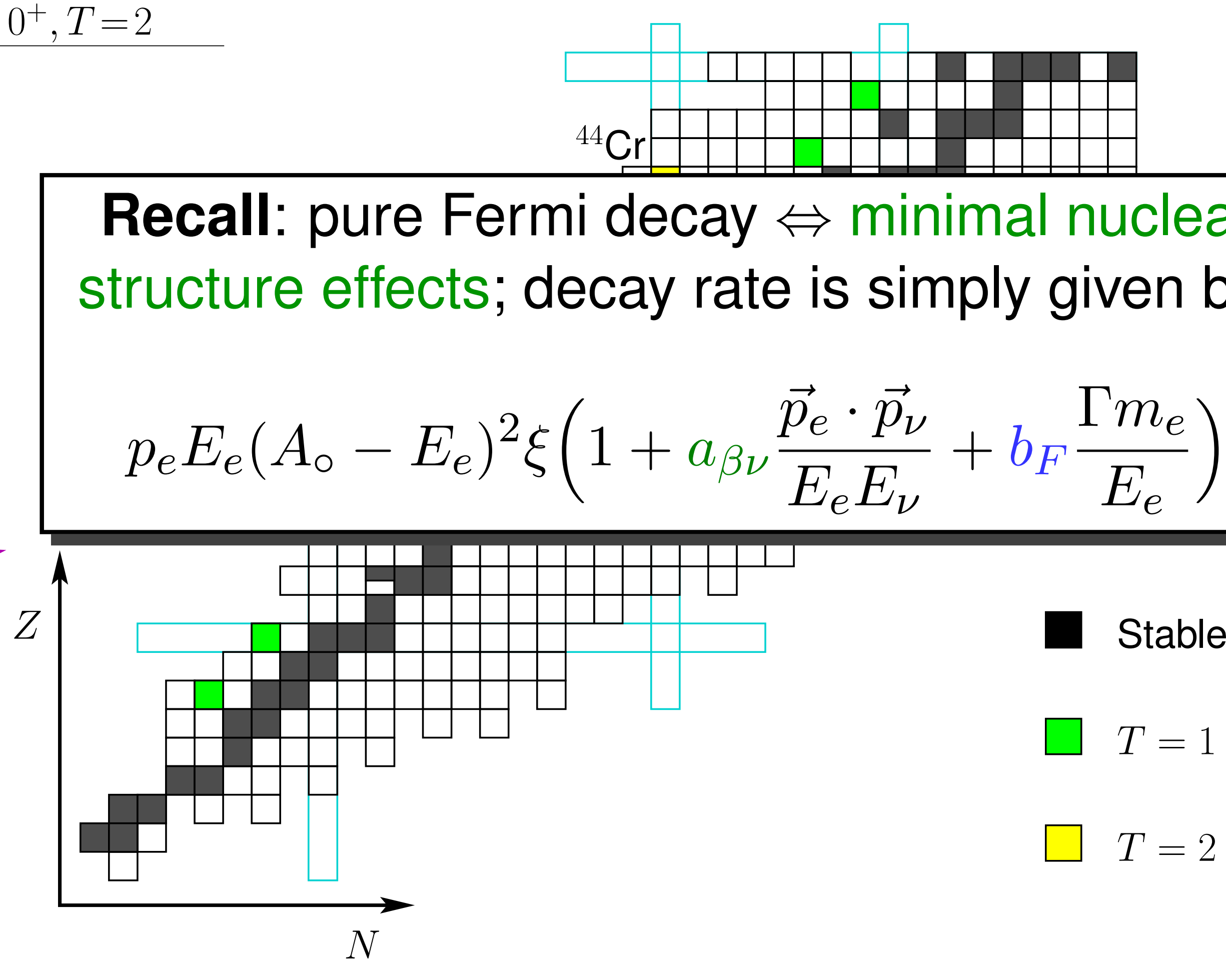


- $\beta - \nu$ correlations
- model-dependence of δ_C calcs seem to depend on T . . .
- new cases for V_{ud}

$T = 2$ superallowed decays







Recall: pure Fermi decay ⇔ minimal nuclear structure effects; decay rate is simply given by:

$$p_e E_e (A_\circ - E_e)^2 \xi \left(1 + a_{\beta\nu} \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b_F \frac{\Gamma m_e}{E_e}\right)$$

- $\beta - \nu$ correlations
- model-dependence of δ_C calcs seem to depend on T ...
- new cases for V_{ud}

$\beta - \nu$ correlation from ^{32}Ar

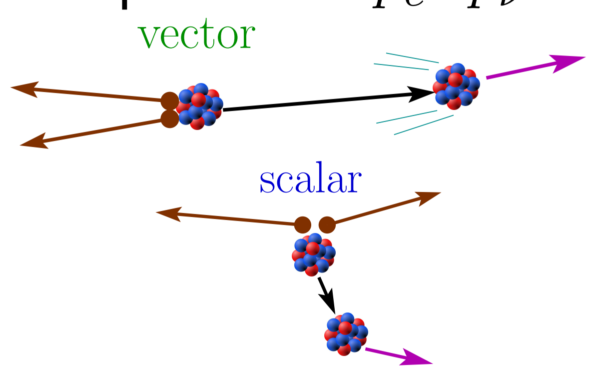
VOLUME 83, NUMBER 7 PHYSICAL REVIEW LETTERS 16 AUGUST 1999

Positron-Neutrino Correlation in the $0^+ \to 0^+$ Decay of ^{32}Ar

E. G. Adelberger,[1] C. Ortiz,[2] A. García,[2] H. E. Swanson,[1] M. Beck,[1] O. Tengblad,[3] M. J. G. Borge,[3] I. Martel,[4]
H. Bichsel,[1] and the ISOLDE Collaboration[4]
[1]*Department of Physics, University of Washington, Seattle, Washington 98195-1560*
[2]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556*
[3]*Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain*
[4]*EP Division, CERN, Geneva, Switzerland CH-1211*
(Received 24 February 1999)

The positron-neutrino correlation in the $0^+ \to 0^+$ β decay of ^{32}Ar was measured at ISOLDE by analyzing the effect of lepton recoil on the shape of the narrow proton group following the superallowed decay. Our result is consistent with the standard model prediction. For vanishing Fierz interference we find $a = 0.9989 \pm 0.0052 \pm 0.0039$, which yields improved constraints on scalar weak interactions.

Doppler shape of delayed proton depends on $\vec{p}_e \cdot \vec{p}_\nu$!



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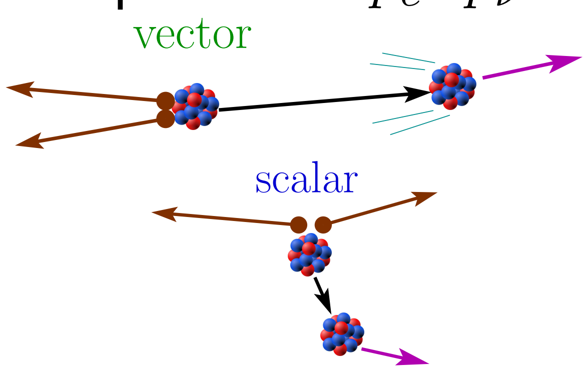
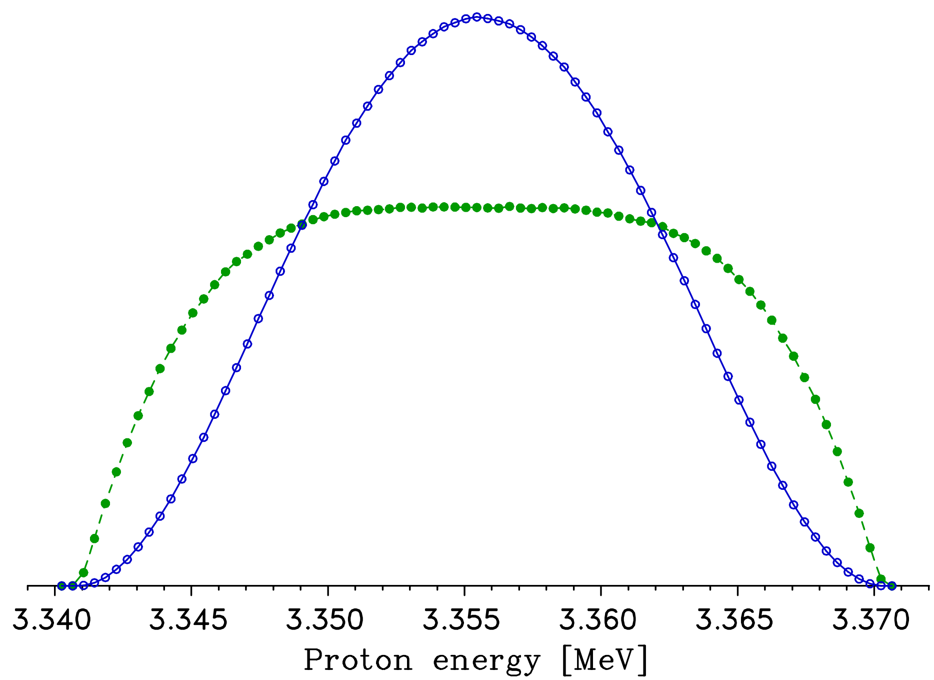
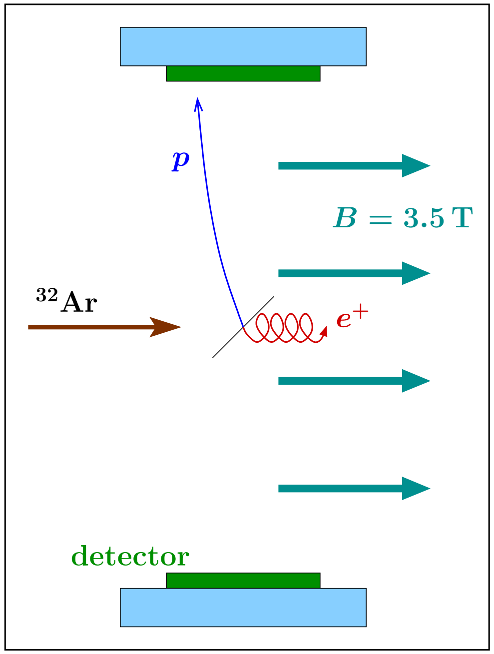




$\beta - \nu$ correlation from ^{32}Ar

Vᴏʟᴜᴍᴇ 83, Nᴜᴍʙᴇʀ 7 PHYSICAL REVIEW LETTERS 16 Aᴜɢᴜsᴛ 1999



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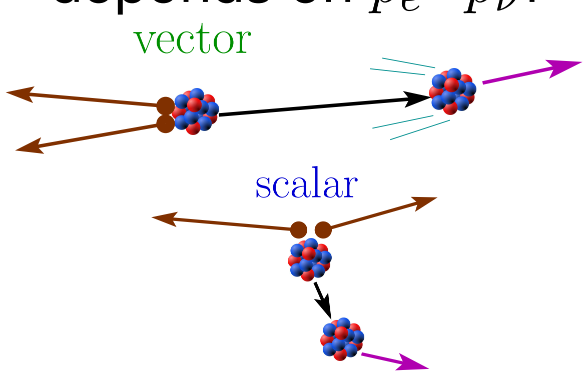

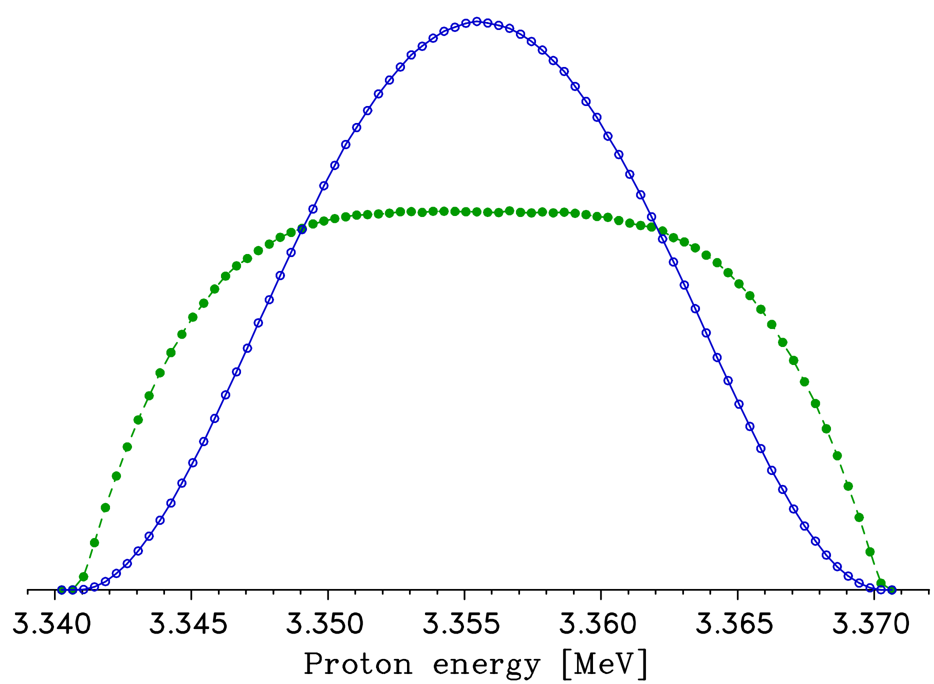

But why throw away useful information??

We can improve the correlation measurement
by retaining information about the β

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utilize technology of Penning traps to provide a
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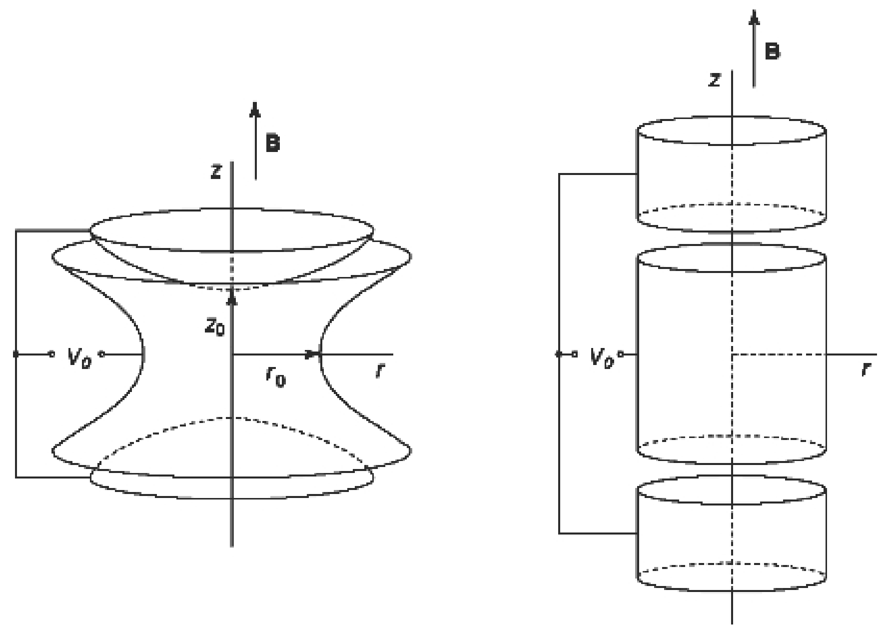

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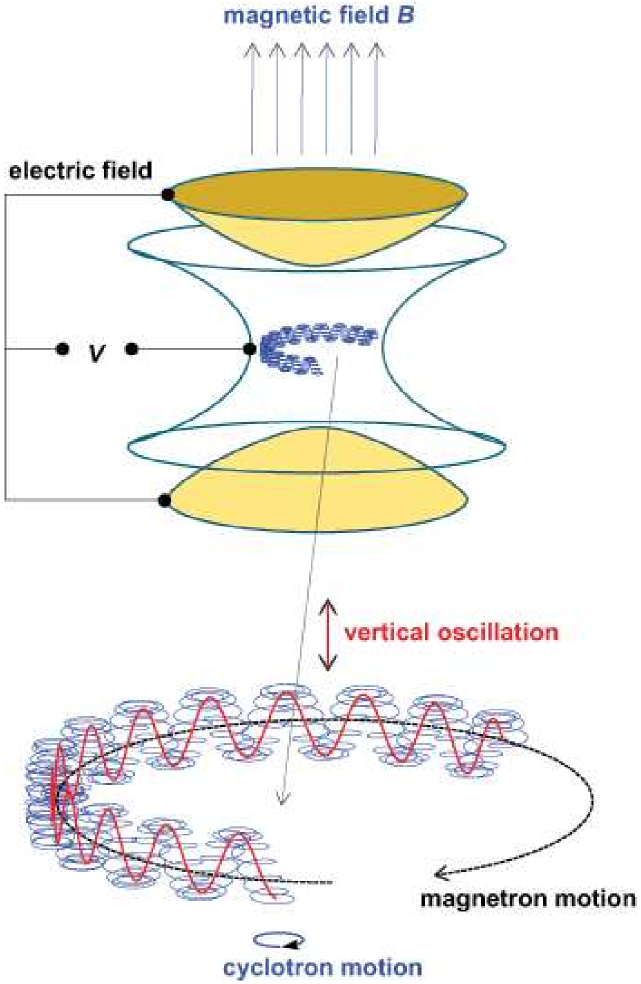

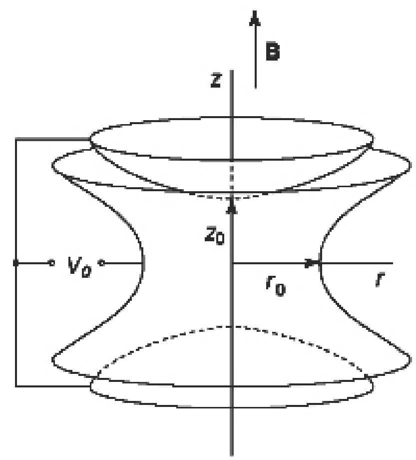

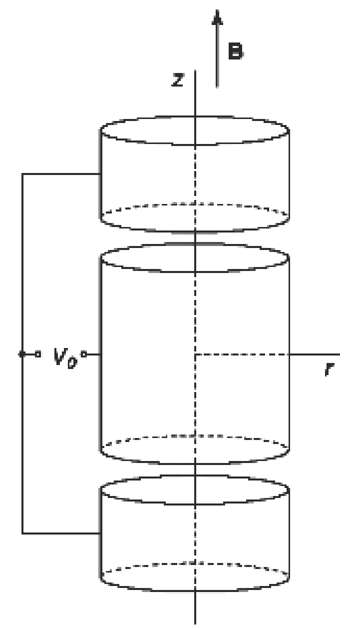

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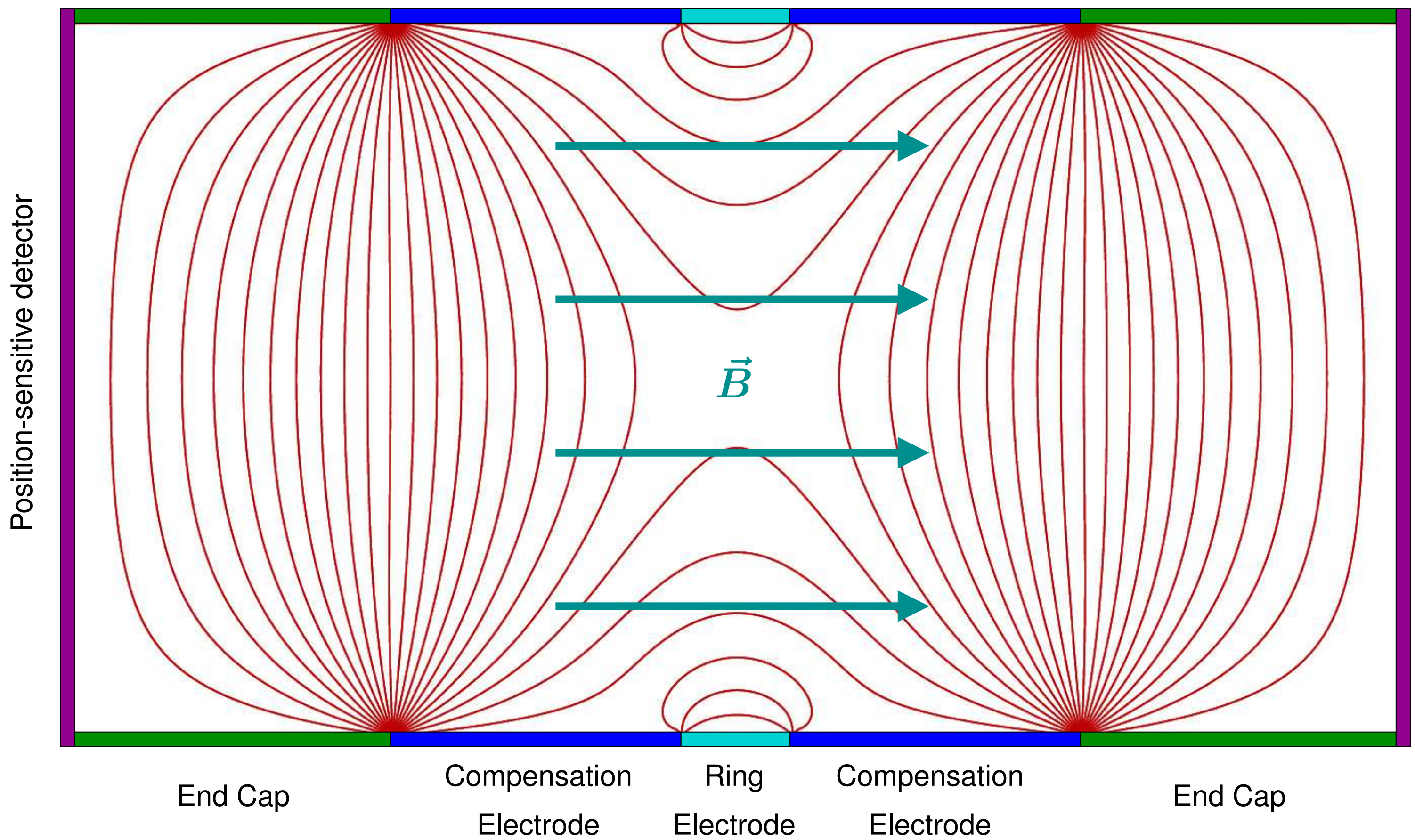

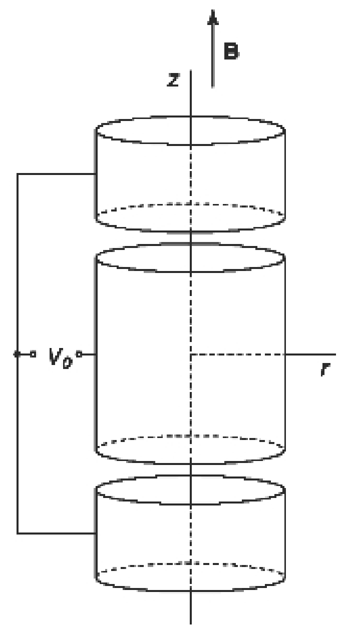

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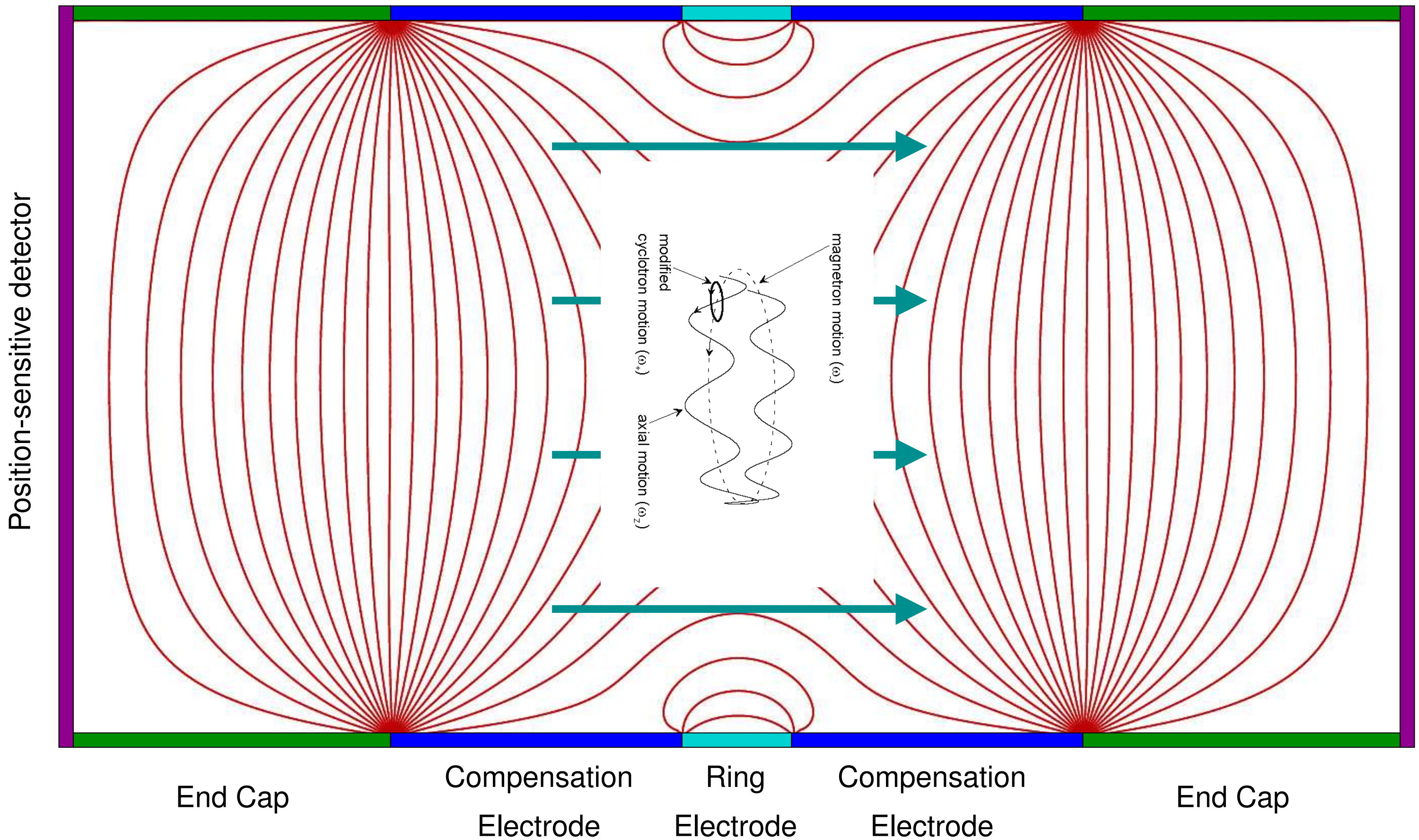

