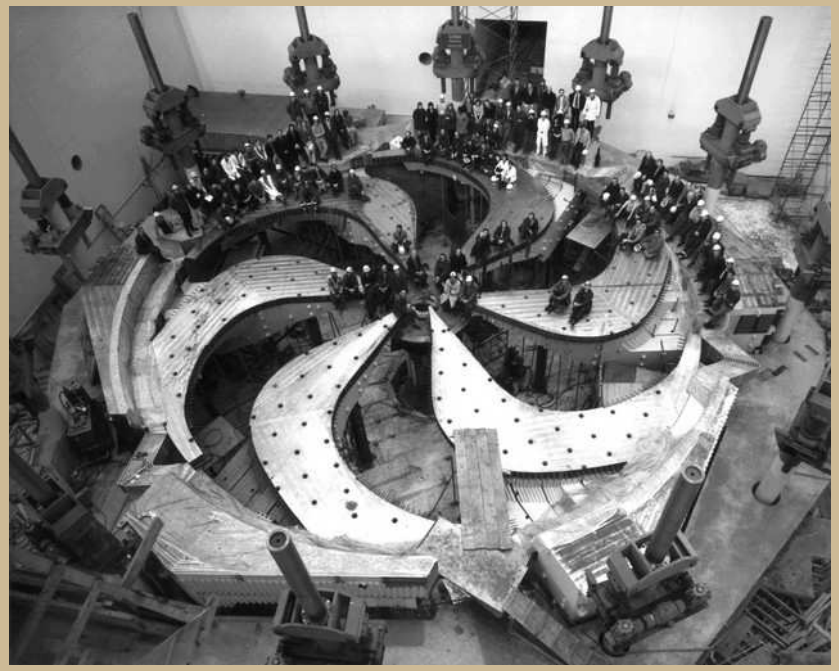
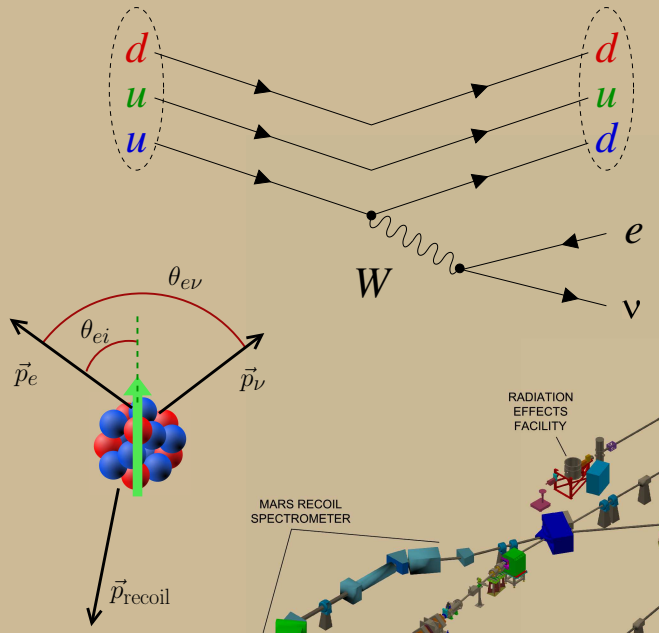
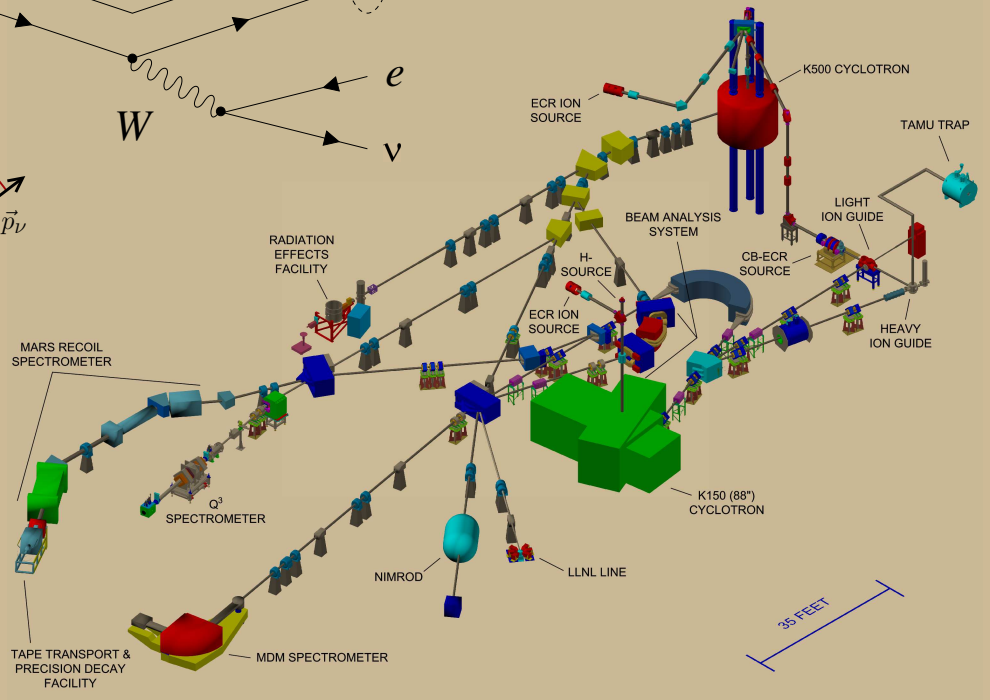
Using Trapped Atoms and Ions for *Fun*damentally *Cool* Physics







Dan Melconian

July 5, 2017

Overview

1. Fundamental symmetries

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

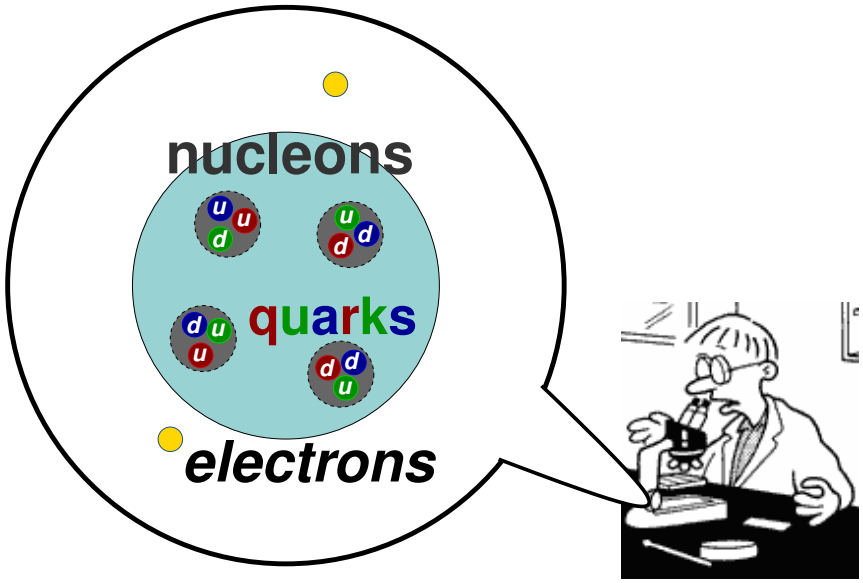
2. TAMU Penning Trap

- **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**
- **preliminary results** of a recent run

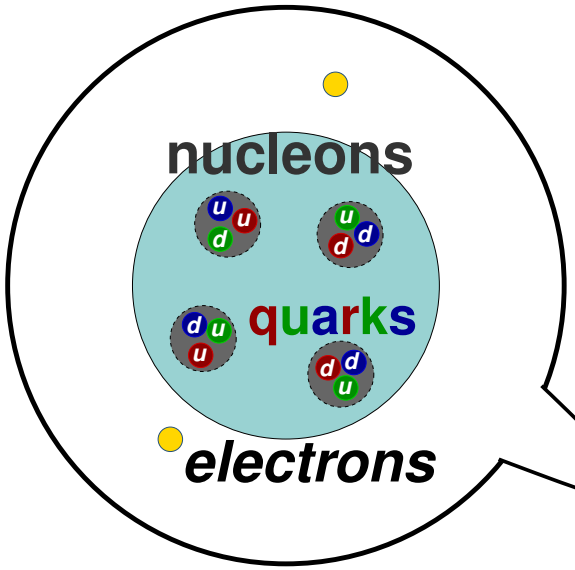
Scope of fundamental physics



the atom

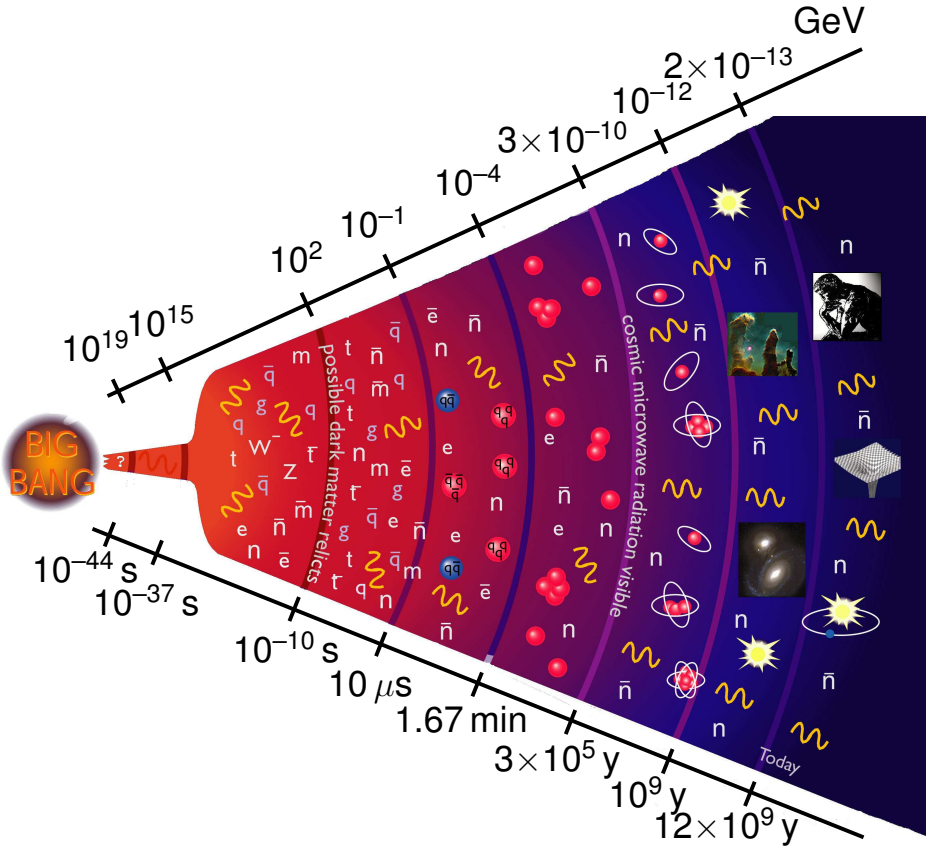
from the very smallest scales . . .