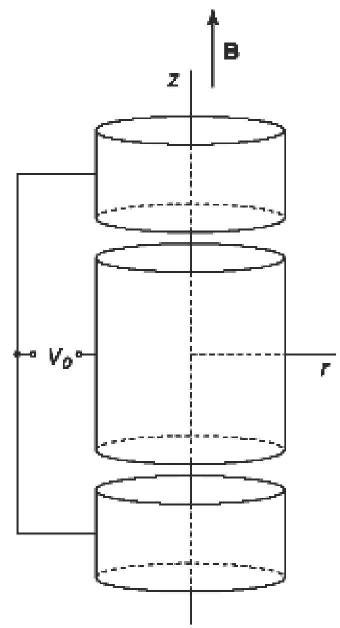

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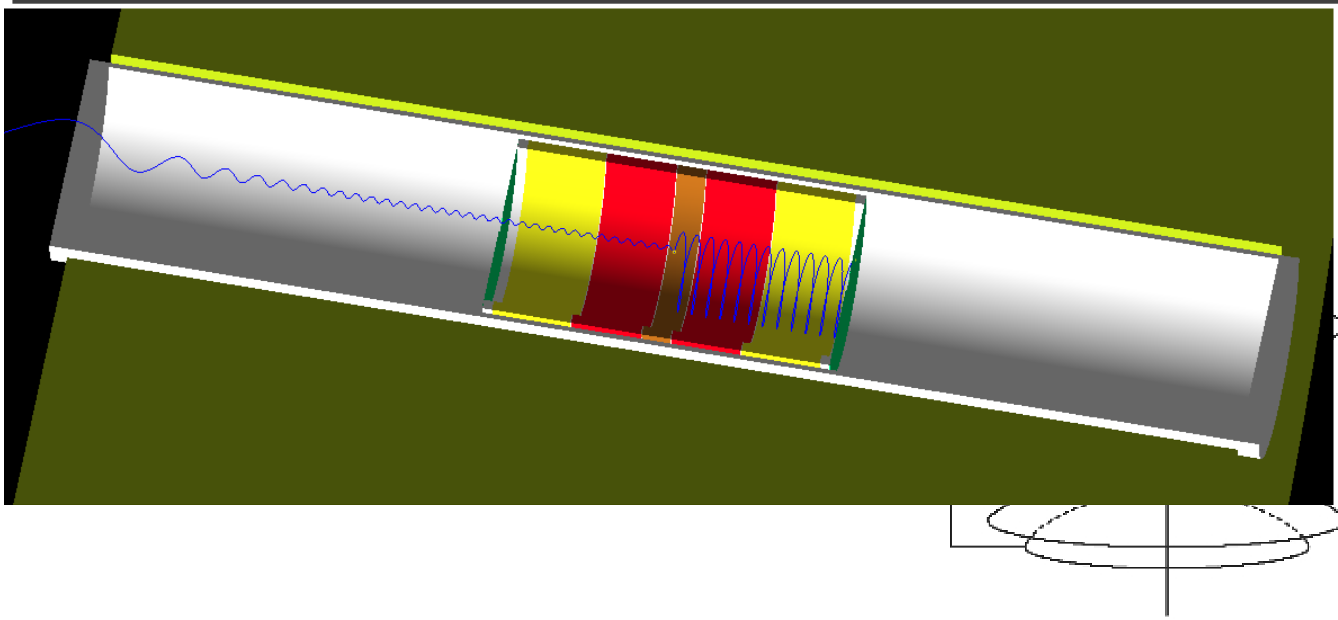

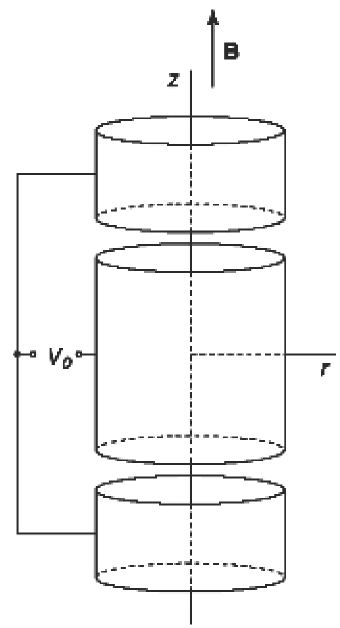

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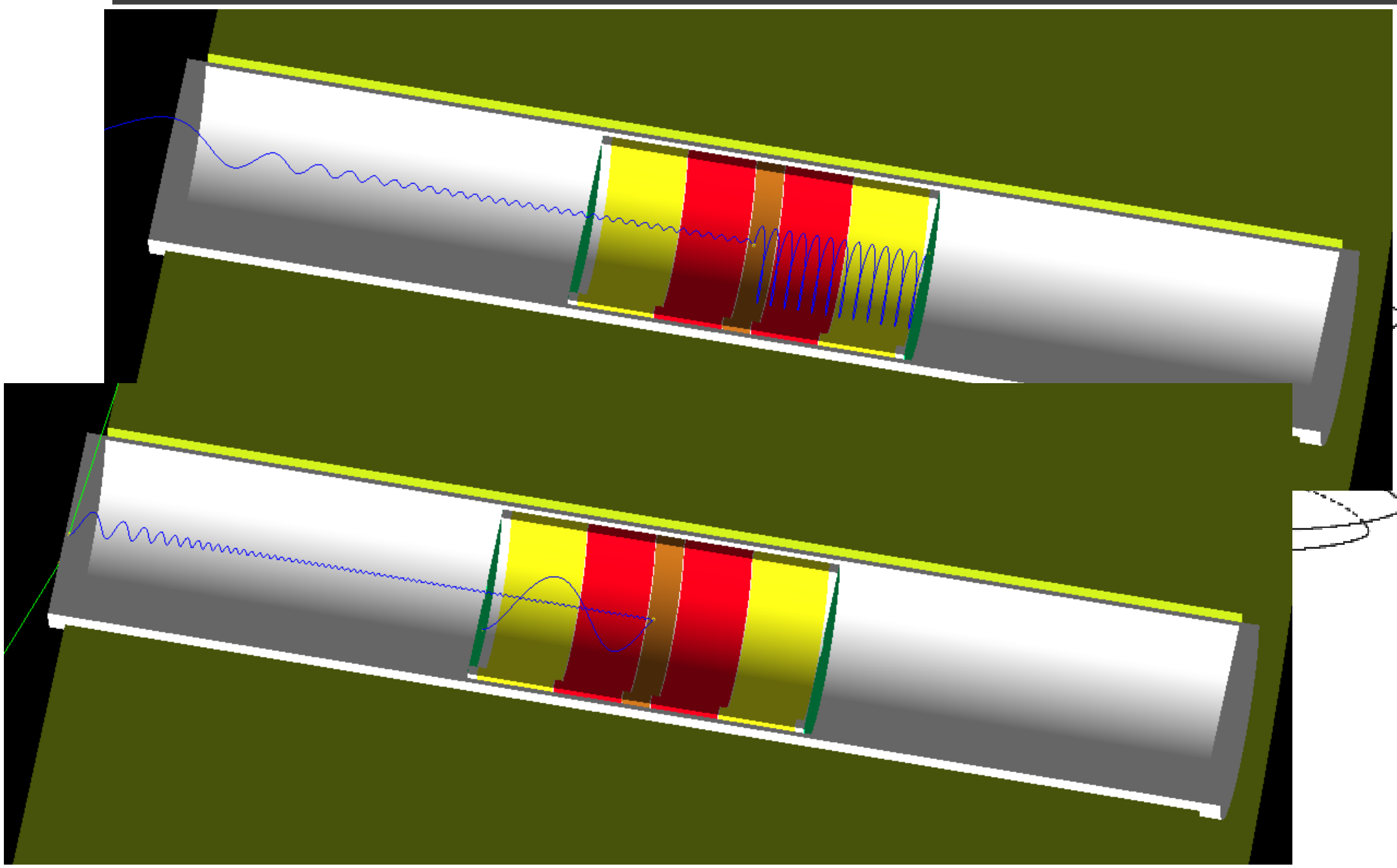

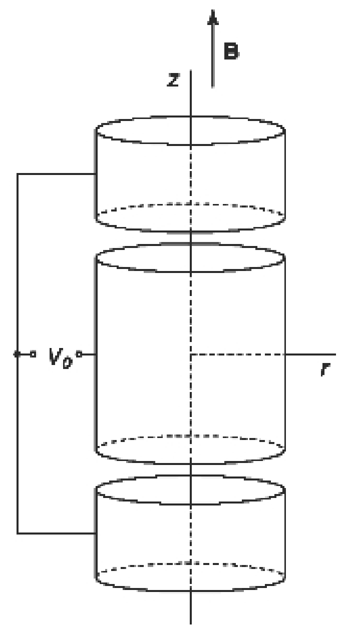

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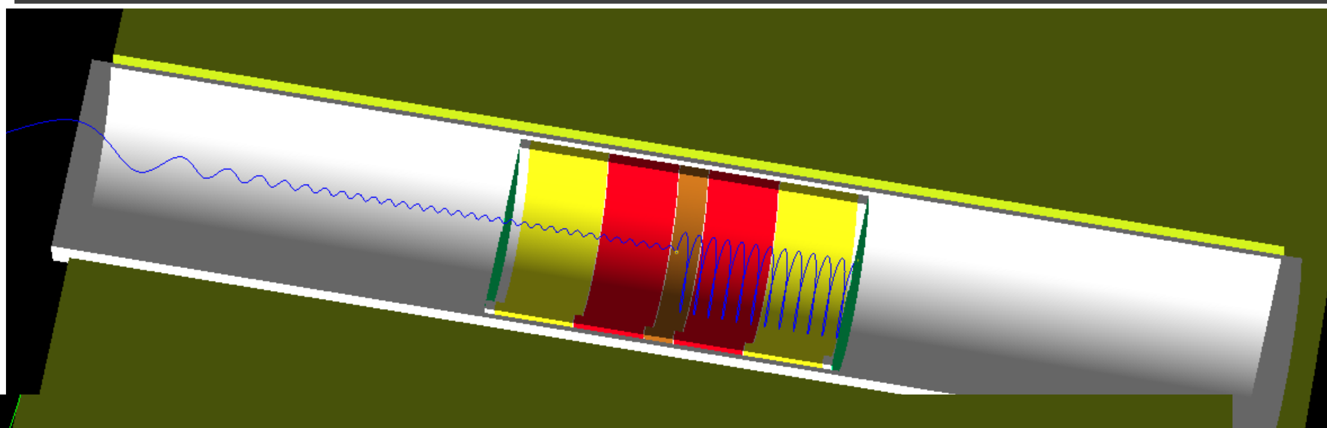
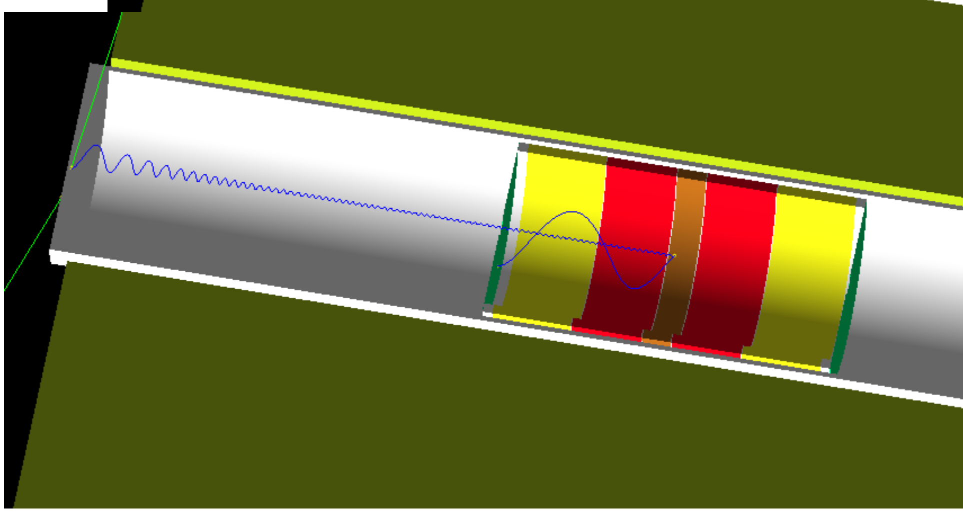
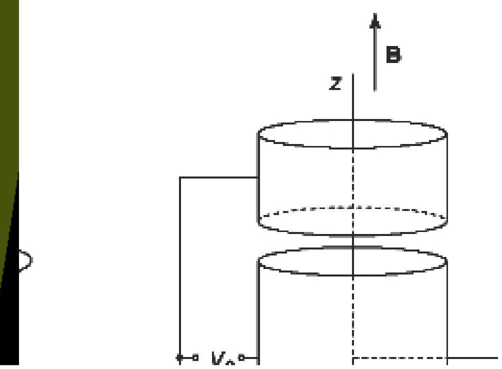
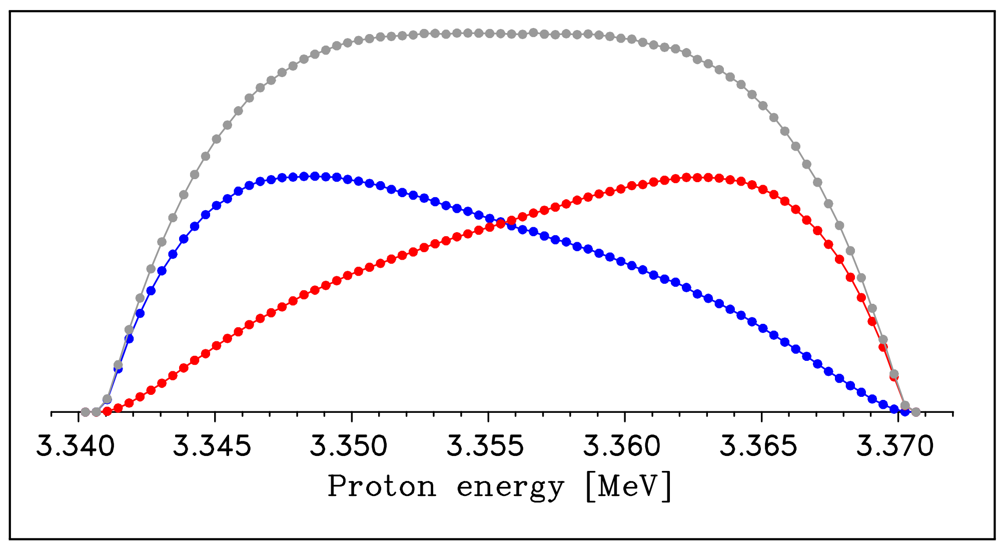
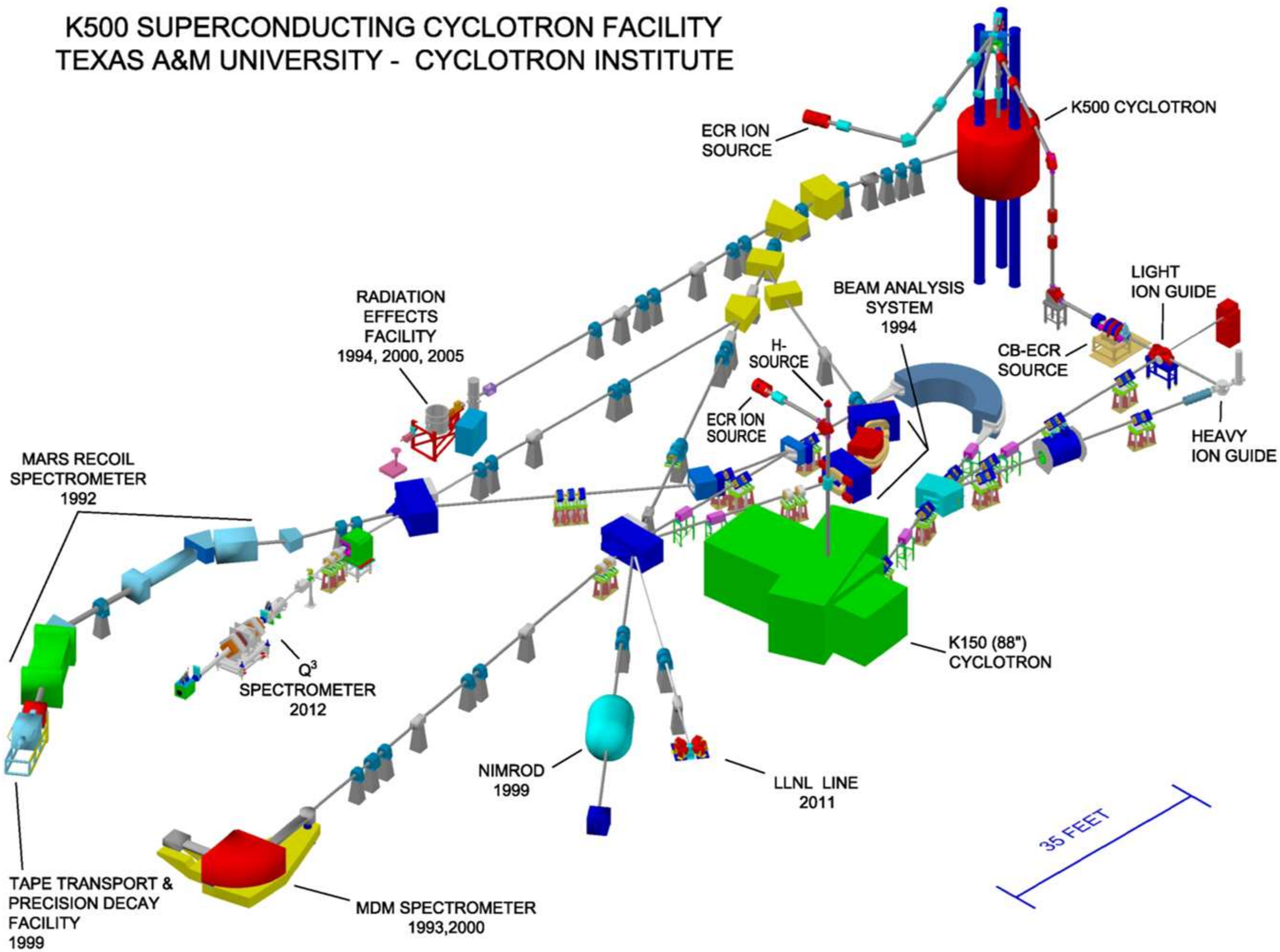






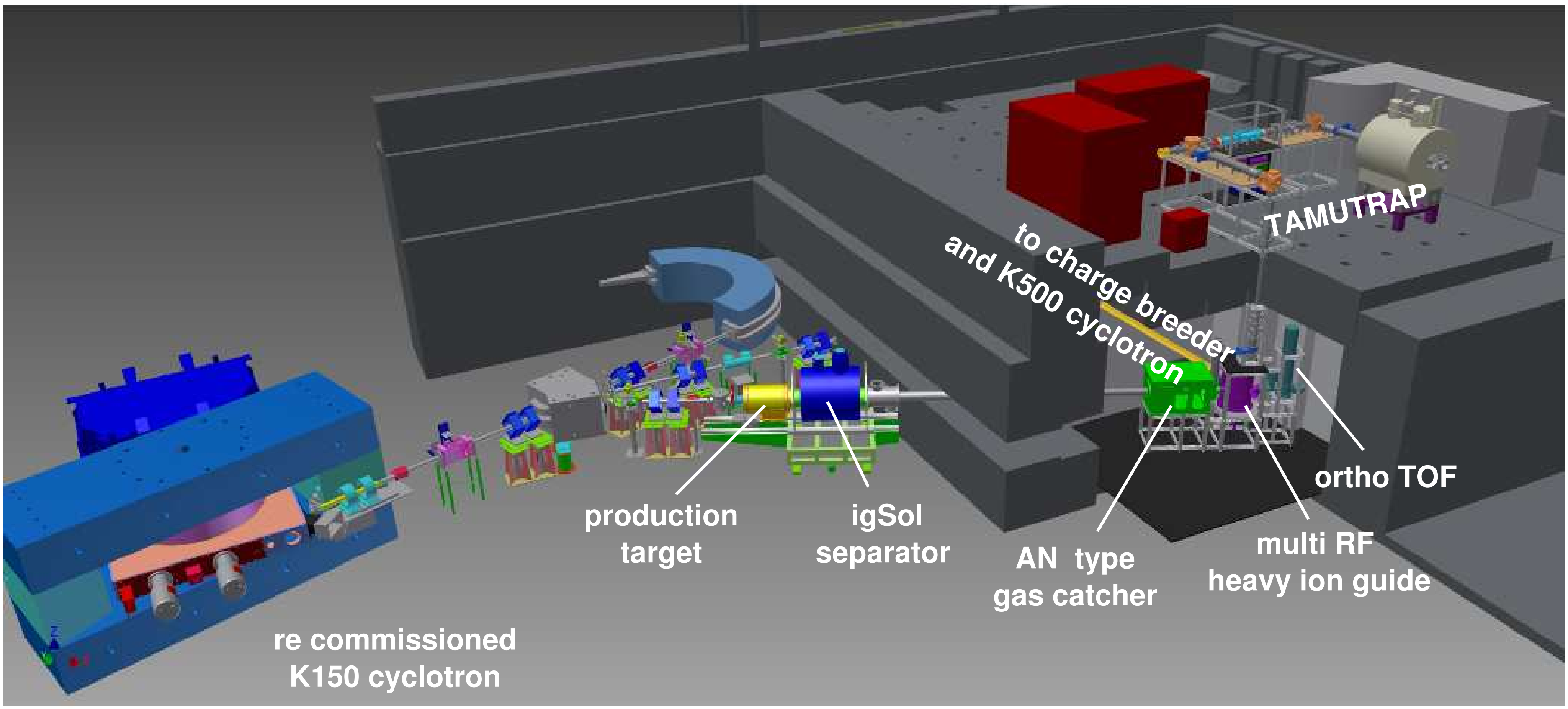


A Penning trap at T-REX CI/TAMU



The Texas A&M University Penning Trap

- will be the **world's most open-geometry** ion trap!
- uniquely suited for studying β-delayed proton decays:
  $\beta - \nu$ correlations, ft values/V_{ud}
- mass measurements, EC studies, laser spectroscopy, ...