Scope of fundamental physics



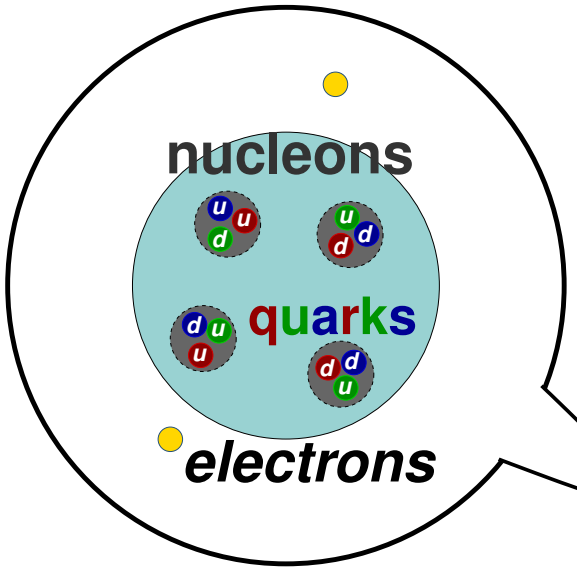
the atom

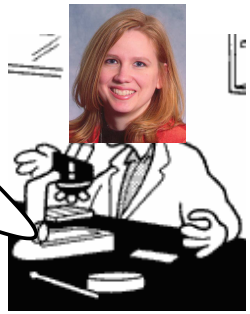
from the very smallest scales . . .



. . . to the very **largest**

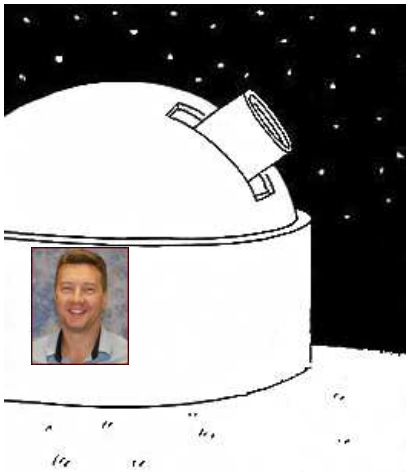
Scope of fundamental nuclear physics

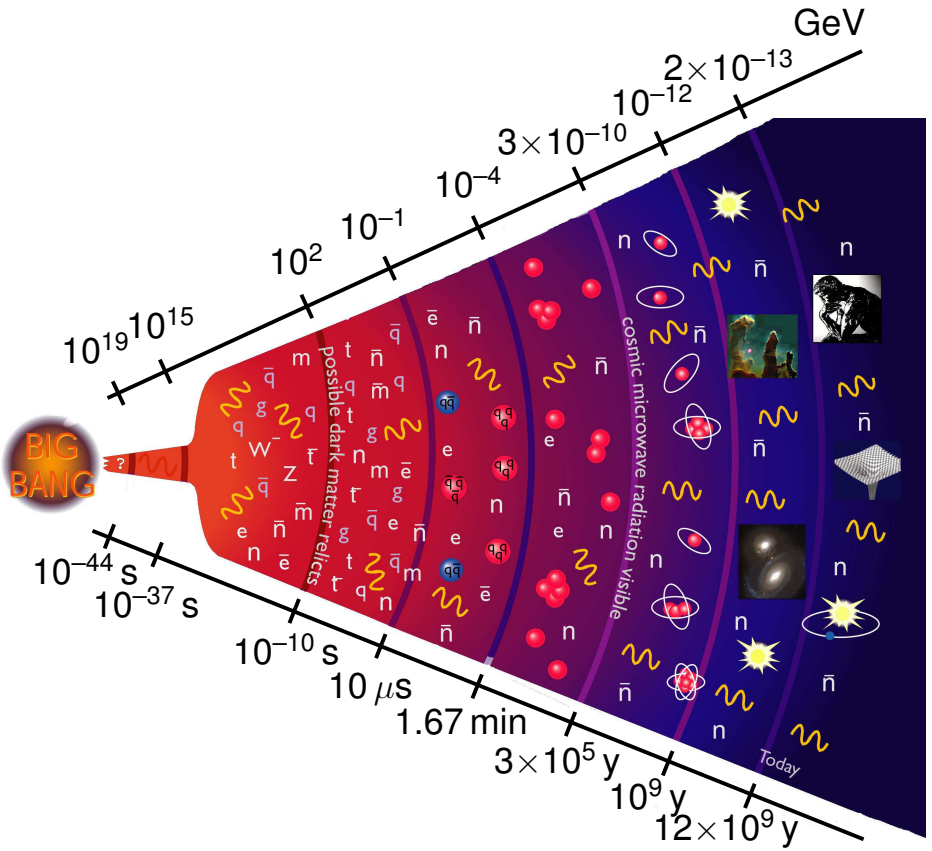




the atom

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 Standard Model

The Standard Model

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

The Standard Model

- **quantum** + **special rel** $\Rightarrow$ **quantum field theory**

The Standard Model

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

The Standard Model

- **quantum** + **special rel** $\Rightarrow$ **quantum field theory**
- Noether's theorem: symmetry $\Leftrightarrow$ conservation law

The Standard Model

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

The Standard Model

- **quantum** + **special rel** $\Rightarrow$ **quantum field theory**
- Noether's theorem: symmetry $\Leftrightarrow$ conservation law

Maxwell's eqns invariant under changes in vector potential	$\Leftrightarrow$	conservation of electric charge, q

The Standard Model

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

The Standard Model

- **quantum** + **special rel** $\Rightarrow$ **quantum field theory**
- Noether's theorem: symmetry $\Leftrightarrow$ conservation law

Maxwell's eqns invariant under changes in vector potential $\Leftrightarrow$ conservation of electric charge, q

and there are other symmetries too:

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

The Standard Model

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

The Standard Model

- **quantum** + **special rel** $\Rightarrow$ **quantum field theory**
- Noether's theorem: symmetry $\Leftrightarrow$ conservation law
- **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

The Standard Model

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**

	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

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

does the Standard Model work??

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

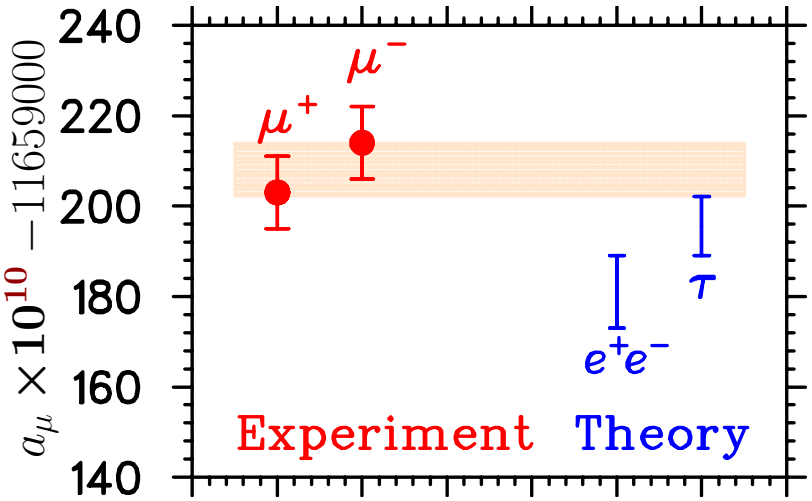
does the Standard Model work??

- ✔ 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**
- ✔ QCD **explains** quark confinement

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

does the Standard Model work??

- ✔ 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**
- ✔ QCD **explains** quark confinement



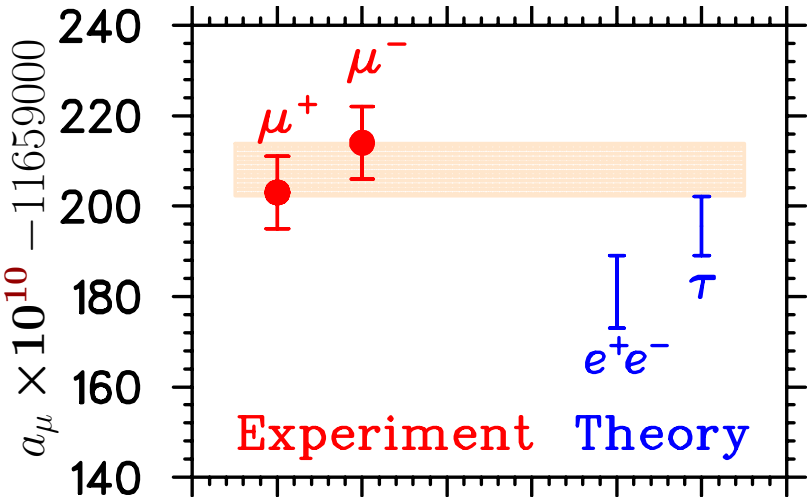
$$a_\mu \equiv \tfrac{1}{2}(g-2)$$

± 1 **part-per-*million*!!**
(PRL **92** (2004) 161802)

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

does the Standard Model work??

- ✔ 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**
- ✔ QCD **explains** quark confinement



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

± 1 **part-per-*million*!!**
(PRL **92** (2004) 161802)

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 **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**? 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** & **astrophys**: SN1987a, Big Bang nucleosynthesis, . . .
- **muon decay**: Michel parameters: ρ, δ, η, and ξ
- **atomic physics**: anapole moment, spectroscopy, . . .

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** & **astrophys**: SN1987a, Big Bang nucleosynthesis, ...
- **muon decay**: Michel parameters: ρ, δ, η, and ξ
- **atomic physics**: anapole moment, spectroscopy, ...

---

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

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

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** & **astrophys**: SN1987a, Big Bang nucleosynthesis, . . .
- **muon decay**: Michel parameters: ρ, δ, η, and ξ
- **atomic physics**: anapole moment, spectroscopy, . . .