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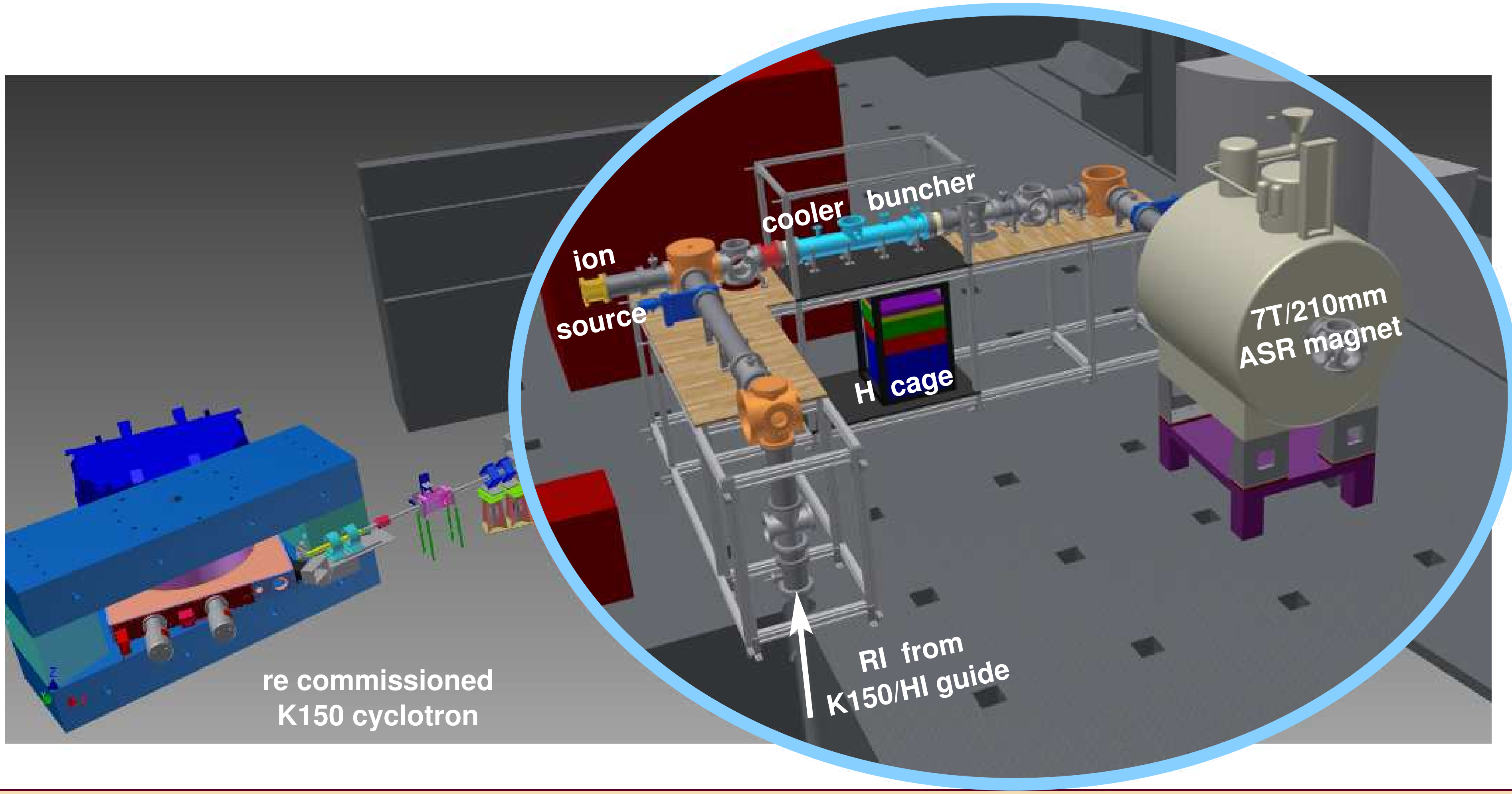

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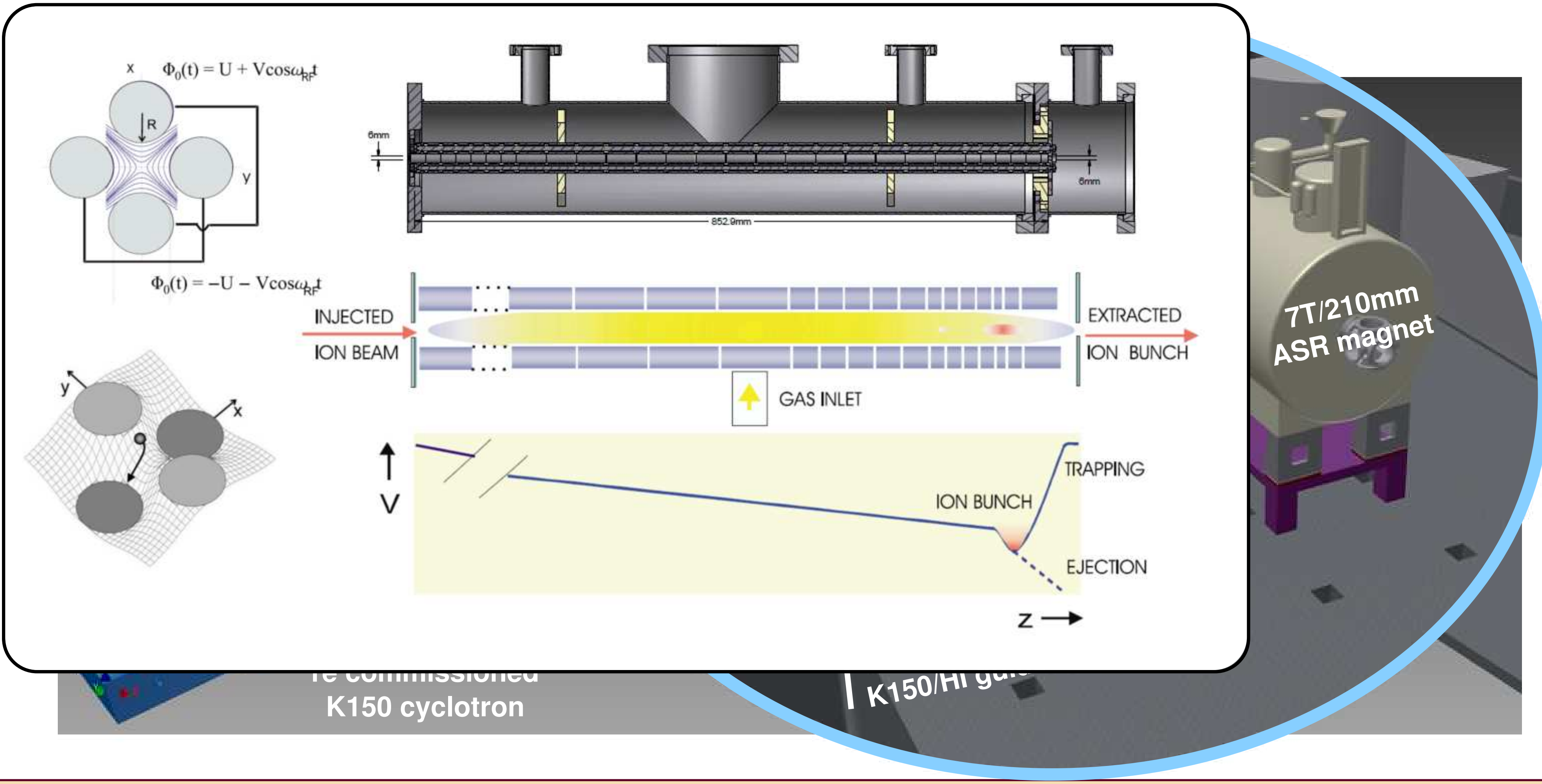
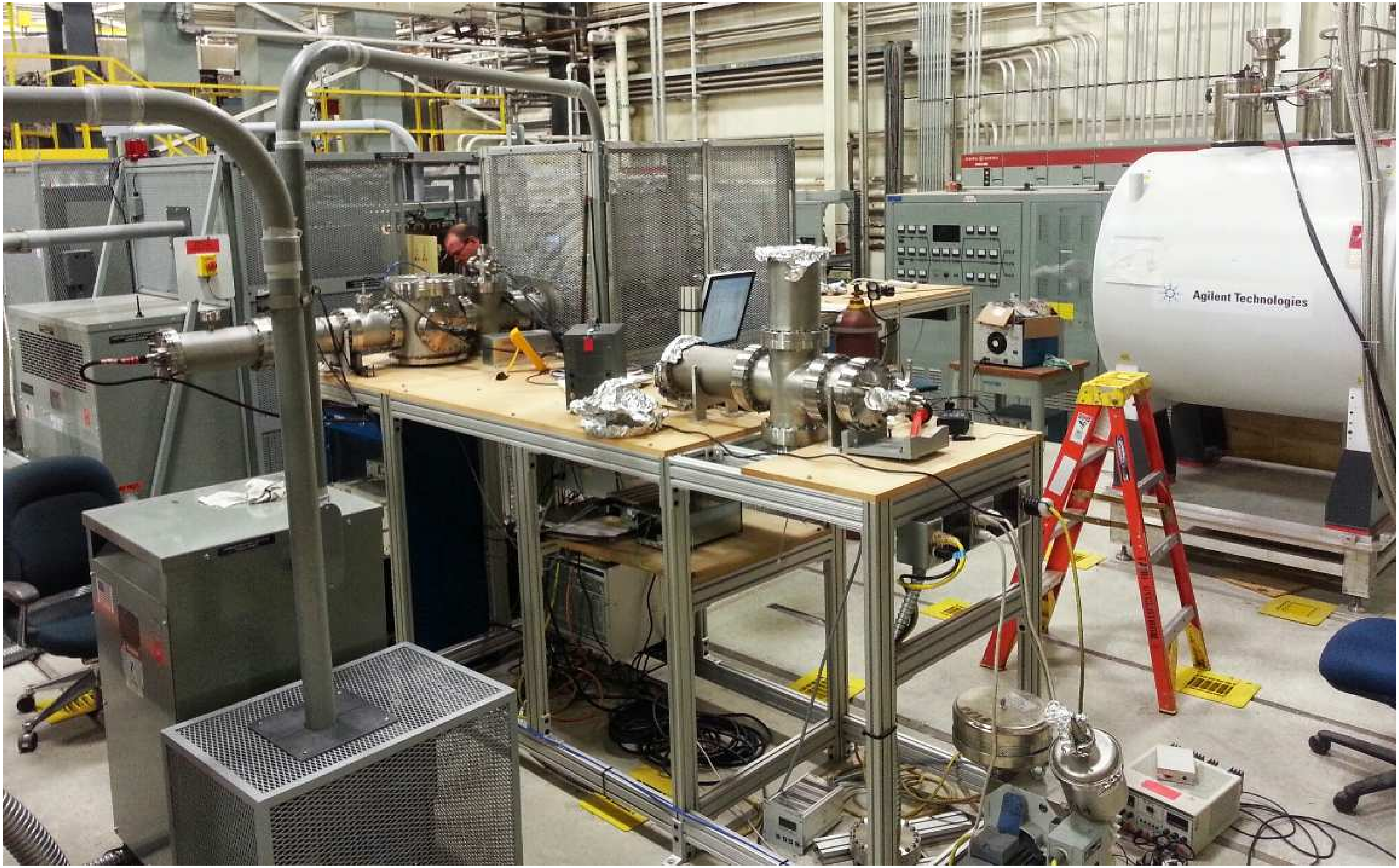
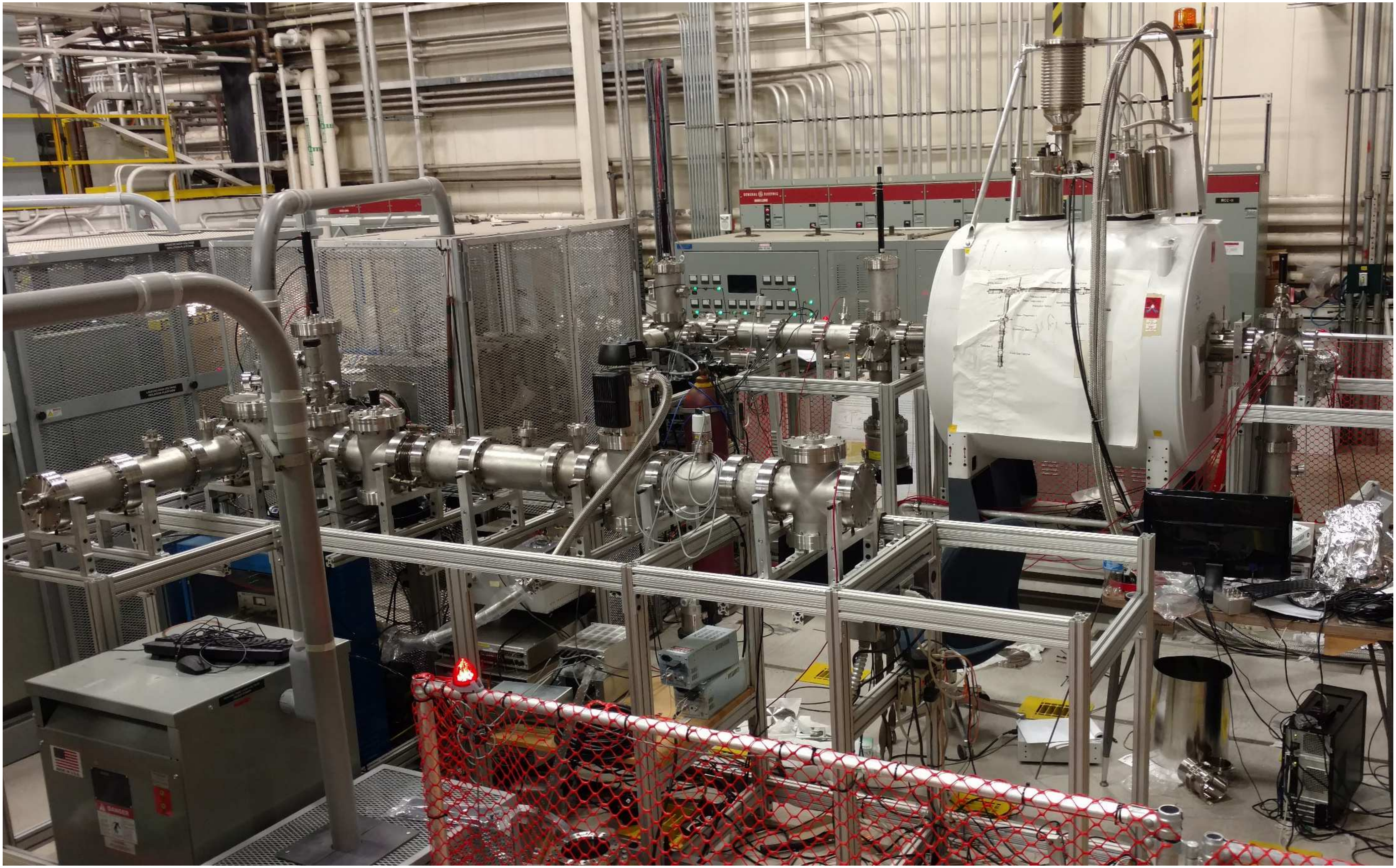


Status in 2013



Current Status



Current Status

Recent Milestones

- RFQ commissioned with high efficiency [Mehlman PhD]

Current Status

Current Status

Recent Milestones

- RFQ commissioned with high efficiency [Mehlman PhD]
- Prototype (45-mm diam) trap installed

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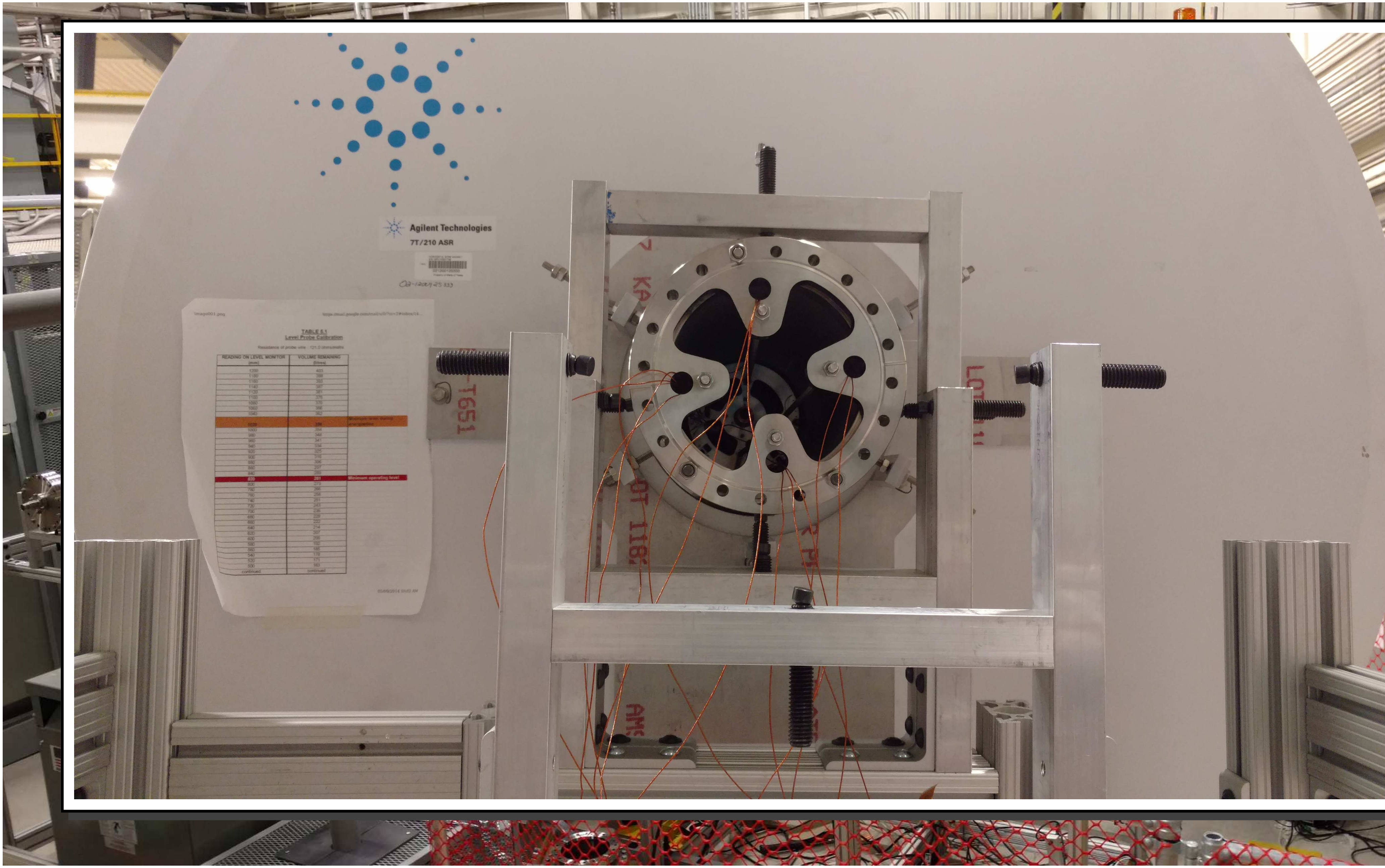

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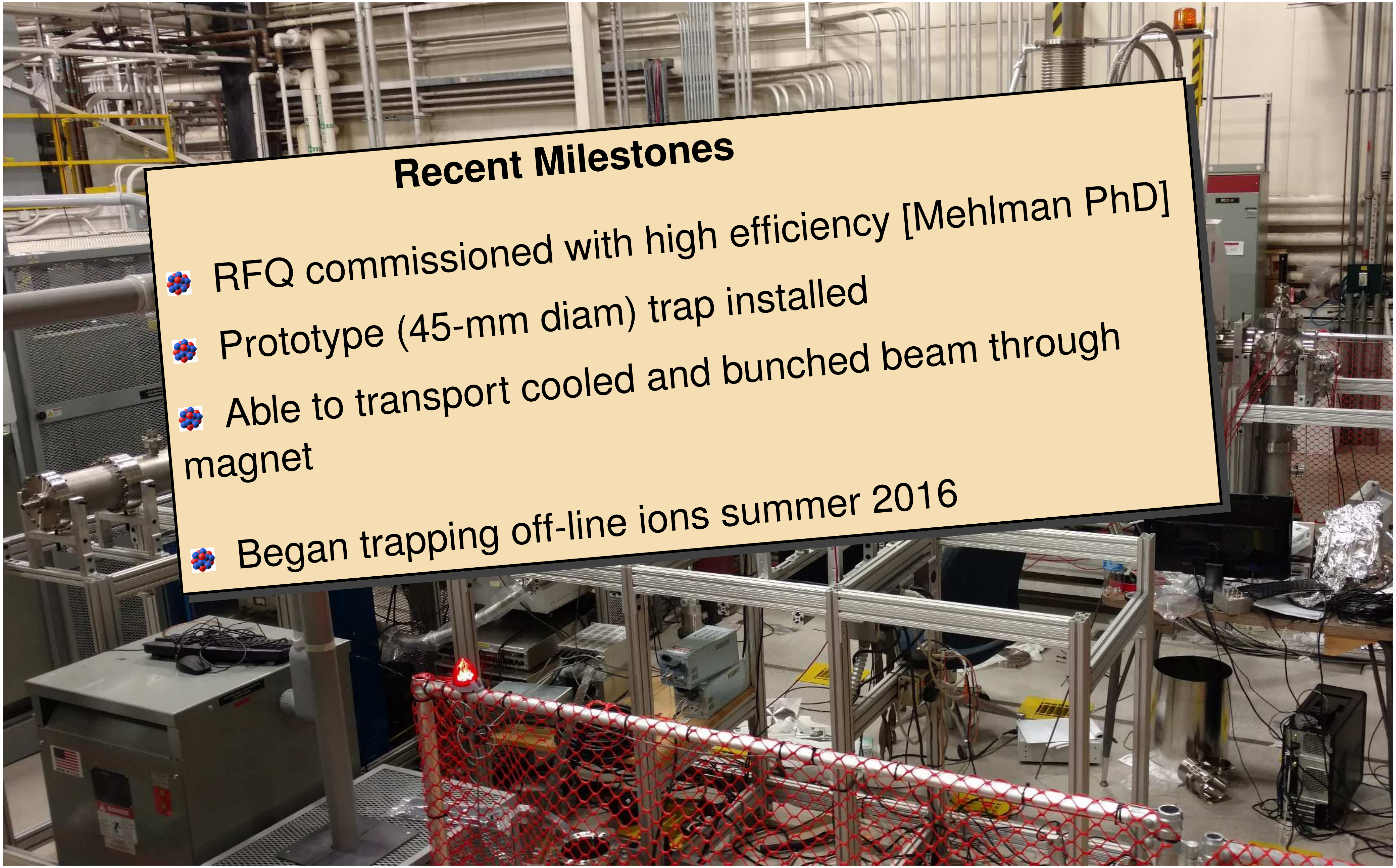

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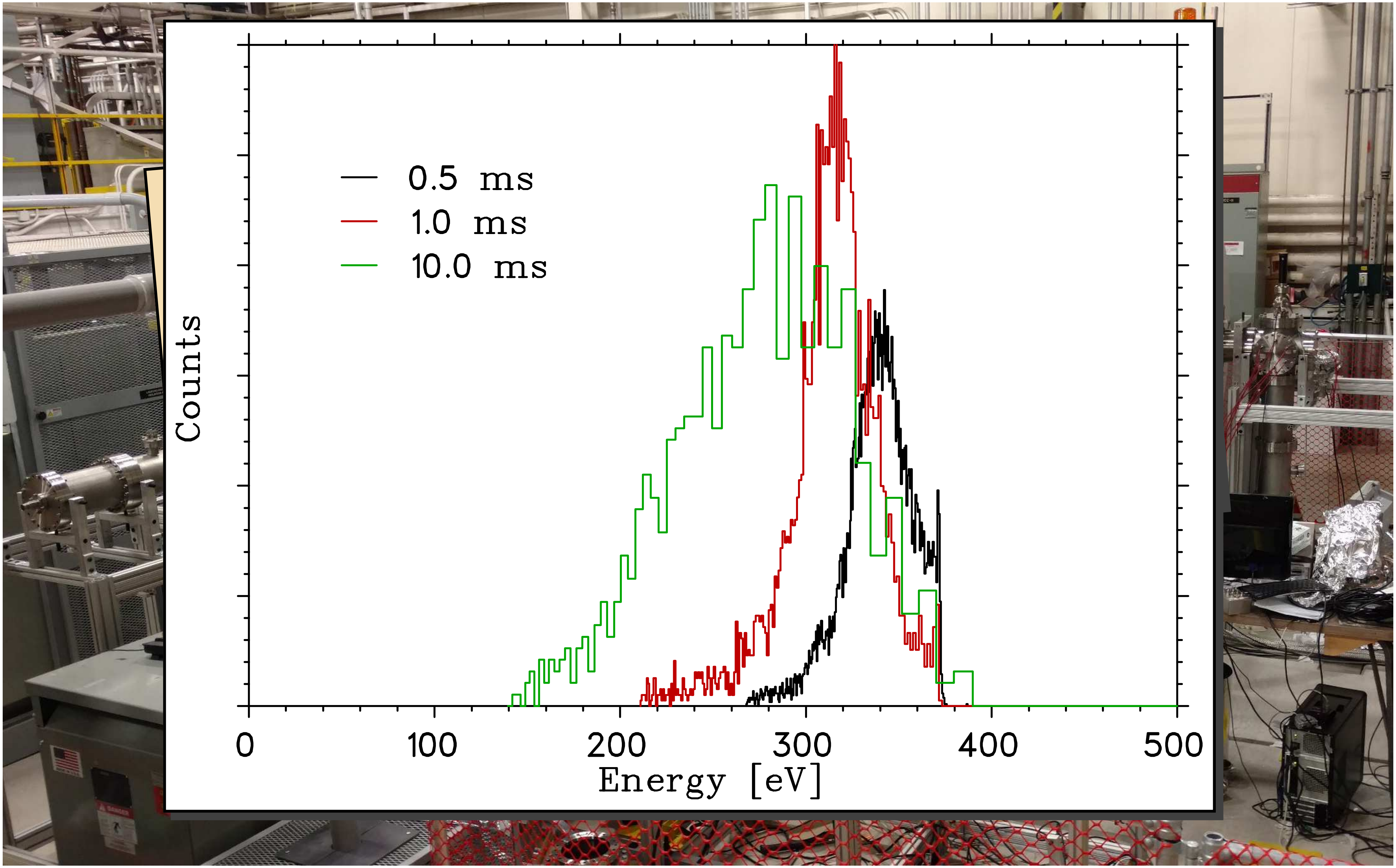

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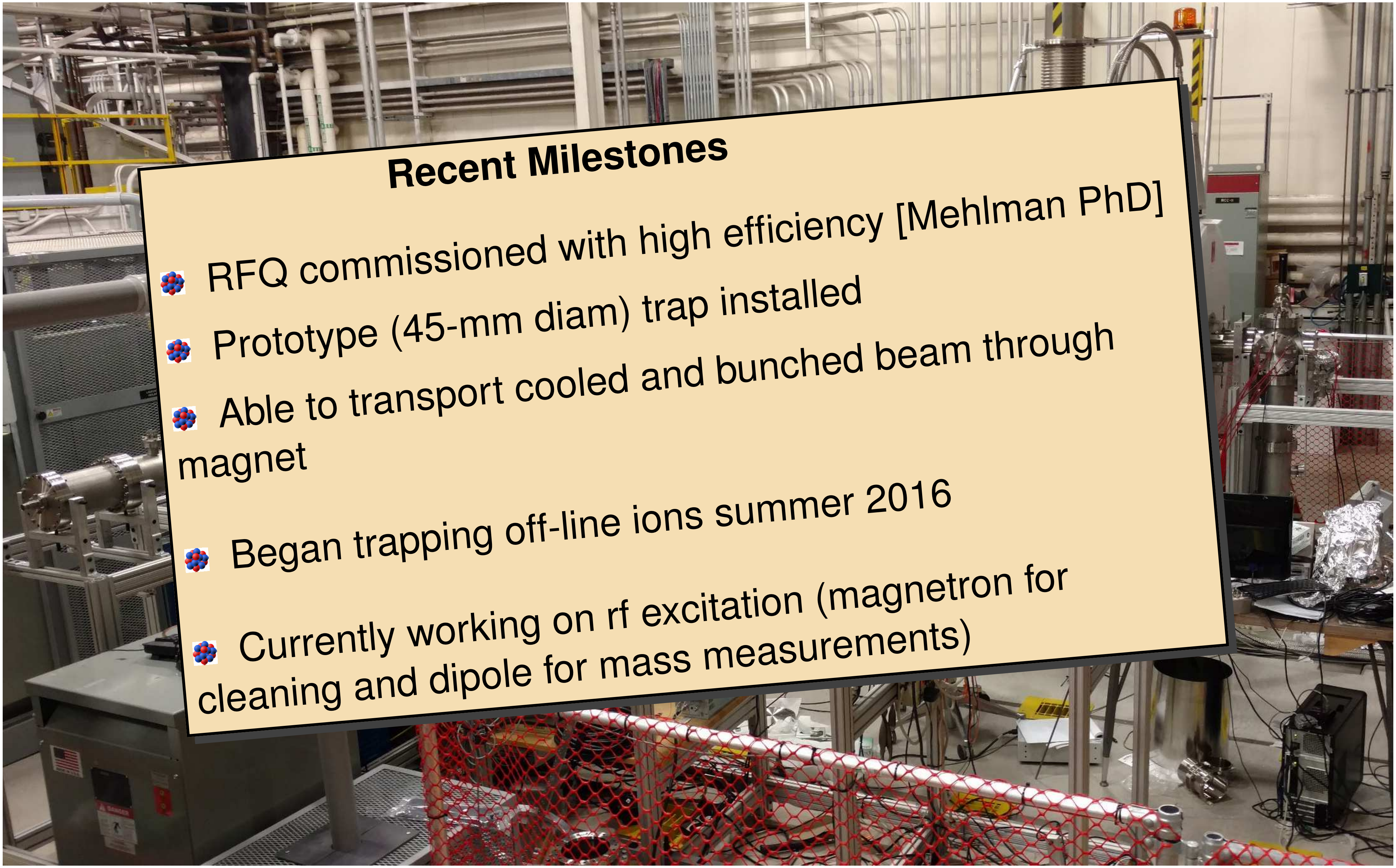

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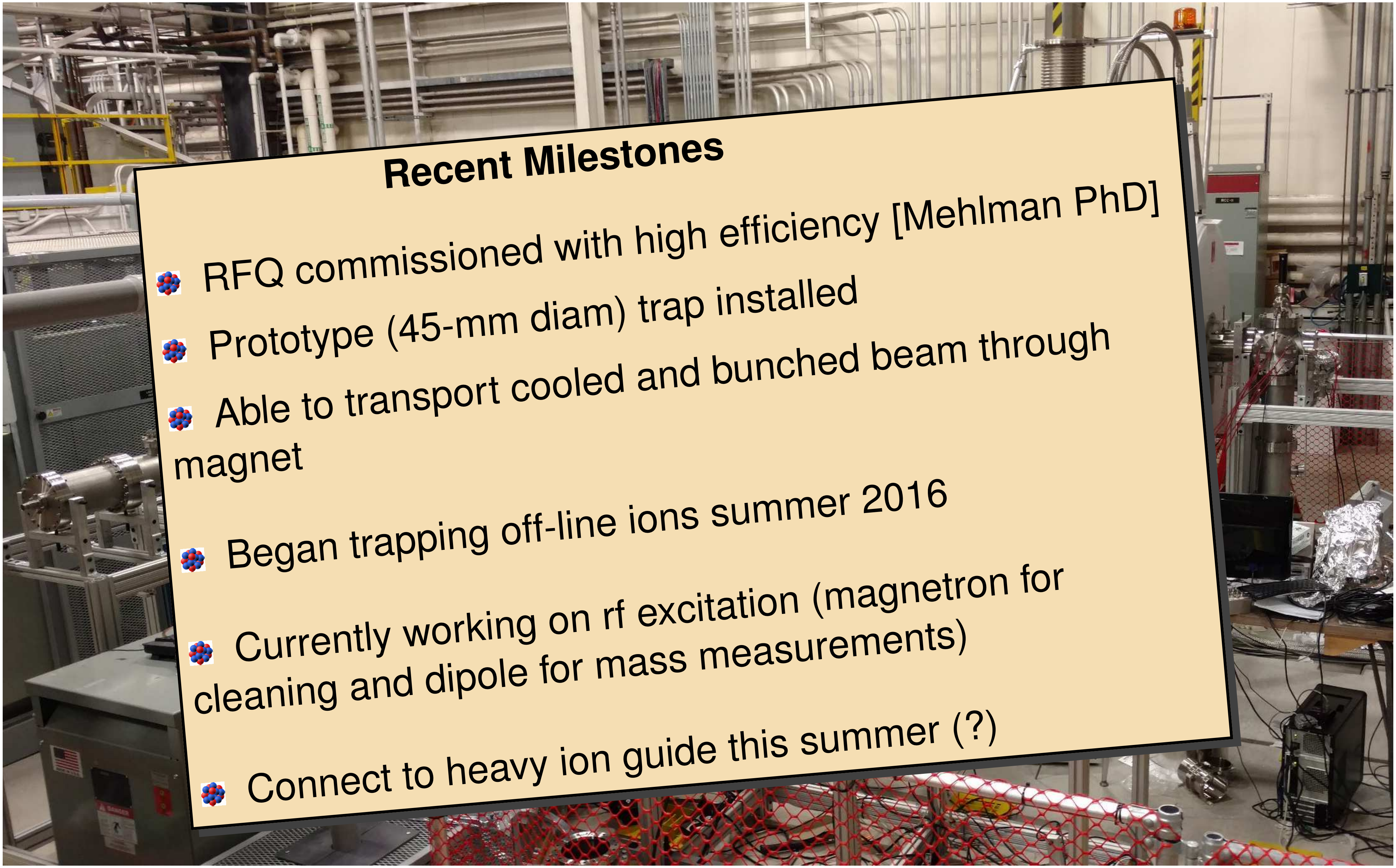

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- Connect to heavy ion guide this summer (?)

Overview

1. Fundamental symmetries

- what is our **current understanding**?
- how do we test what lies **beyond**?

2. TAMU Penning Trap

- **physics** of superallowed β decay
- **ion trapping** of proton-rich nuclei at T-REX

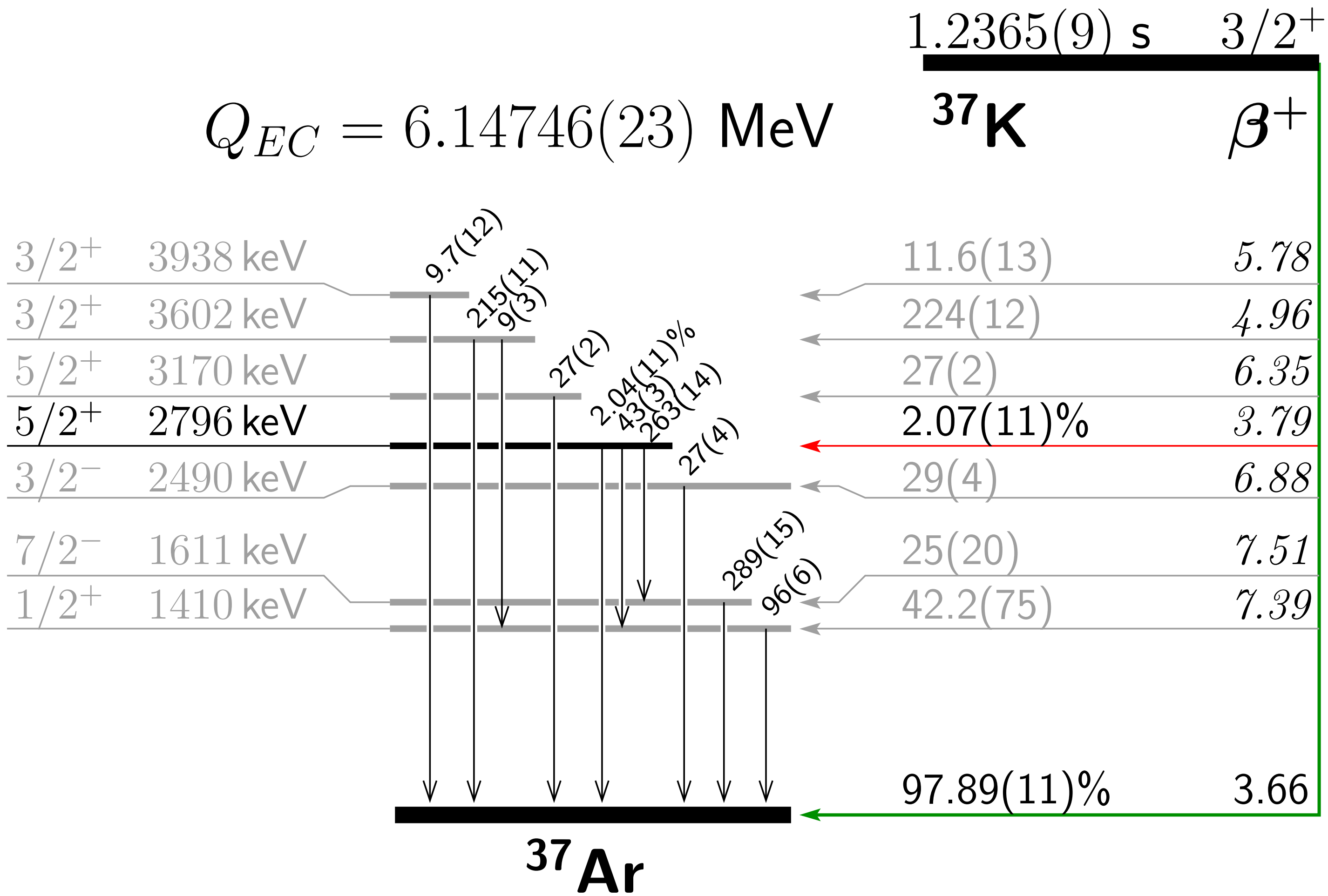
3. TRIUMF Neutral Atom Trap

- angular correlations of **polarized ^{37}K**
- **recent results**

The β^+-decay of ^{37}K

Almost as simple as $0^+ \rightarrow 0^+$:

- **isobaric analogue** decay
- **strong** branch to g.s.



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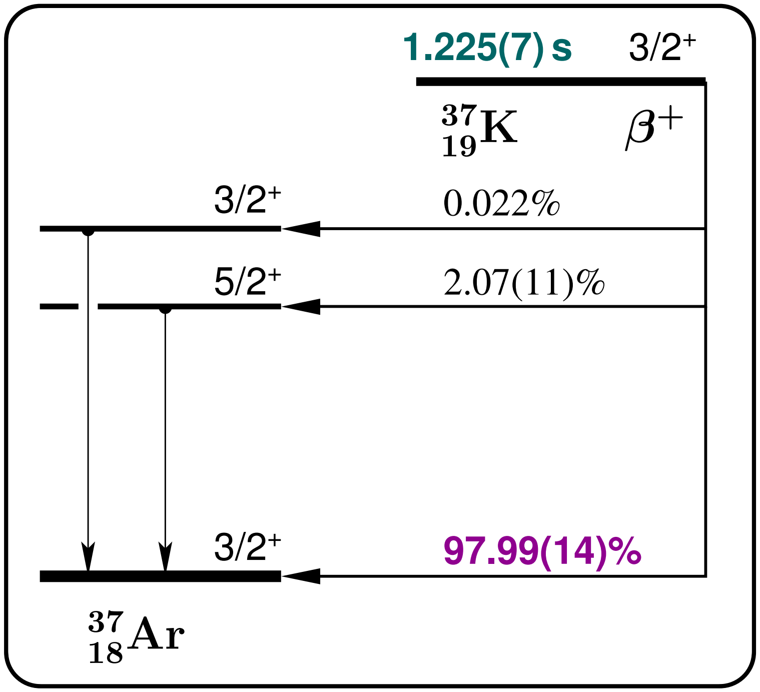

- **isobaric analogue** decay
- **strong** branch to g.s.

- **polarization/alignment**
- **mixed** Fermi/Gamow-Teller

$\Rightarrow$ need $\rho \equiv G_A M_{GT} / G_V M_F$ to get SM prediction for correlation parameters

get ρ from the comparative half-life: $$\rho^2 = \frac{2\mathcal{F}t^{0^+\to 0^+}}{\mathcal{F}t} - 1$$

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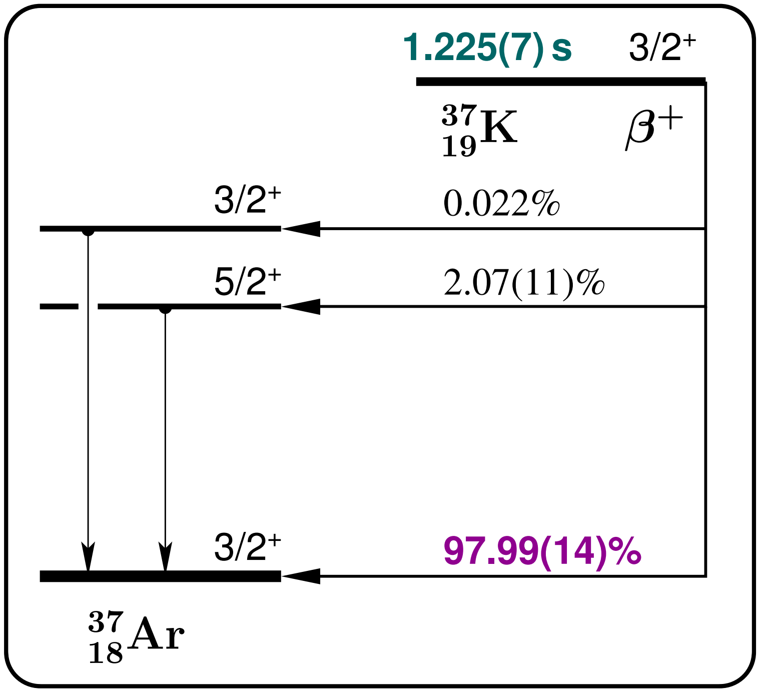

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get ρ from the comparative half-life:

$$\rho^2 = \frac{2\mathcal{F}t^{0^+\rightarrow 0^+}}{\mathcal{F}t} - 1$$

Q_{EC}: ±0.003%

BR: ±0.14%

$t_{1/2}$: **±0.57%**

$$\mathcal{F}t = 4562(28) \Rightarrow$$

$$\rho = 0.5874(\mathbf{71})$$

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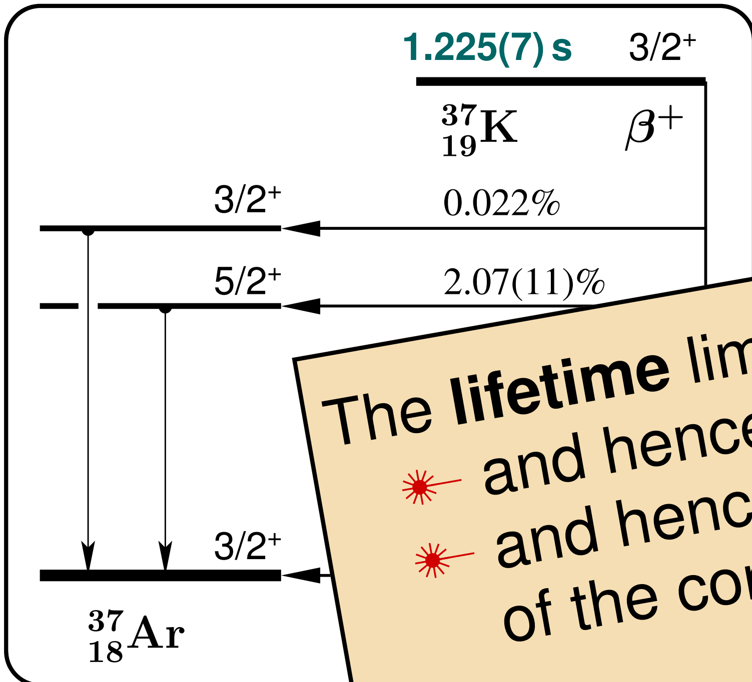

- **isobaric analogue** decay
- **strong** branch to g.s.
- ...**alignment**
- ...Gamow-Teller
- ...$M_{GT}/G_V M_F$
- ...n for correlation

...0^+ ... $- 1$

get ρ fro...

Q_{EC}: $\pm$0.0...

BR: $\pm$0.1...

$t_{1/2}$: $\pm$**0.5**...

$\rho = 0.5874(\mathbf{71})$

The **lifetime** limited the $\mathcal{F}t$ value

- and hence precision of ρ
- and hence the SM predictions of the correlation parameters

The β^+-decay of ^{37}K

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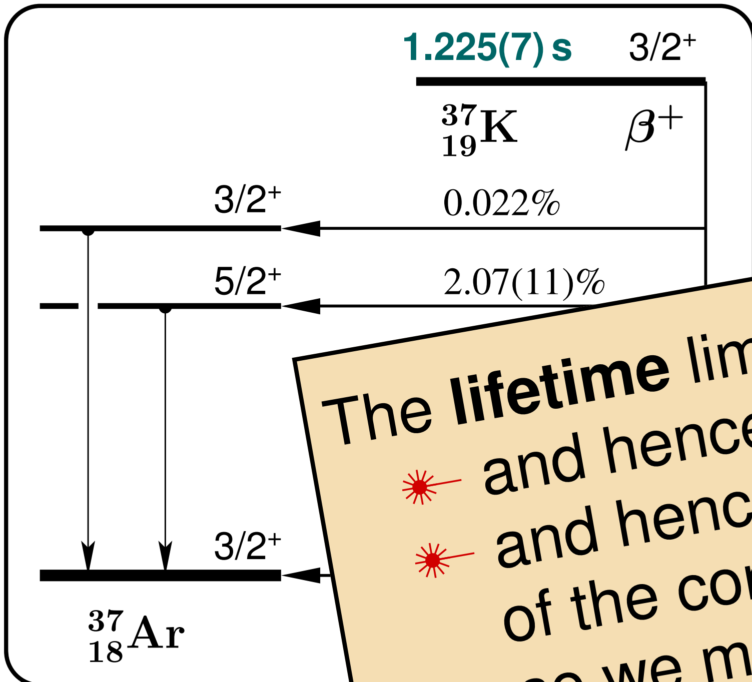

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0^+

$- 1$

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$t_{1/2}$: **±0.5**

$\rho = 0.5874(\mathbf{71})$

The **lifetime** limited the $\mathcal{F}t$ value

- and hence precision of ρ
- and hence the SM predictions of the correlation parameters
- so we measured the lifetime at the CI:

a $4.4\times$ improvement:

$$t_{1/2} = 1236.51 \pm 0.47 \pm 0.83 \text{ ms}$$

P. Shidling *et al.*, Phys. Rev. C **90**, 032501(R) (2014)

Angular distribution of a $\frac{3}{2}^+ \to \frac{3}{2}^+$ decay

$$dW \sim 1 + a_{\beta\nu}\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} + b\Gamma\frac{m}{E_e} + \frac{\vec{I}}{I}\cdot\left[\boldsymbol{A_\beta}\frac{\vec{p}_e}{E_e} + \boldsymbol{B_\nu}\frac{\vec{p}_\nu}{E_\nu} + \boldsymbol{D}\frac{\vec{p}_e\times\vec{p}_\nu}{E_eE_\nu}\right]$$

Correlation	Expectation
$\beta-\nu$ correlation:	$a_{\beta\nu} = 0.6580(\mathbf{61})$
Fierz interference parameter:	$b_{\rm Fierz} = 0$ (sensitive to scalars and tensors)
β asymmetry:	$A_\beta = -0.5739(\mathbf{21})$
ν asymmetry:	$B_\nu = -0.7791(\mathbf{58})$
Time-violating D coefficient:	$D = 0$ (sensitive to imaginary couplings)
	$\vdots$
a $\beta-$recoil observable specific to our geometry	$R_{\rm slow} \sim \frac{1-a_{\beta\nu}-2c_{\rm align}/3\ -\ (A_\beta-B_\nu)}{1-a_{\beta\nu}-2c_{\rm align}/3\ +\ (A_\beta-B_\nu)} = 0$

Recall: measurements of these correlations to $\lesssim \mathbf{0.1\%}$
complement collider experiments and test the SM

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Correlation	Expectation
$\beta - \nu$ correlation:	$a_{\beta\nu} = 0.6580(\mathbf{61}) \rightarrow 0.6668(\mathbf{18})$
Fierz interference parameter:	$b_{\rm Fierz} = 0$ (sensitive to scalars and tensors)
β asymmetry:	$A_\beta = -0.5739(\mathbf{21}) \rightarrow -0.5719(\mathbf{7})$
ν asymmetry:	$B_\nu = -0.7791(\mathbf{58}) \rightarrow -0.7703(\mathbf{18})$
Time-violating D coefficient:	$D = 0$ (sensitive to imaginary couplings)
	$\vdots$
a $\beta-$recoil observable specific to our geometry	$R_{\rm slow} \sim \frac{1-a_{\beta\nu}-2c_{\rm align}/3 - (A_\beta - B_\nu)}{1-a_{\beta\nu}-2c_{\rm align}/3 + (A_\beta - B_\nu)} = 0$

Recall: measurements of these correlations to $\lesssim \mathbf{0.1\%}$
complement collider experiments and test the SM

(data in hand for improved branching ratios)

E.g.: Right-handed currents

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

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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?

$\Rightarrow$ 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 $\qquad R_{\mathrm{slow}} = 0$

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

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

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

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

where $\mathbf{x} \approx (M_L/M_R)^2 - \zeta$ and $\mathbf{y} \approx (M_L/M_R)^2 + \zeta$ are RHC parameters that are **zero** in the SM.

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Again, goal must be $\lesssim \mathbf{0.1\%}$ to have an impact

Thank you, AMO physicists!!