---

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

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

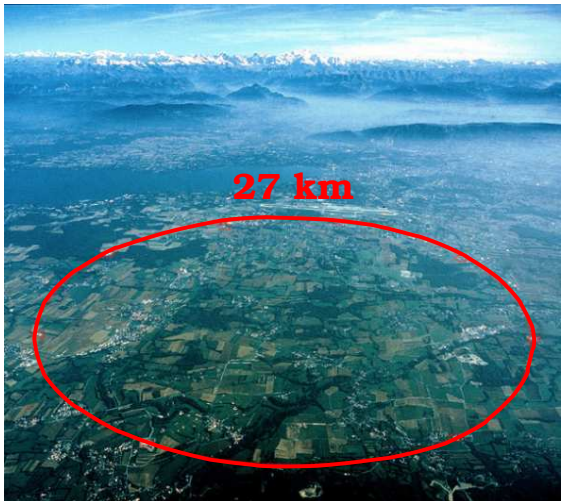
often they are **interdisciplinary**

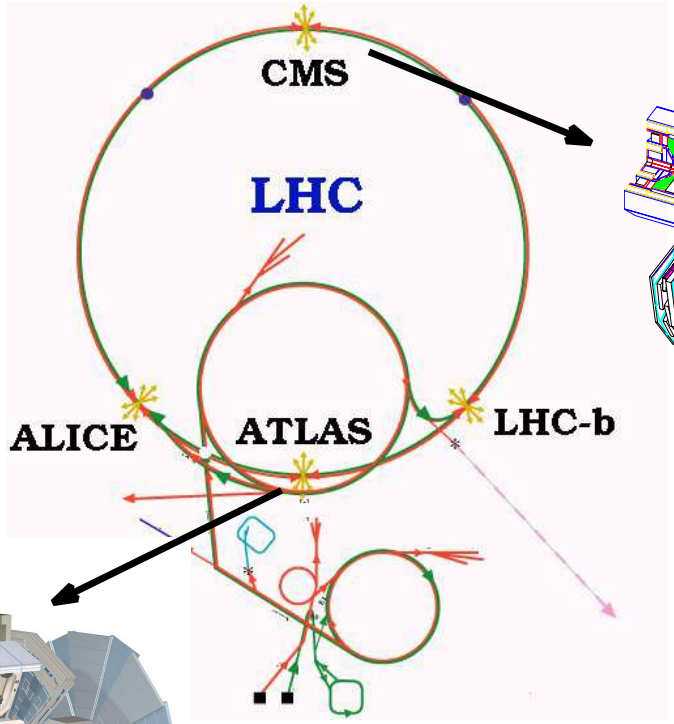
(fun and a great basis for graduate students!)

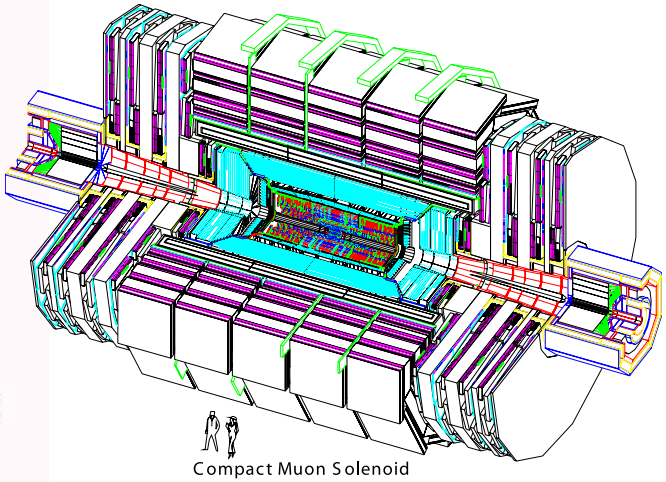
How does high-energy test the SM?

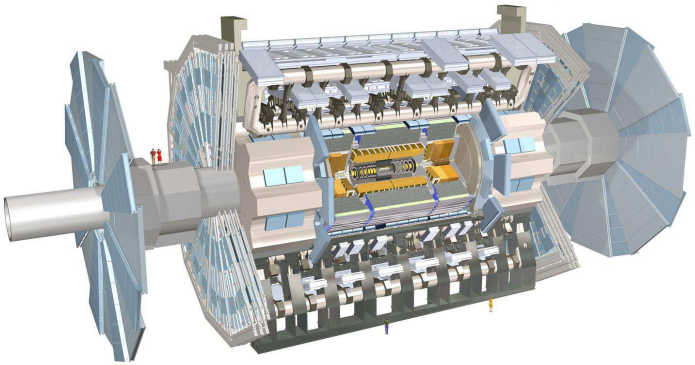
colliders: CERN, SLAC, FNAL, BNL, KEK, DESY, ...