Atomic methods have opened up a new vista in precision work and provide the ability to push β decay measurements to $\lesssim 0.1\%$

- laser-cooling and trapping (magneto-optical traps)
- sub-level state manipulation (optical pumping)
- characterization/diagnostics (photoionization)

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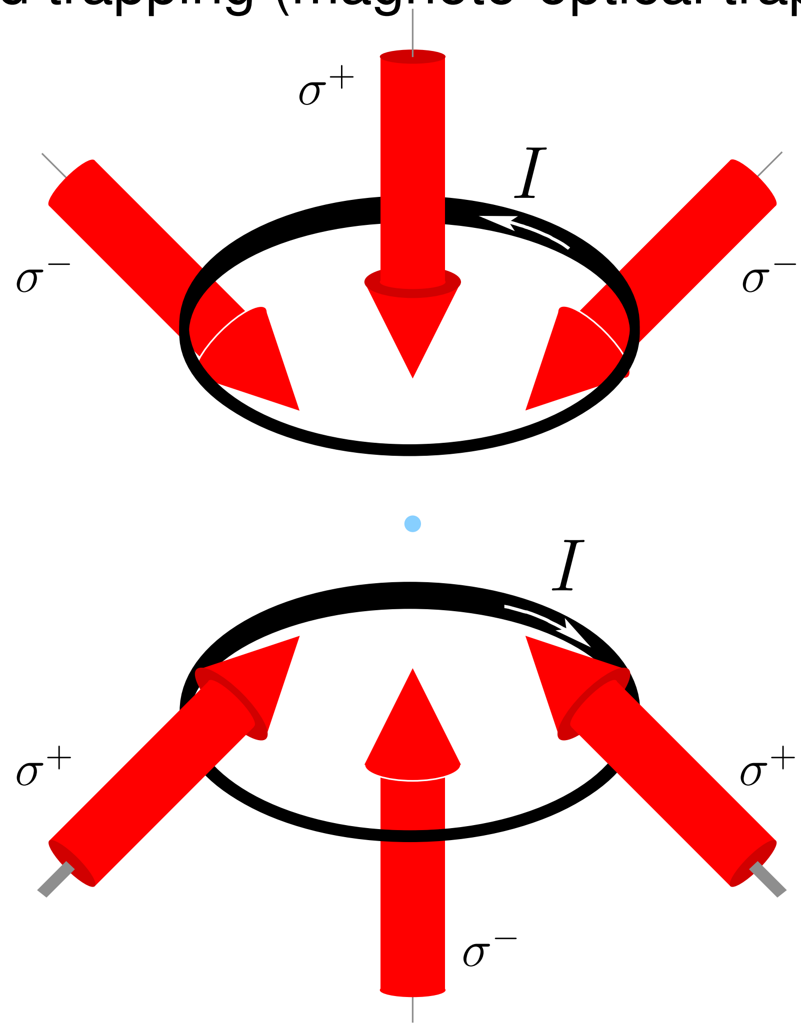

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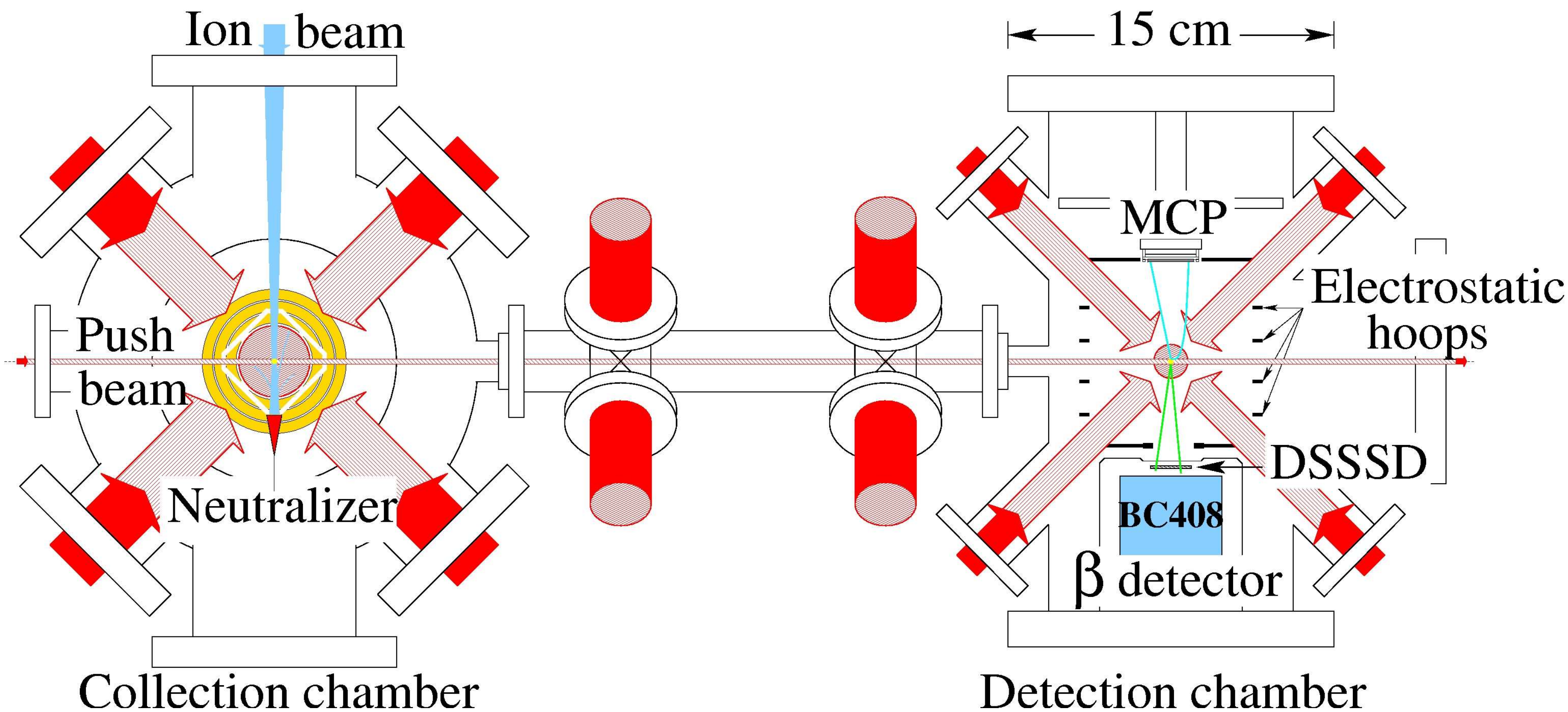

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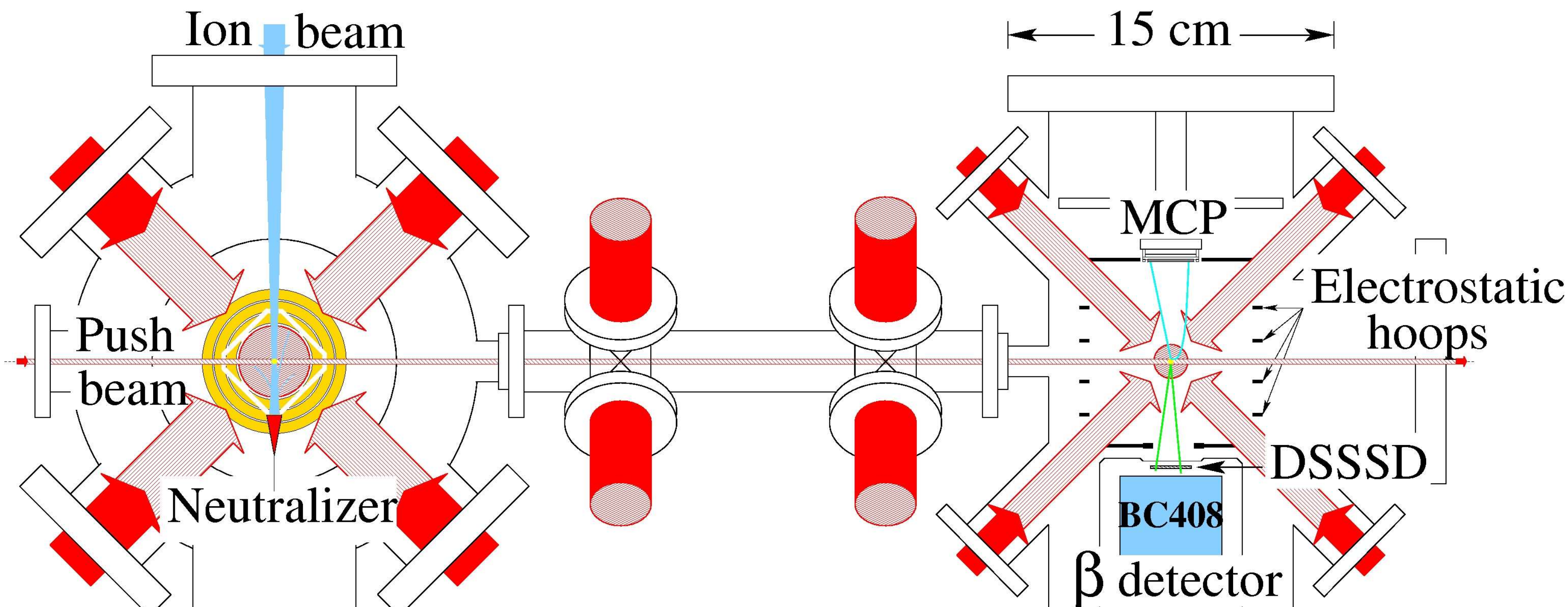

Traps provide a **backing-free**, very **cold** ($\lesssim 1$ mK), **localized** ($\sim 1\ \mathrm{mm}^3$) source of **isomerically-selective**, **short-lived** radioactive atoms

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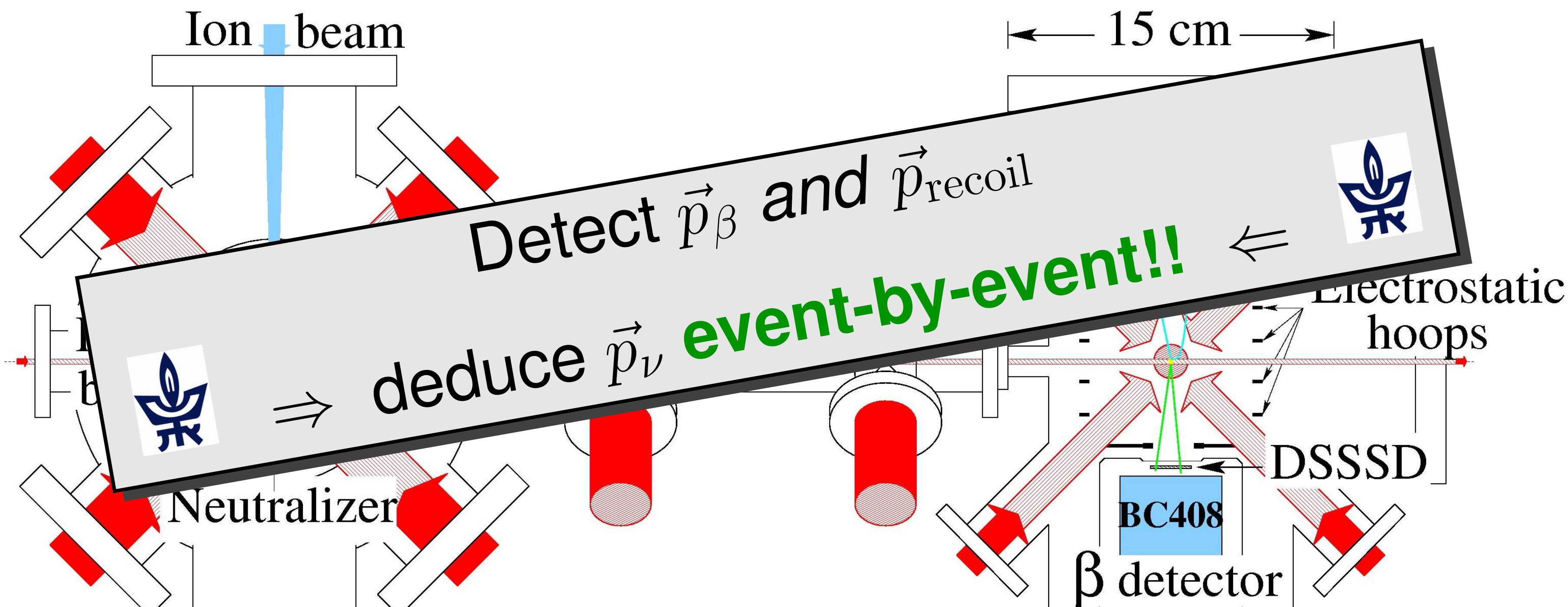

Detect $\vec{p}_\beta$ and $\vec{p}_{\rm recoil}$ $\Leftarrow$

$\Rightarrow$ deduce $\vec{p}_\nu$ **event-by-event!!**

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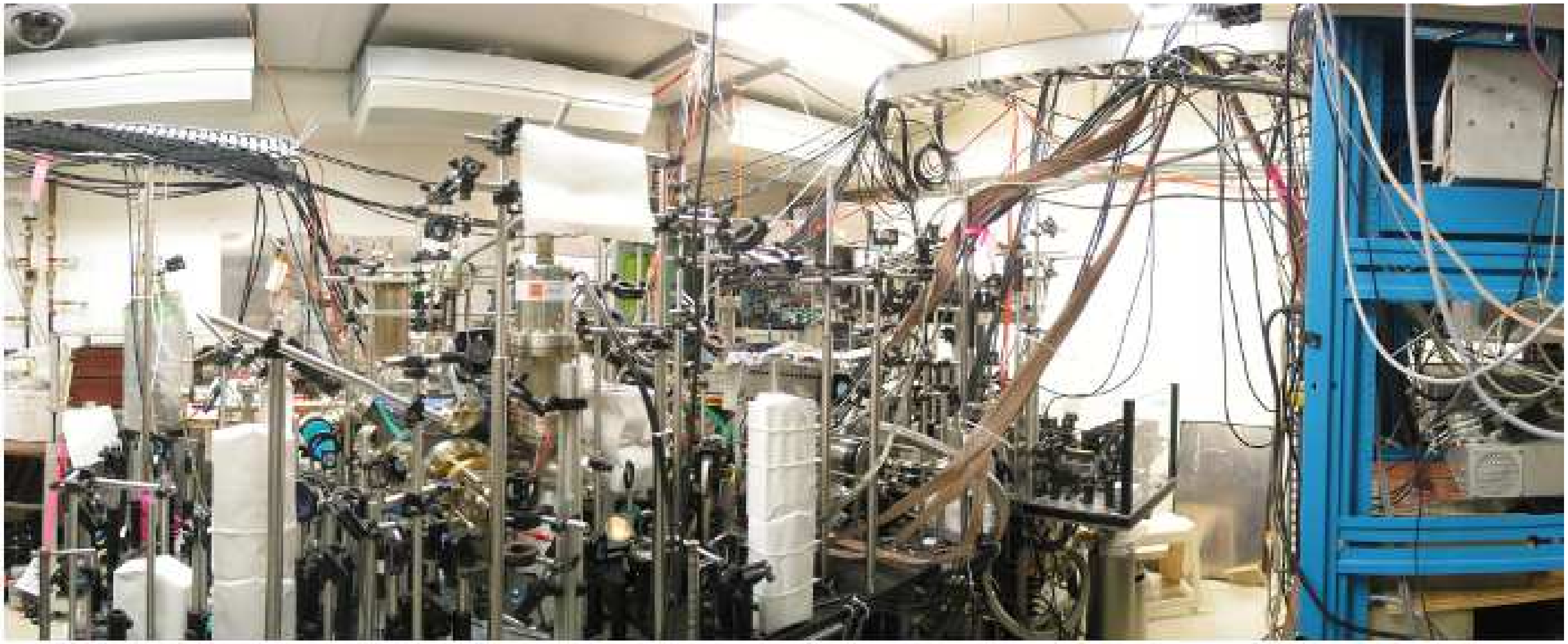
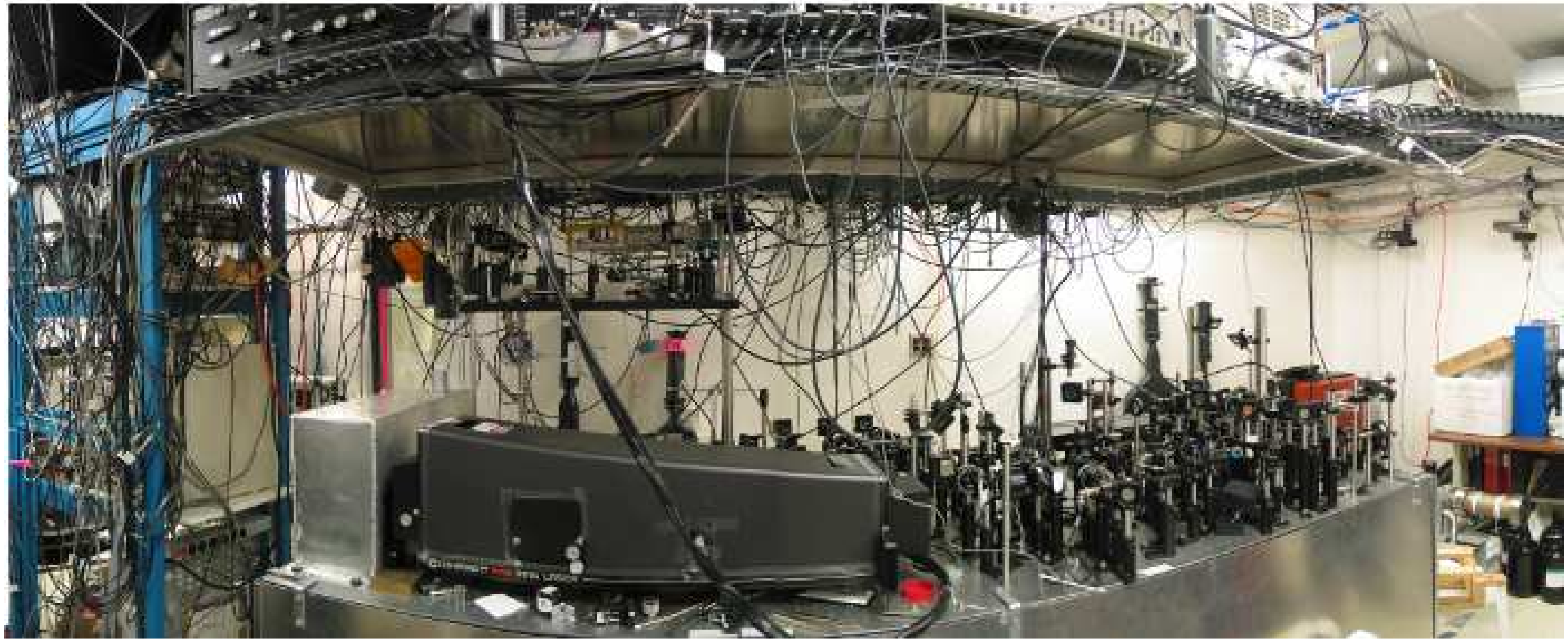
The TRINAT lab

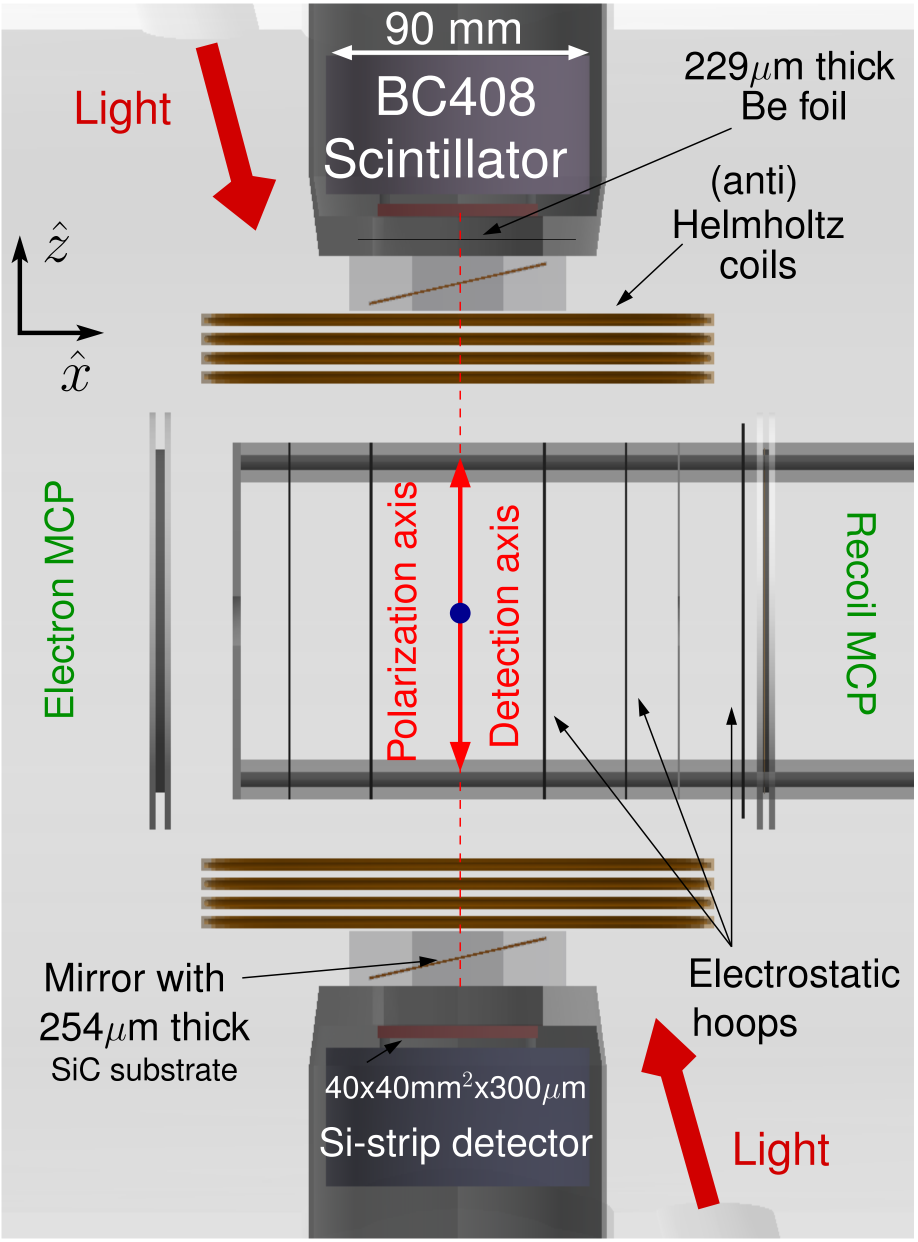




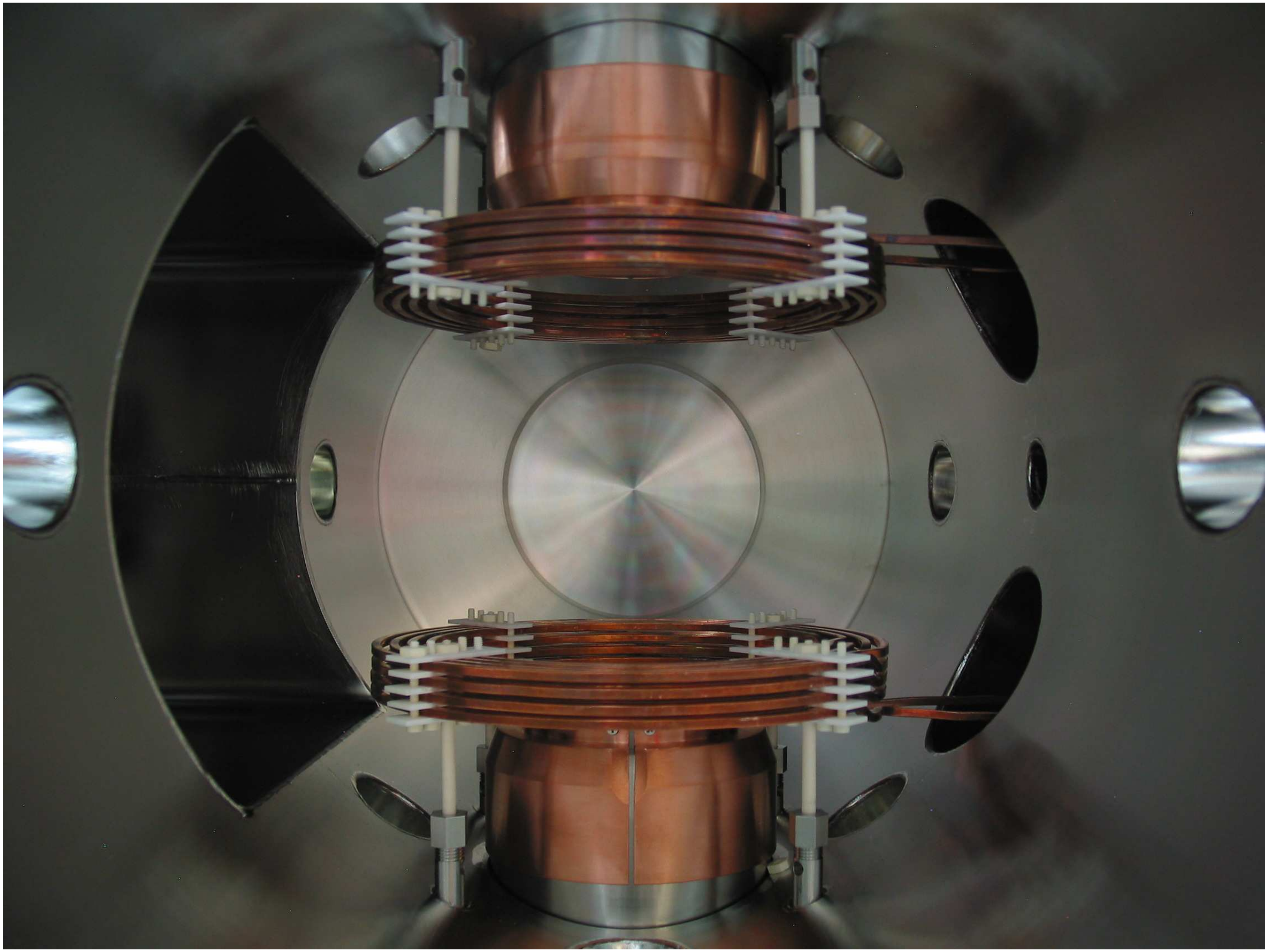
The measurement chamber

- Shake-off e^- detection
  $\rightsquigarrow$ know decay occured from trap
- Better control of OP beams
  $\rightsquigarrow$ less heating, higher P
- $B_{\text{quad}} \to B_{\text{OP}}$ quickly: AC-MOT
  $\rightsquigarrow$ better duty cycle, higher polarization
- Increased β/recoil solid angles
  $\rightsquigarrow$ better statistics
- Stronger E-field (one day...)
  $\rightsquigarrow$ better separation of charge states, higher statistics