direct search of particles



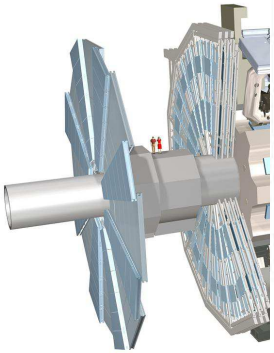


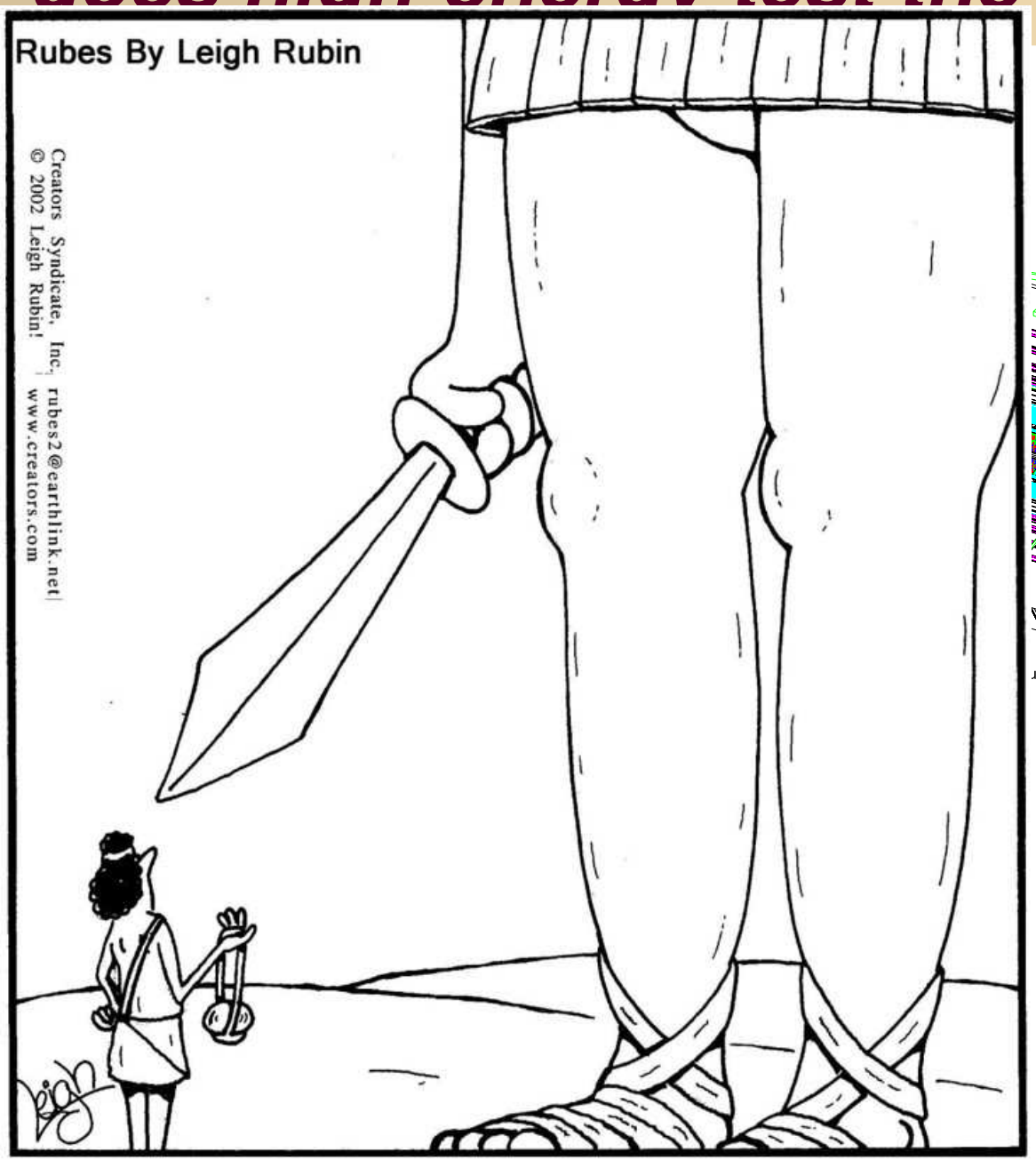


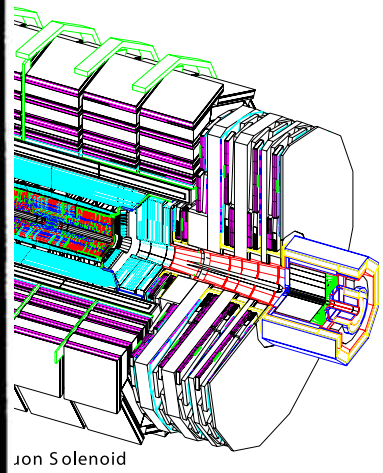


How does high-energy test the SM?

co . . . .



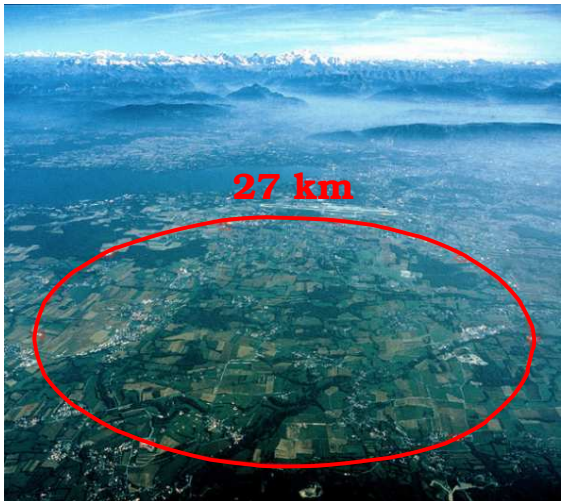


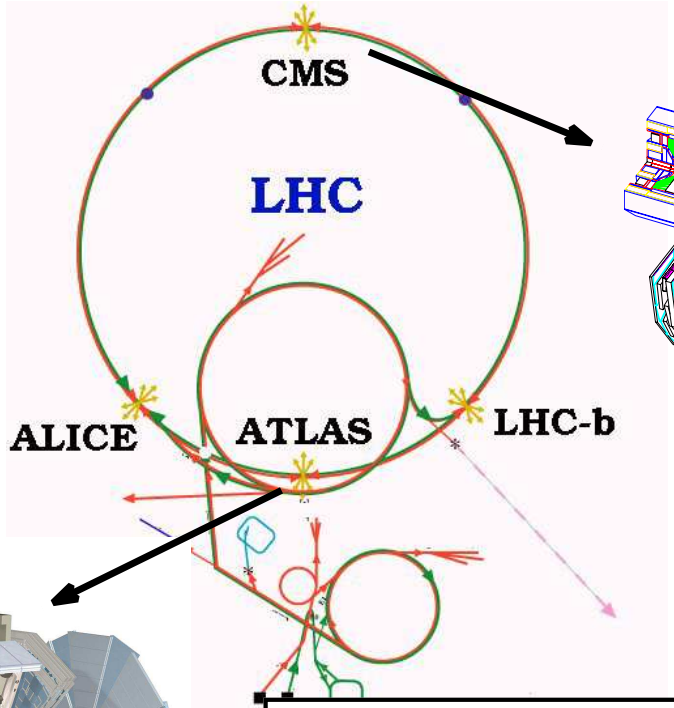


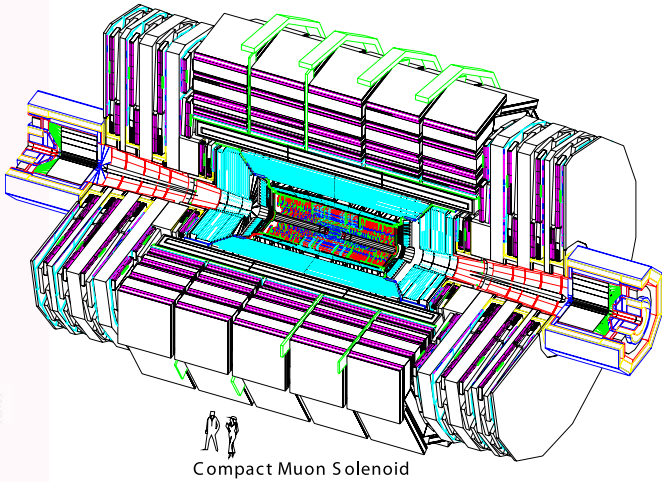
How does high-energy test the SM?