⋮



Outline of polarized experiment



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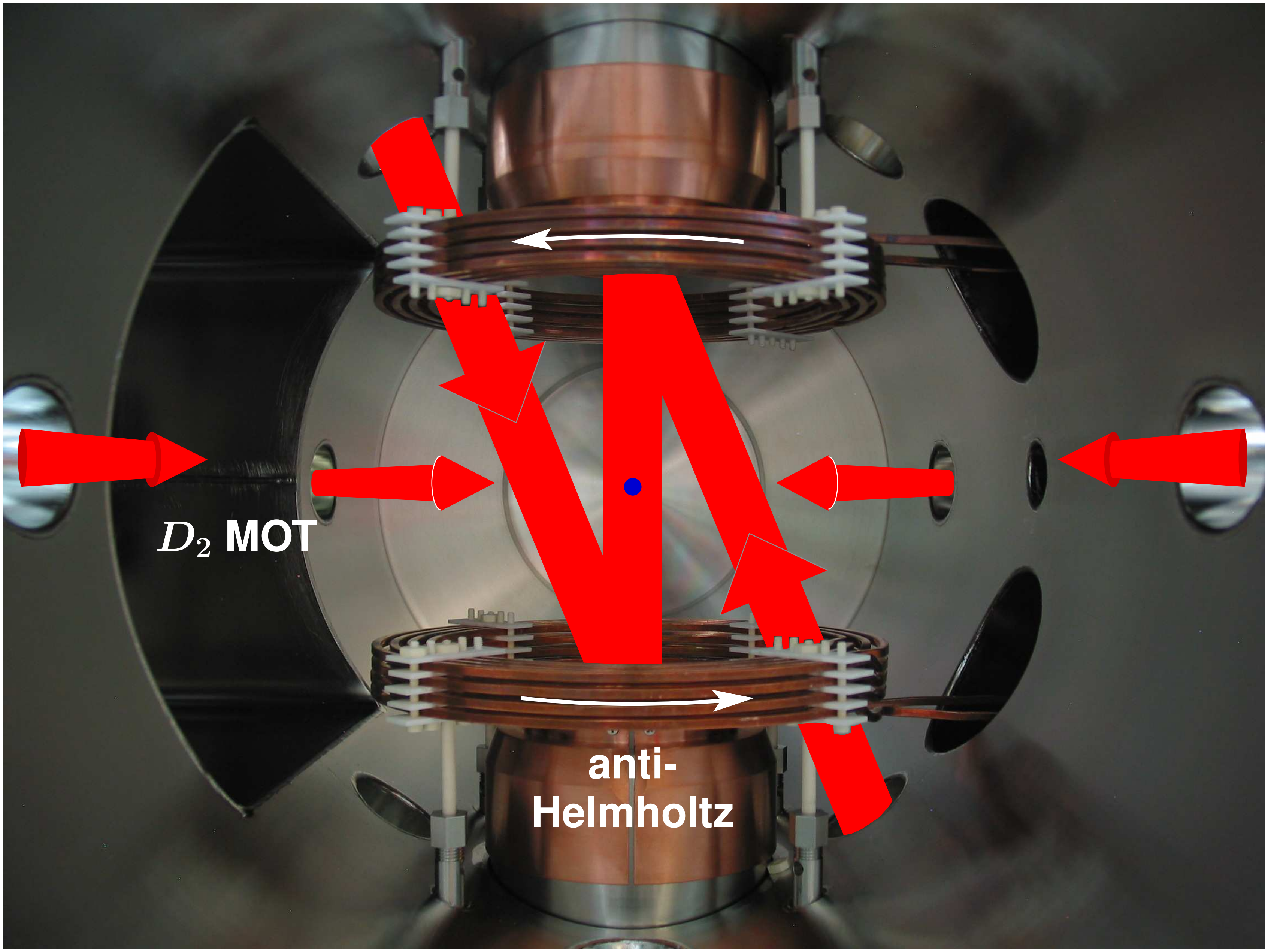

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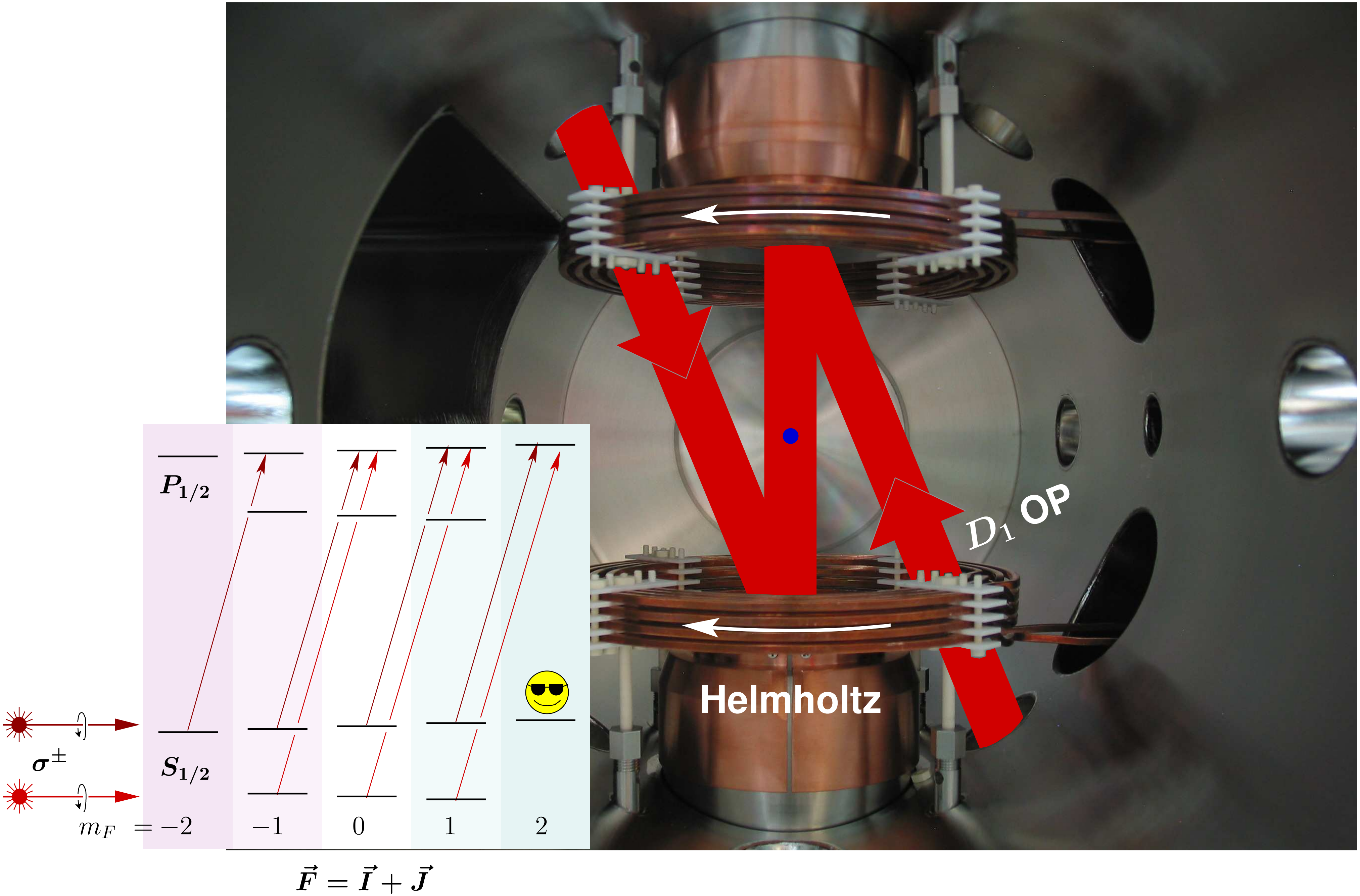

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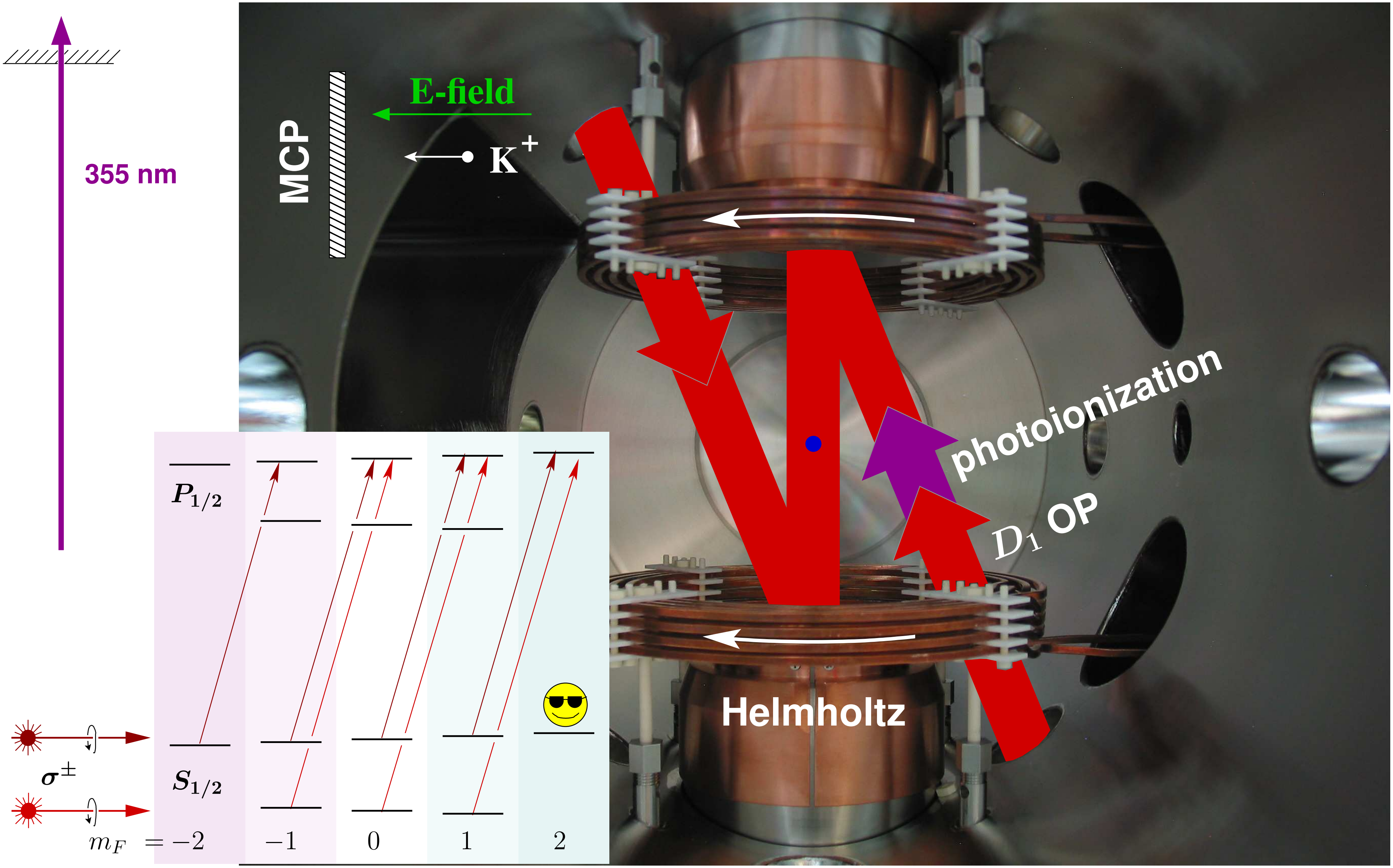
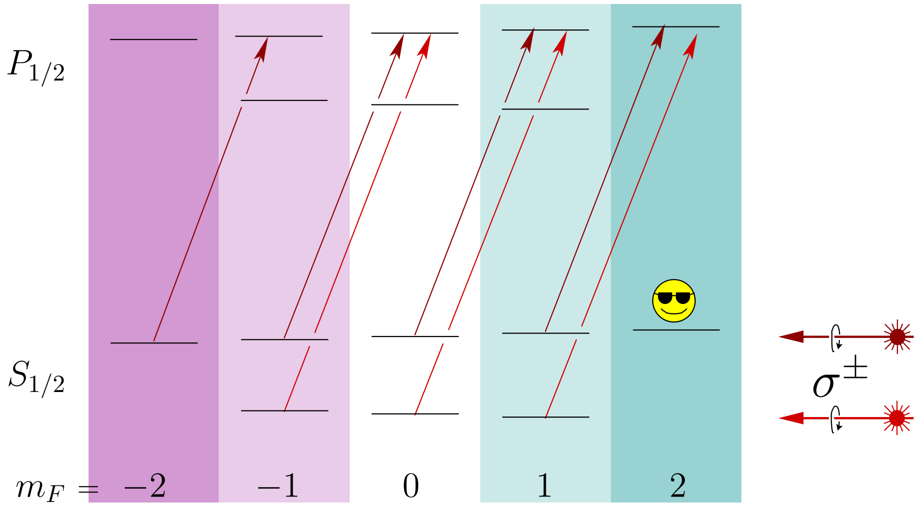
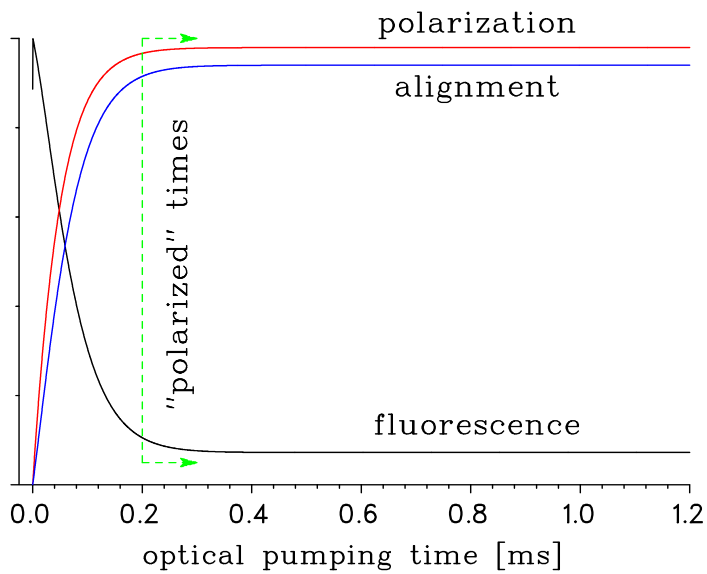


$\vec{F} = \vec{I} + \vec{J}$

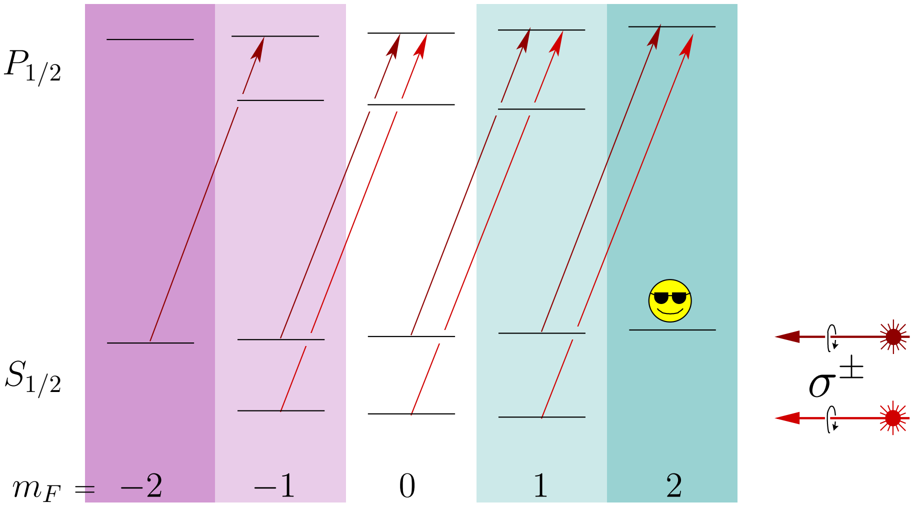
Deduce P based on a model of the excited state populations

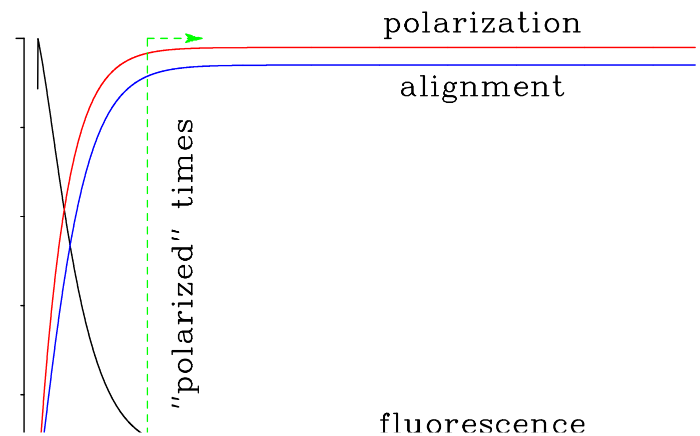


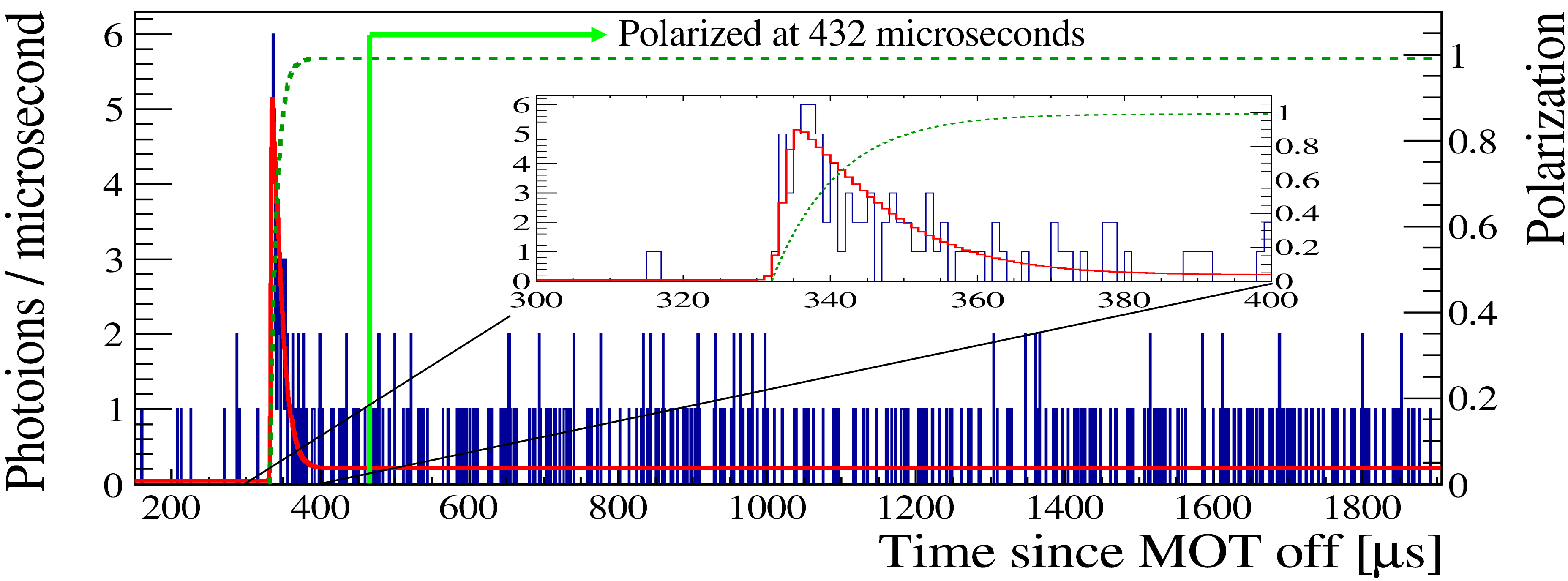


Atomic measurement of P

Deduce P based on a model of the excited state populations







Polarization error budget

Source	ΔP [$\times 10^{-4}$] σ^-	σ^+	ΔT [$\times 10^{-4}$] σ^-	σ^+
Systematics				
Initial alignment	3	3	10	8
Global fit vs. average	2	2	7	6
Uncertainty on s_3^{out}	1	2	11	5
Cloud temperature	2	0.5	3	2
Binning	1	1	4	3
Uncertainty in B_z	0.5	3	2	7
Initial polarization	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
Total uncertainty	9	8	27	22

Polarization error budget

ΔP [$\times 10^{-4}$] ΔT [$\times 10^{-4}$]

New J. Phys. **18** (2016) 073028 doi:10.1088/1367-2630/18/7/073028

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PAPER

Precision measurement of the nuclear polarization in laser-cooled, optically pumped ^{37}K

B Fenker[1,2,7], J A Behr[3], D Melconian[1,2,7], R M A Anderson[3], M Anholm[3,4], D Ashery[5], R S Behling[1,6], I Cohen[5], I Craiciu[3], J M Donohue[3], C Farfan[3], D Friesen[3], A Gorelov[3], J McNeil[3], M Mehlman[1,2], H Norton[3], K Olchanski[3], S Smale[3], O Thériault[3], A N Vantyghem[3] and C L Warner[3]

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7 Authors to whom any correspondence should be addressed.

Polarization error budget

$\Delta P\ [\times 10^{-4}]$ $\Delta T\ [\times 10^{-4}]$

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1 Cyclotron Ins
2 Department o
3 TRIUMF, 400
4 Department o
5 School of Phy
6 Department o
7 Authors to wh

$$\Rightarrow \boxed{\langle P_{\mathrm{nucl}} \rangle = \mathbf{99.13(8)\%}}$$

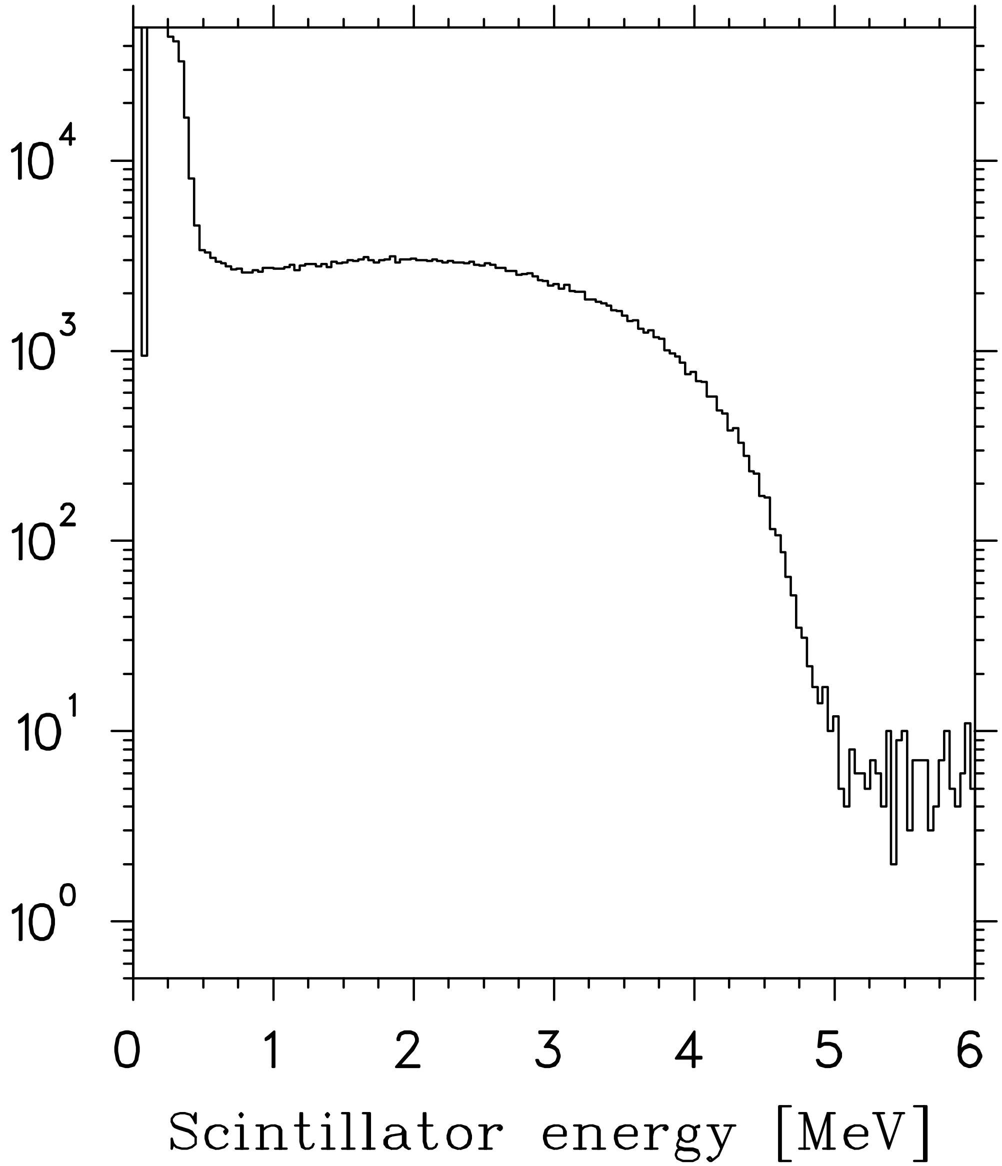
(*c.f.* neutrons: 99.7(1)% [PERKEOII], 99.3(3)% [UCNA])

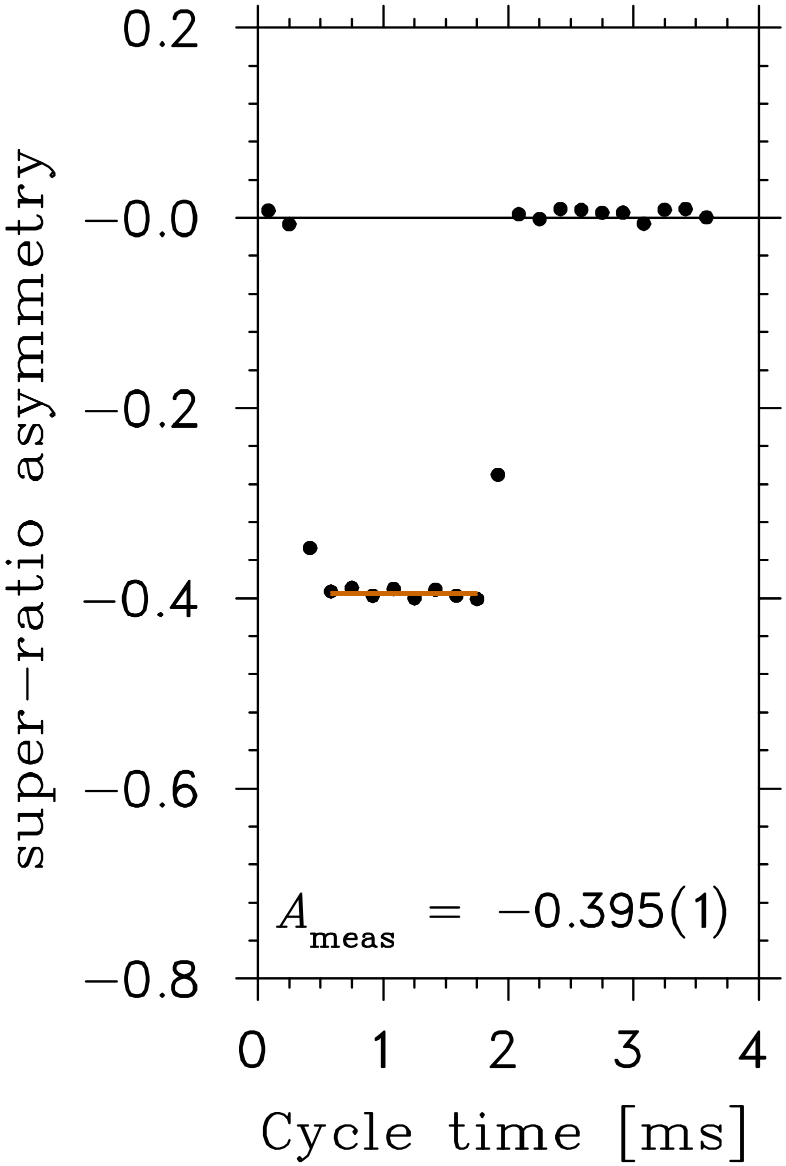
and

$$\langle T_{\mathrm{align}} \rangle = \mathbf{-0.9767(25)}$$

Scintillator spectra — June 2014

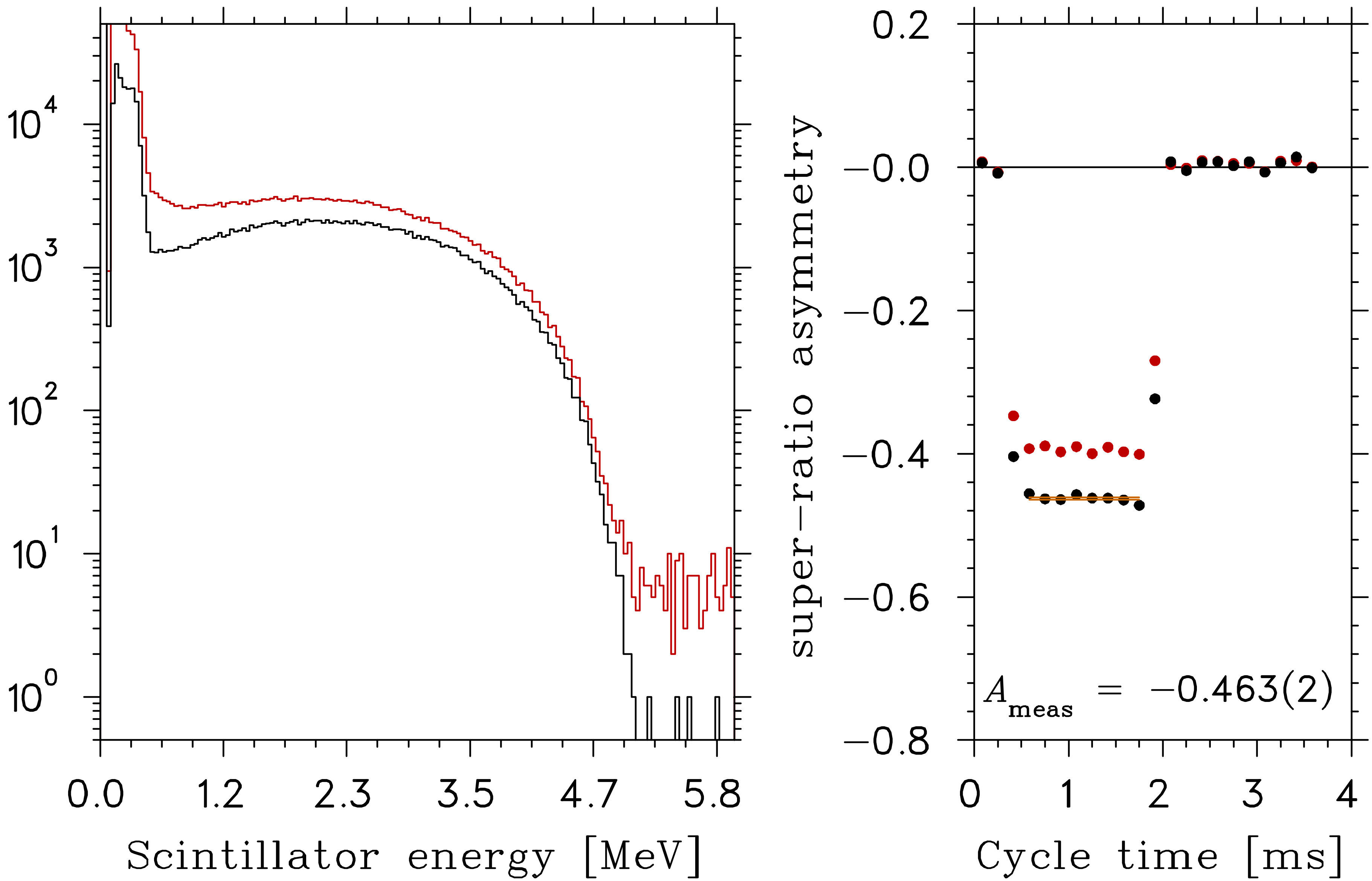
Just the raw data; a slight lower-energy cut to get rid of 511s





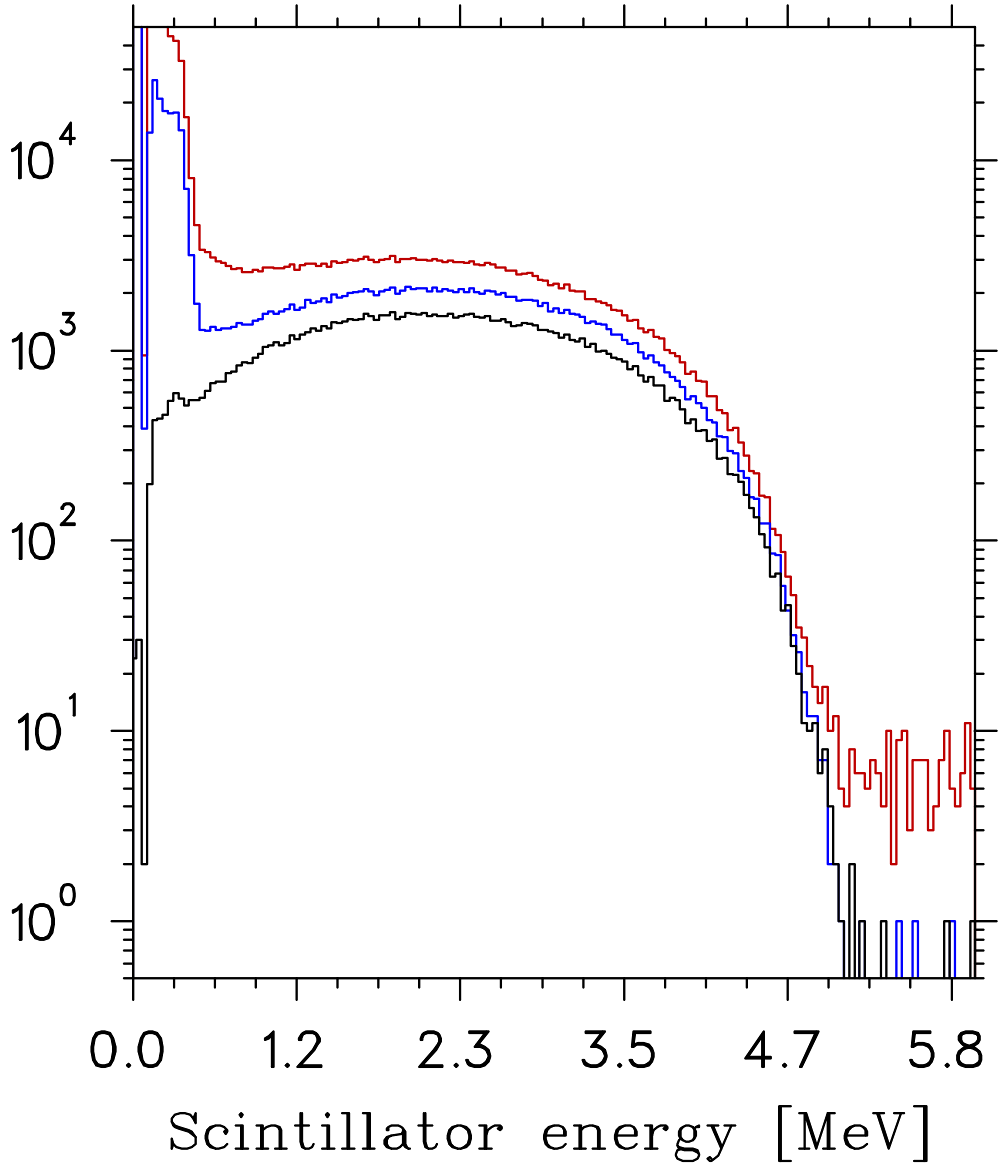
Scintillator spectra — June 2014

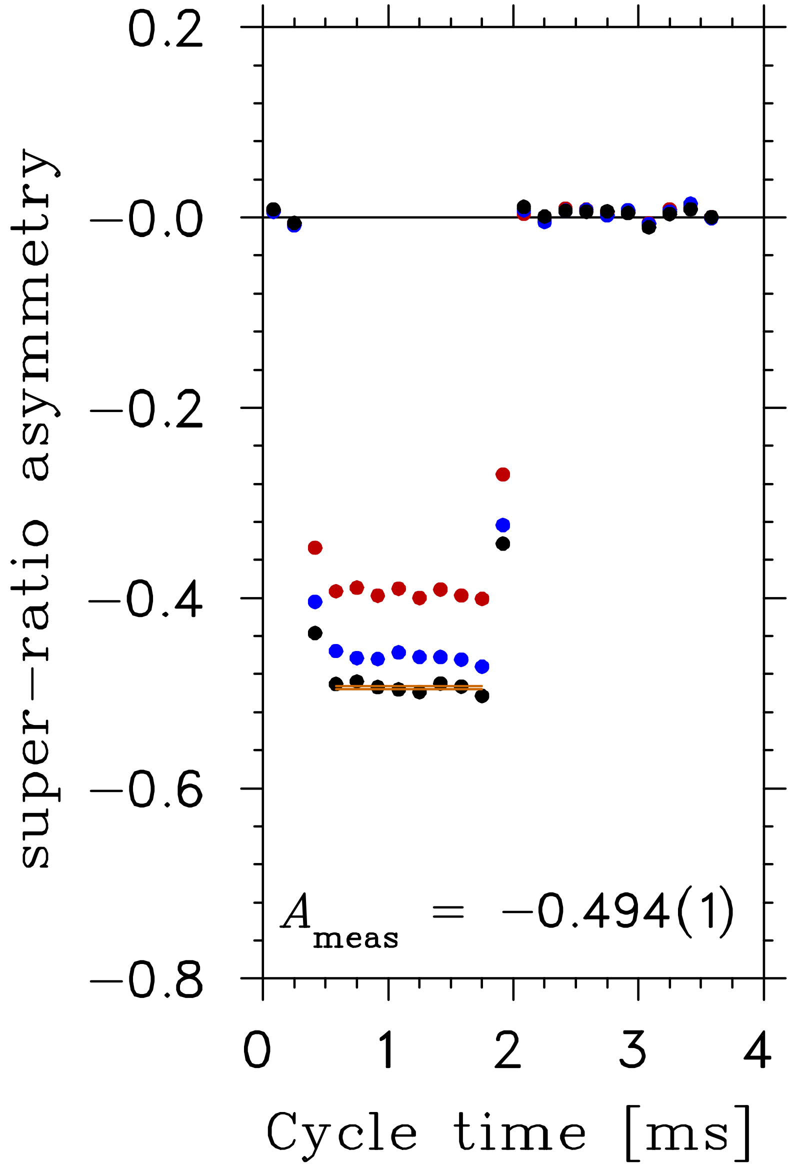
Requiring a shake-off e^- ⇒ decay occured from trap!



Scintillator spectra — June 2014

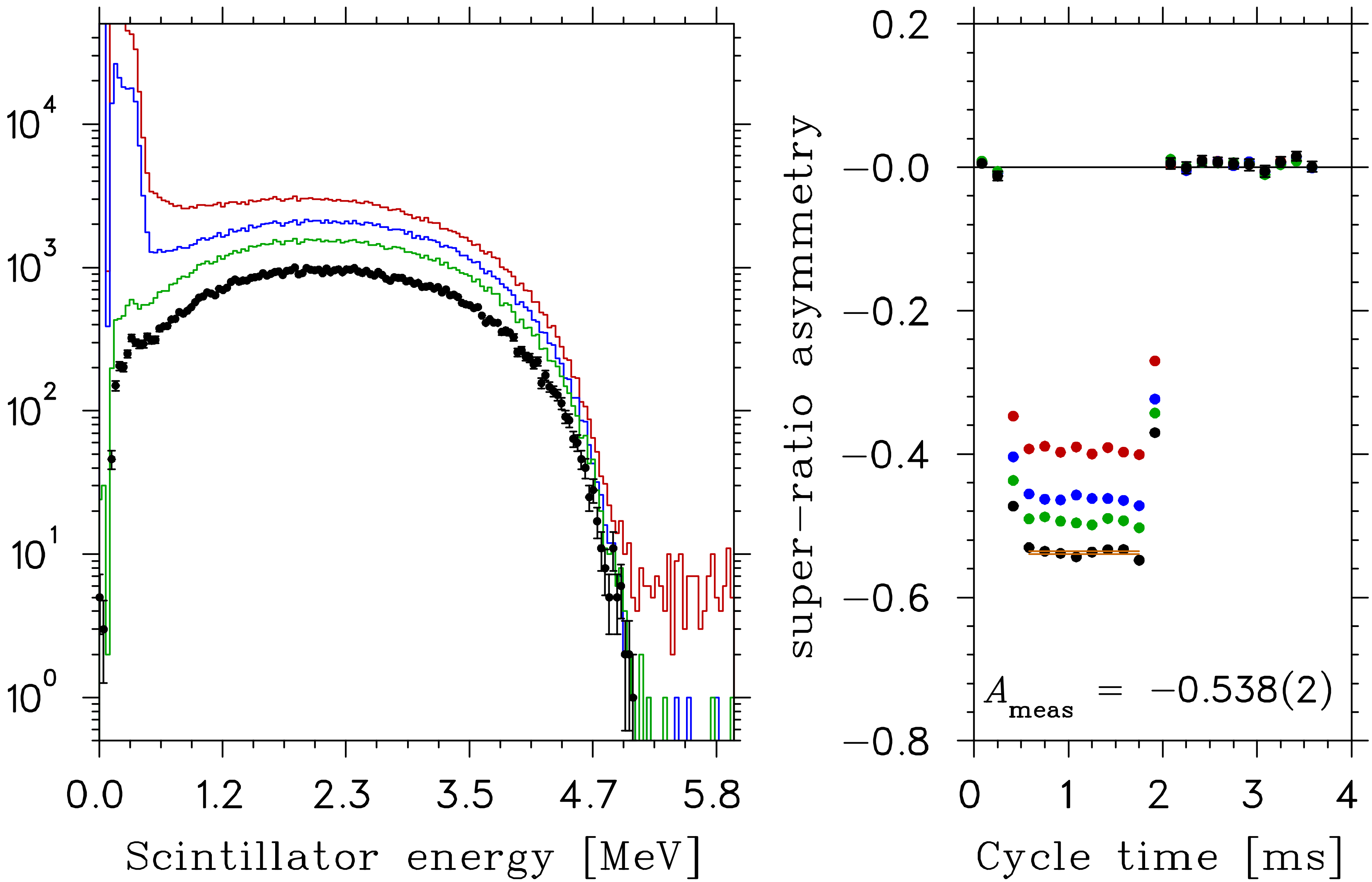
Requiring a ΔE coincidence $\Rightarrow$ remove γs



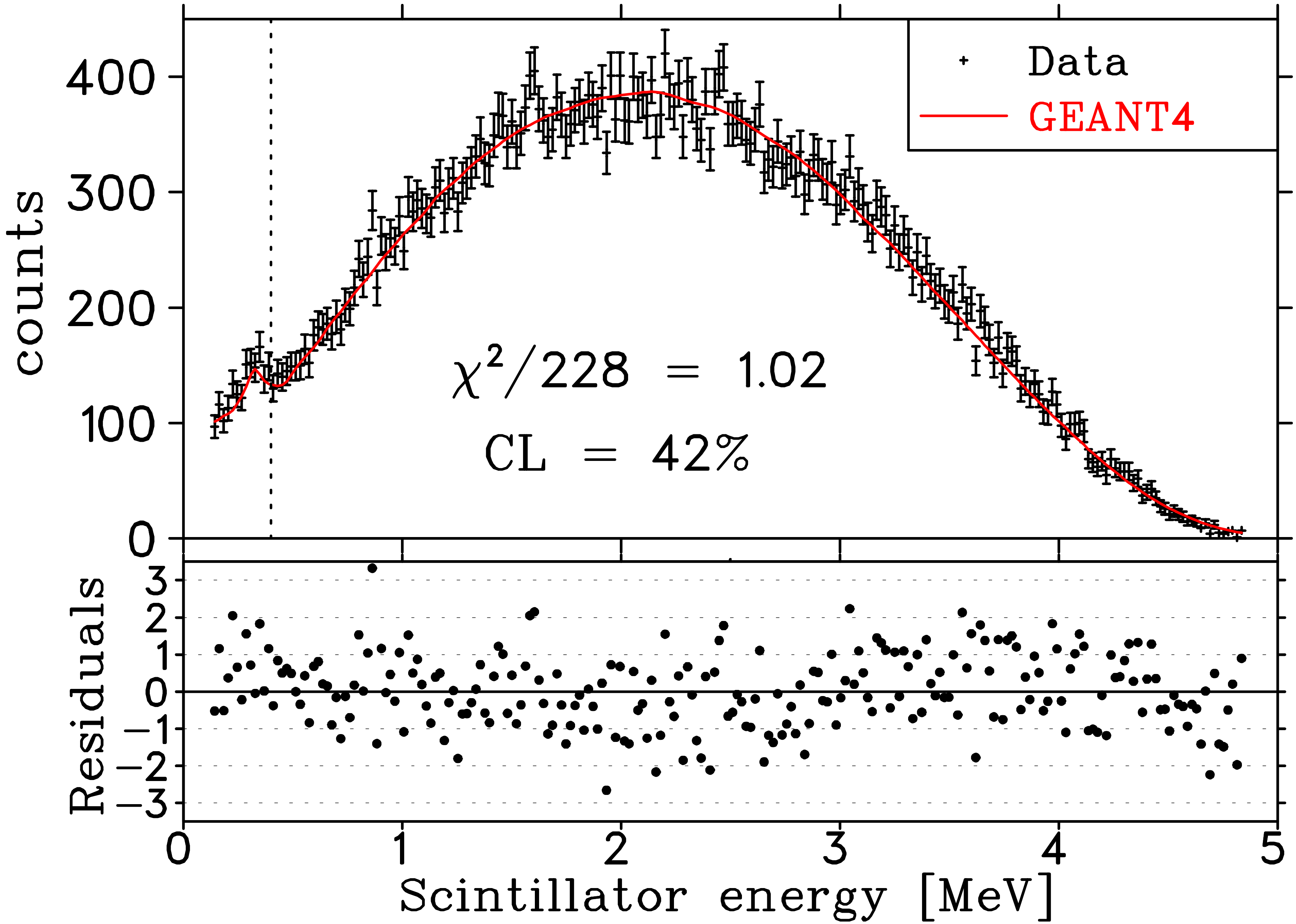


Scintillator spectra — June 2014

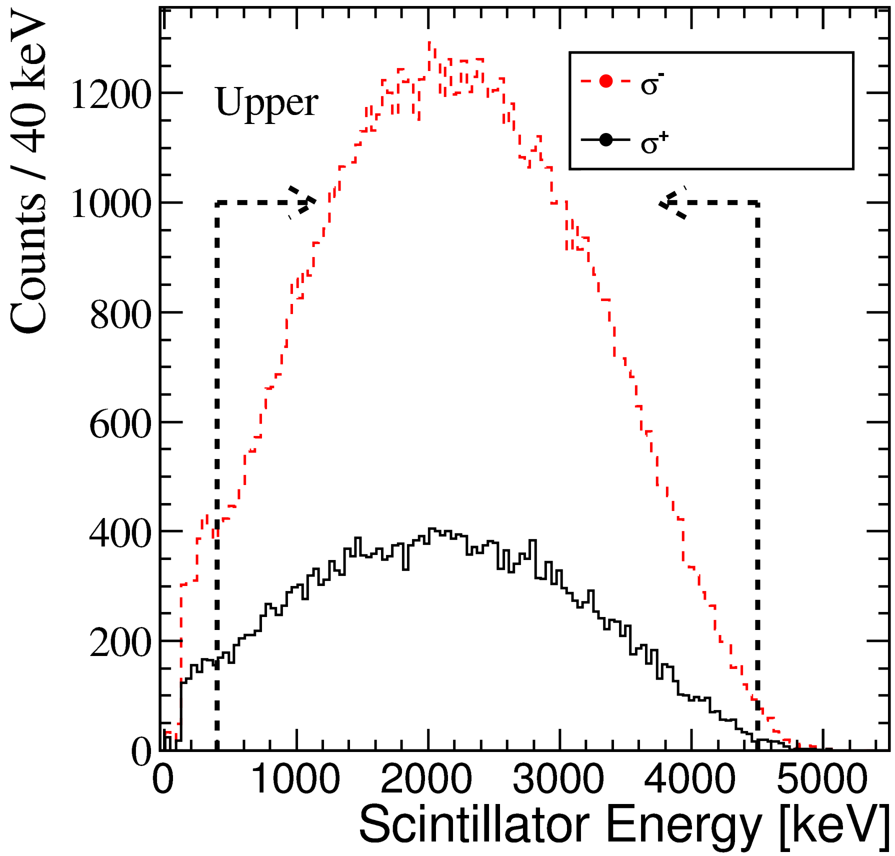
Put in all the basic analysis cuts ⇒ clean spectrum!!