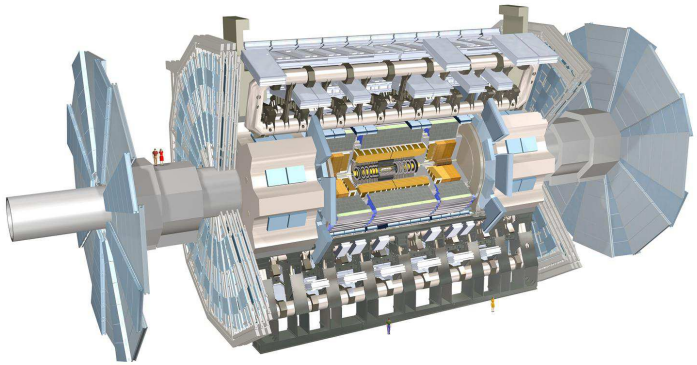
colliders: CERN, SLAC, FNAL, BNL, KEK, DESY, ...

direct search of particles









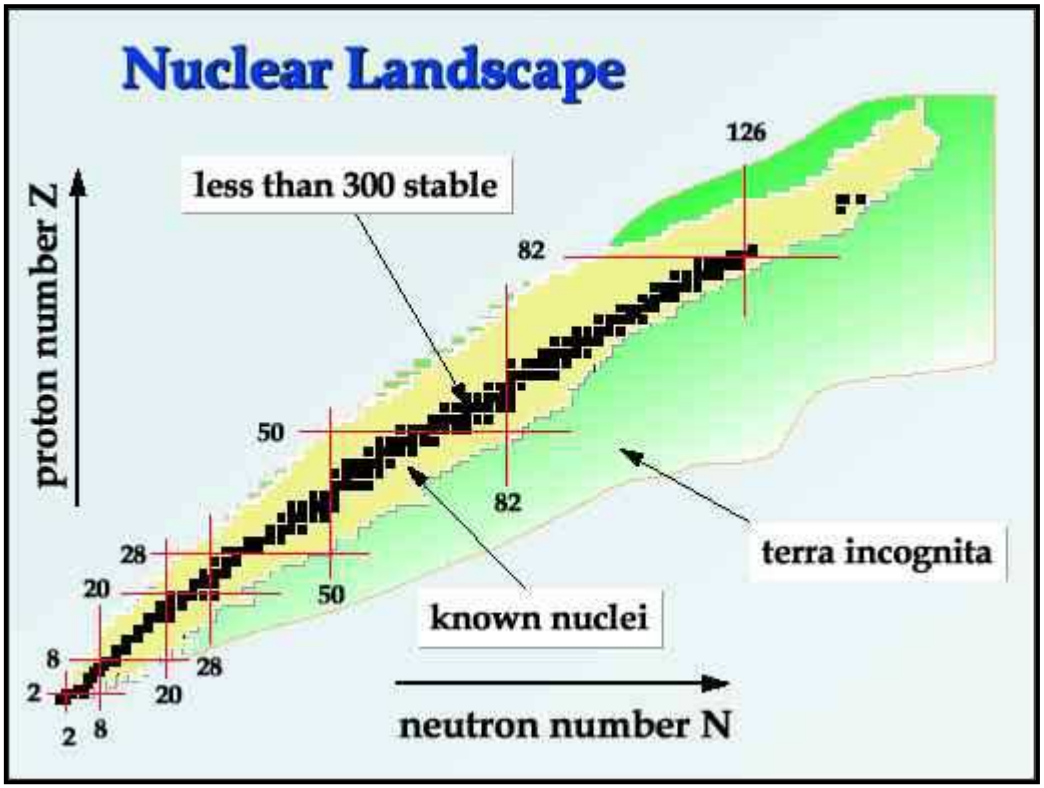
"go big or go home"

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

How do we test the SM?

nuclear physics: radioactive ion beam facilities

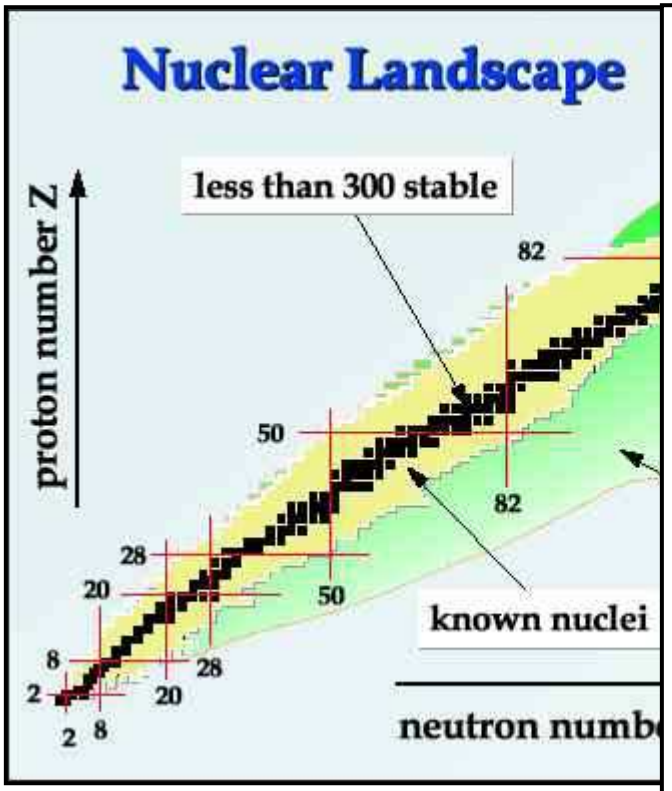
indirect search via precision measurements