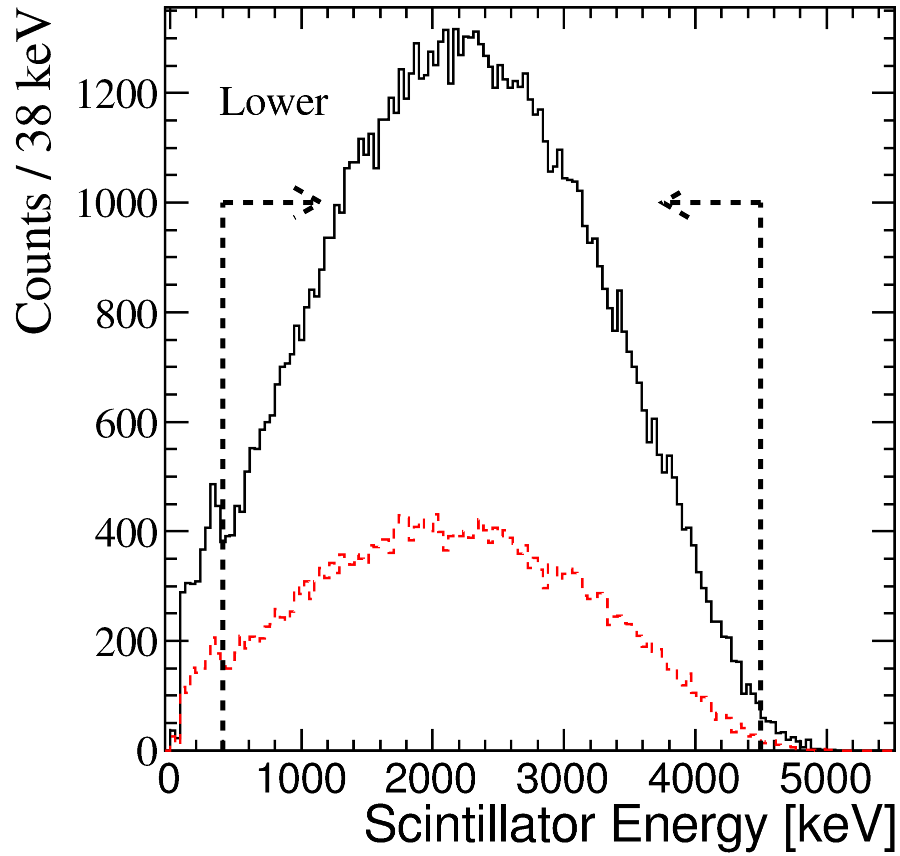


Energy Spectrum Compared to GEANT4



Asymmetry Measurement (briefly)





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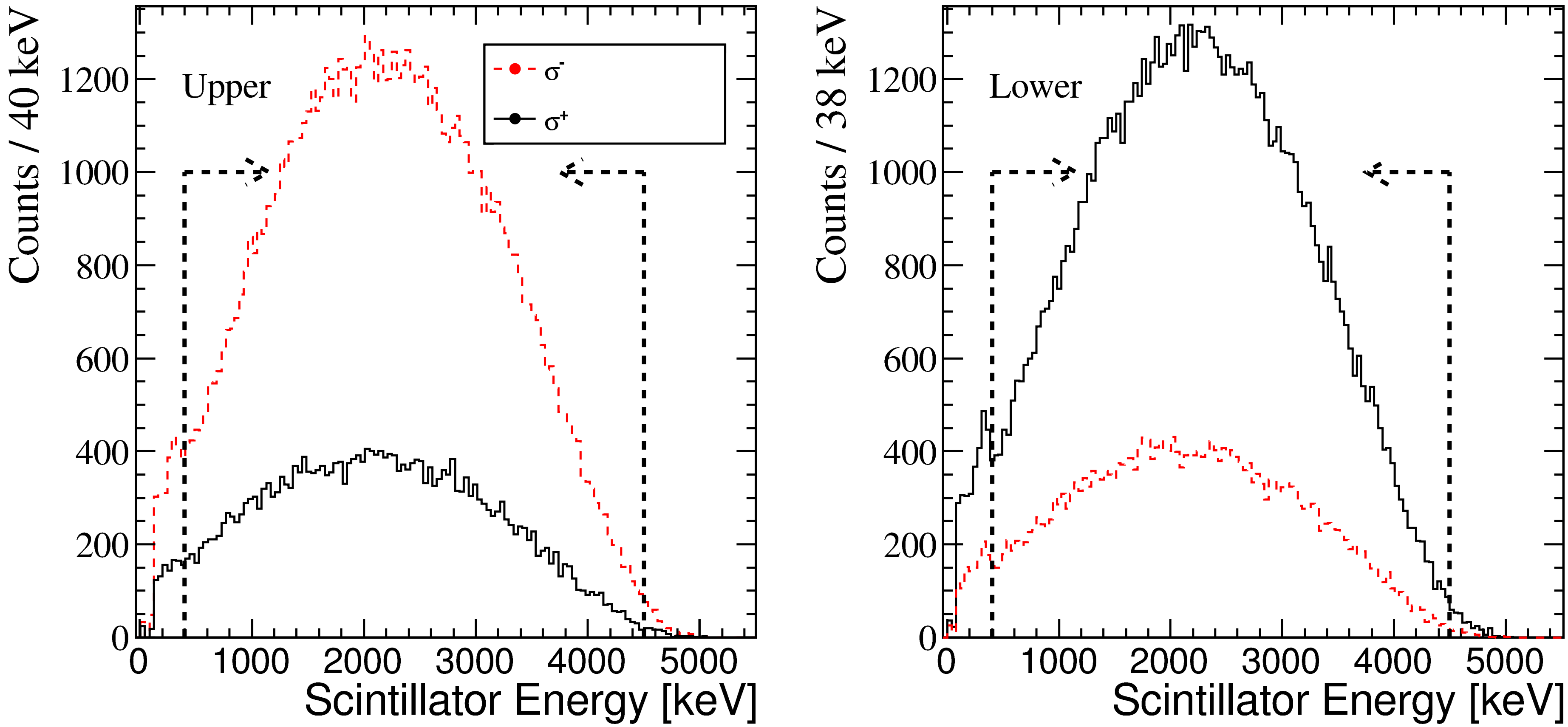

$$A_{\mathrm{obs}}(E_e) = \frac{1 - S(E_e)}{1 + S(E_e)}, \quad \text{where } S(E_e) \equiv \sqrt{\frac{r_1^-(E_e) r_2^+(E_e)}{r_1^+(E_e) r_2^-(E_e)}}$$

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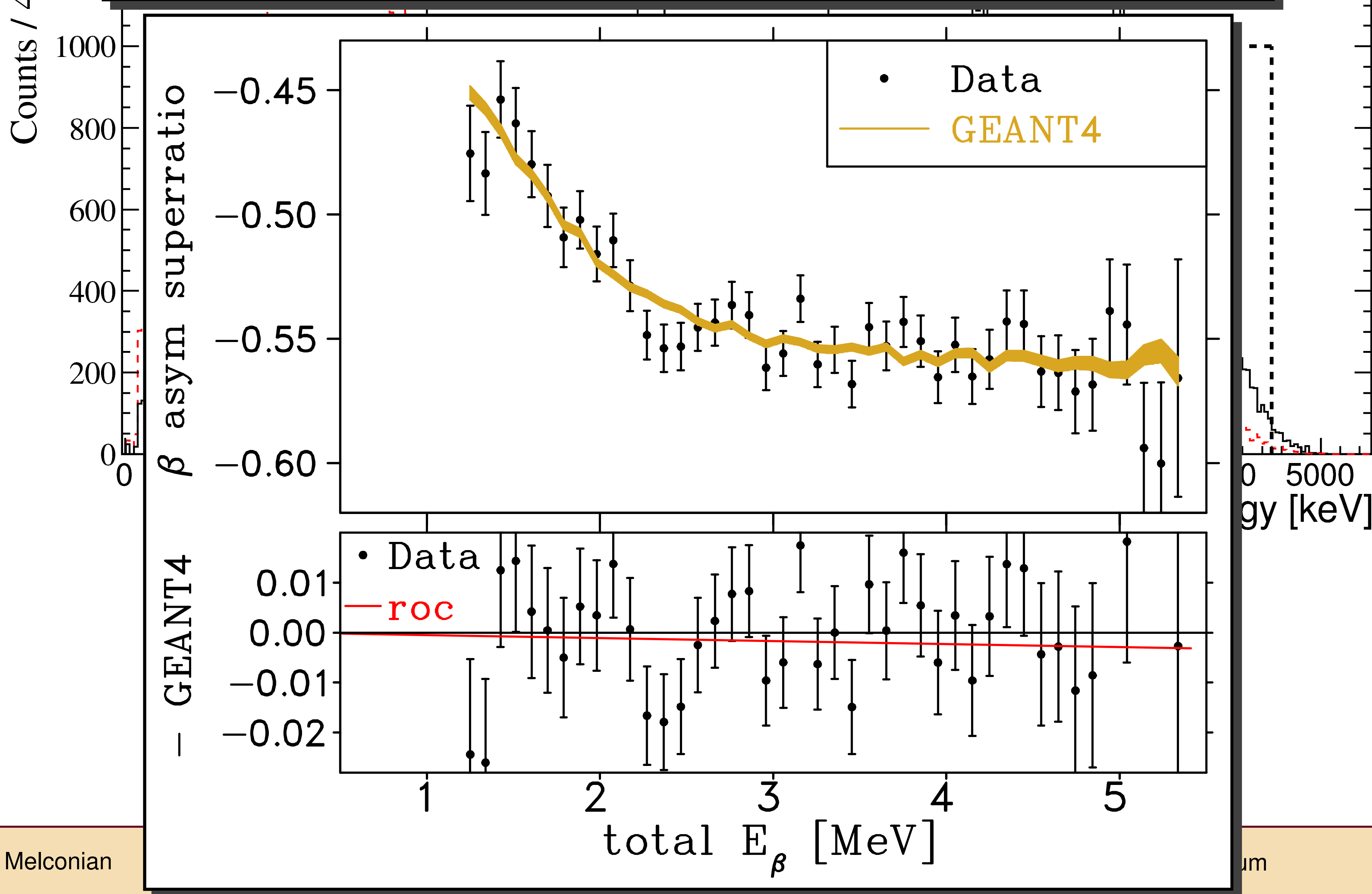
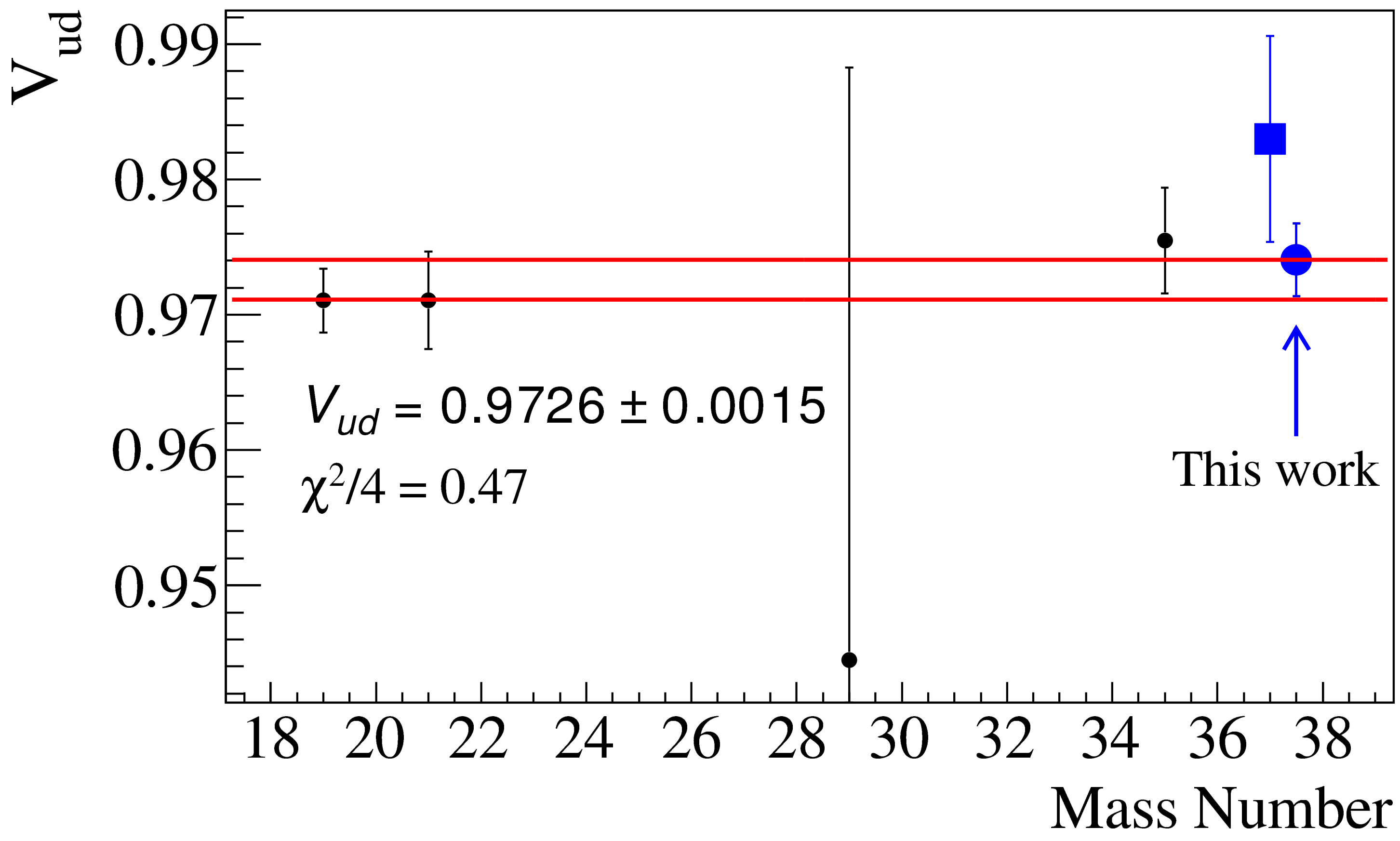


A_β Error Budget

Source		Corr	Uncert [$\times 10^{-4}$]
Backgrounds		1.0013	7
Trap parameters	position		4
	velocity		5
	temp, width		1
Thresholds/cuts	ΔE pos		5
	ΔE energy agreement		2
	ΔE threshold		1
	E threshold		0.3
G4 phys list			4
Shake-off e^- TOF			3
$E + \Delta E$			1
E calibration			0.1
Total systematics			12
Statistical			13
Polarization			5
Total uncertainty			18

Impact of A_β Measurement

- In terms of CKM unitarity, our A_β result improved V_{ud} by nearly a factor of five: $|V_{ud}| = 0.981^{+12}_{-10} \to 0.9745(25)$.



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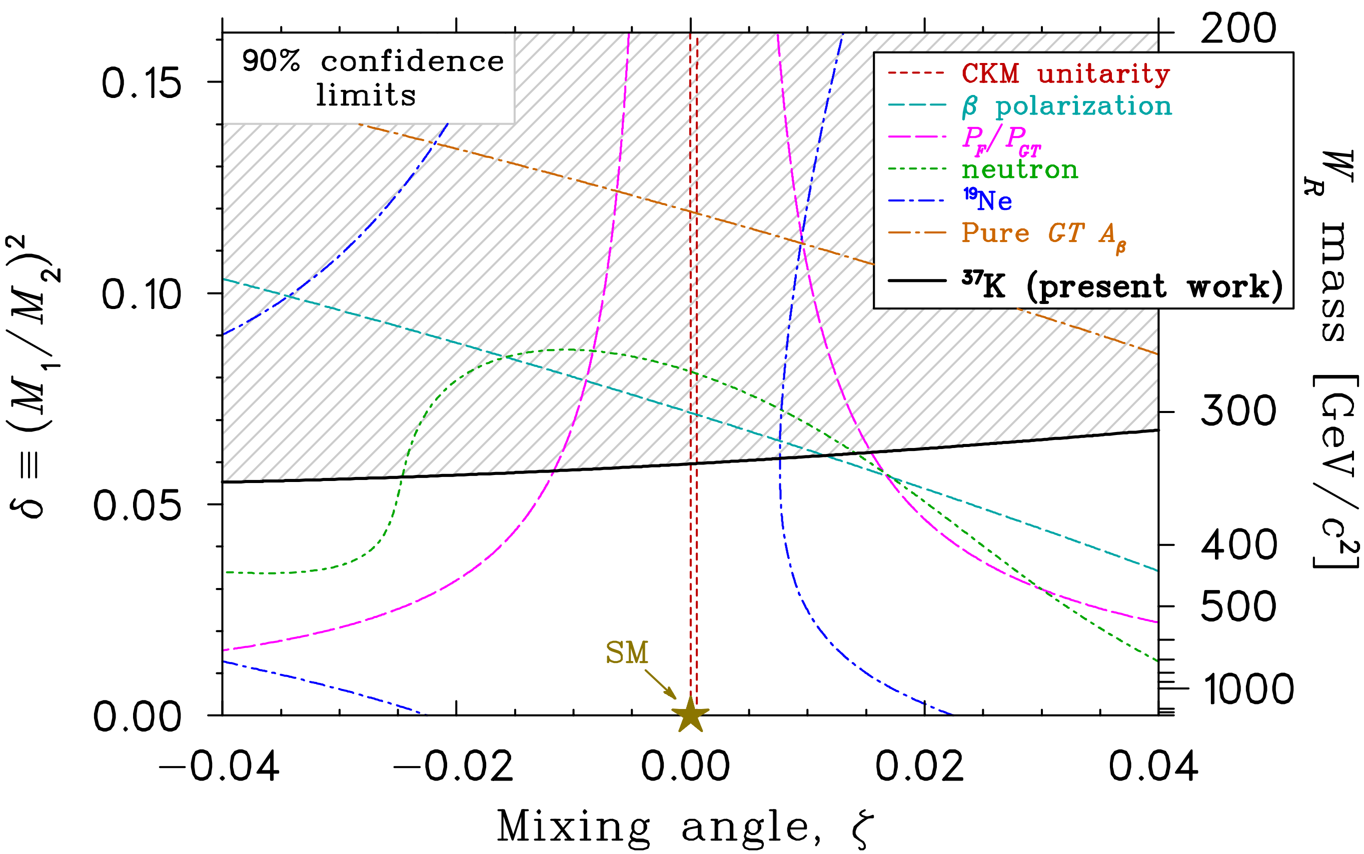

Impact of A_β Measurement

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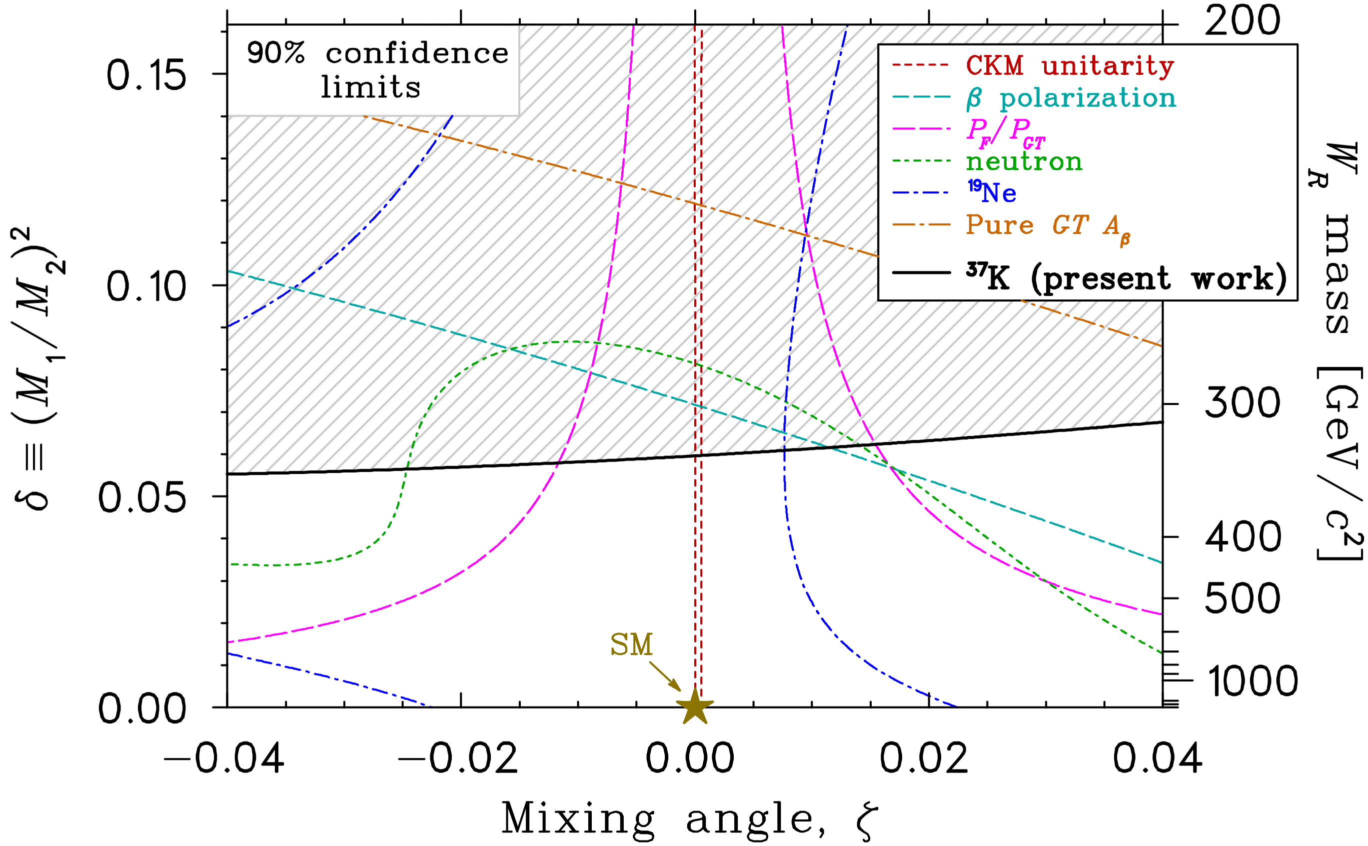
- In terms of right-handed currents, our result is the best nuclear limit: $M_{W_R} > 351$ GeV (in minimal left-right symmetric models)
- Analysis of Fierz and second-class currents (E-dependent observables) to be finished soon



Summary

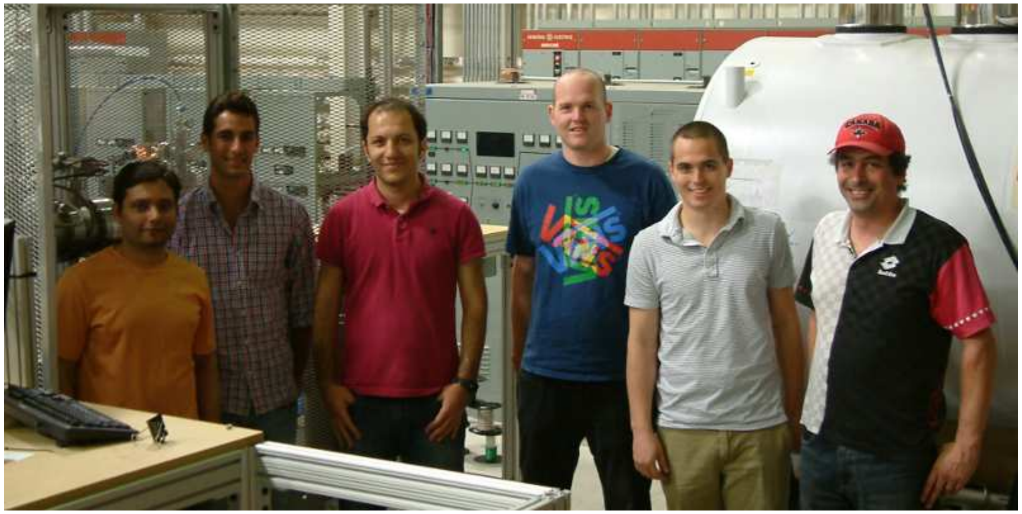
- The SM is fantastic, but **not** our “ultimate” theory
- There are many exciting avenues to find more a complete model
- **Nuclear approach:** precision measurement of correlation parameters

- Penning trap + RIB CI = ***cool*** physics
  - largest open-area Penning trap especially suited for β-delayed proton decays
  - will search for scalar currents via $a_{\beta\nu}$ and b_{Fierz}

- (AC-)MOT + opt. pumping = ***cool*** physics
  - extremely precise, high nuclear polarization: $\langle P \rangle = 99.13(8)\%$
  - best nuclear limit on $M_{W_R} > 351$ GeV (at $\zeta = 0$).
  - on the way to a 0.1% measurement of A_β and other (un)polarized correlations

The Mad Trappers/Thanks

TAMU: S. Behling, E. Bennett, Y. Boran, B. Fenker, M. Mehlman, J. Patti, P. Shidling
+ TAMU/REU undergrads
+ ENSICAEN interns



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+ ENSICAEN

And thank you for your attention!

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