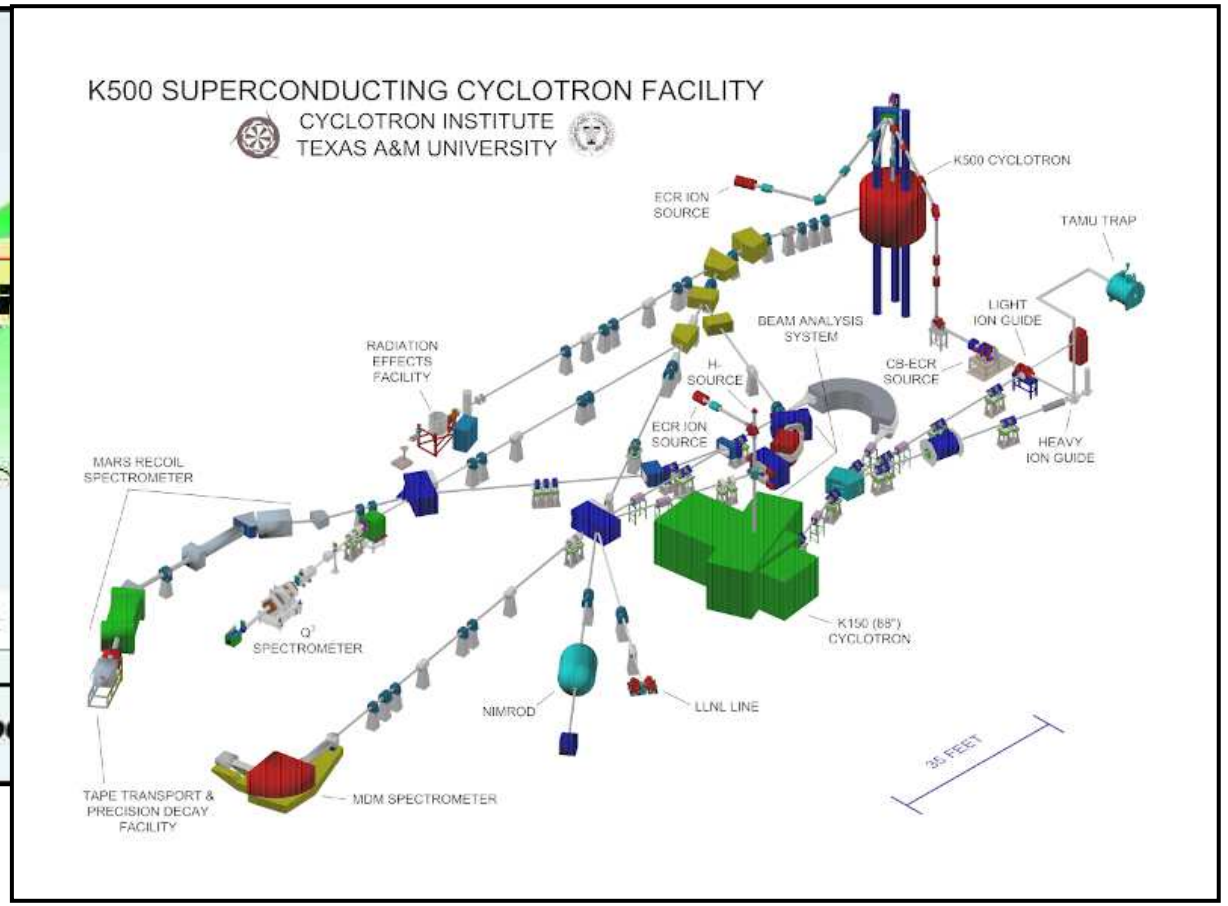


How do we test the SM?

nuclear physics: radioactive ion beam facilities

indirect search via precision measurements

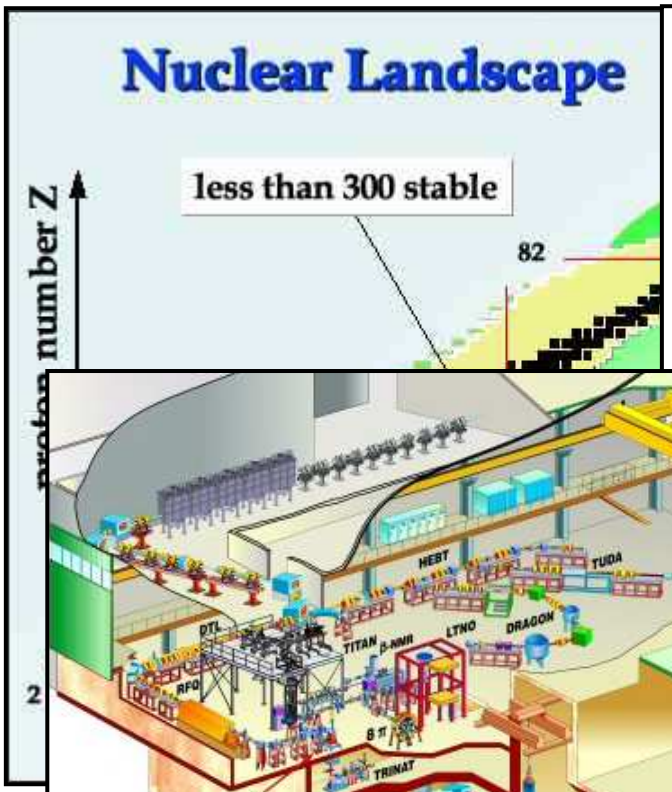


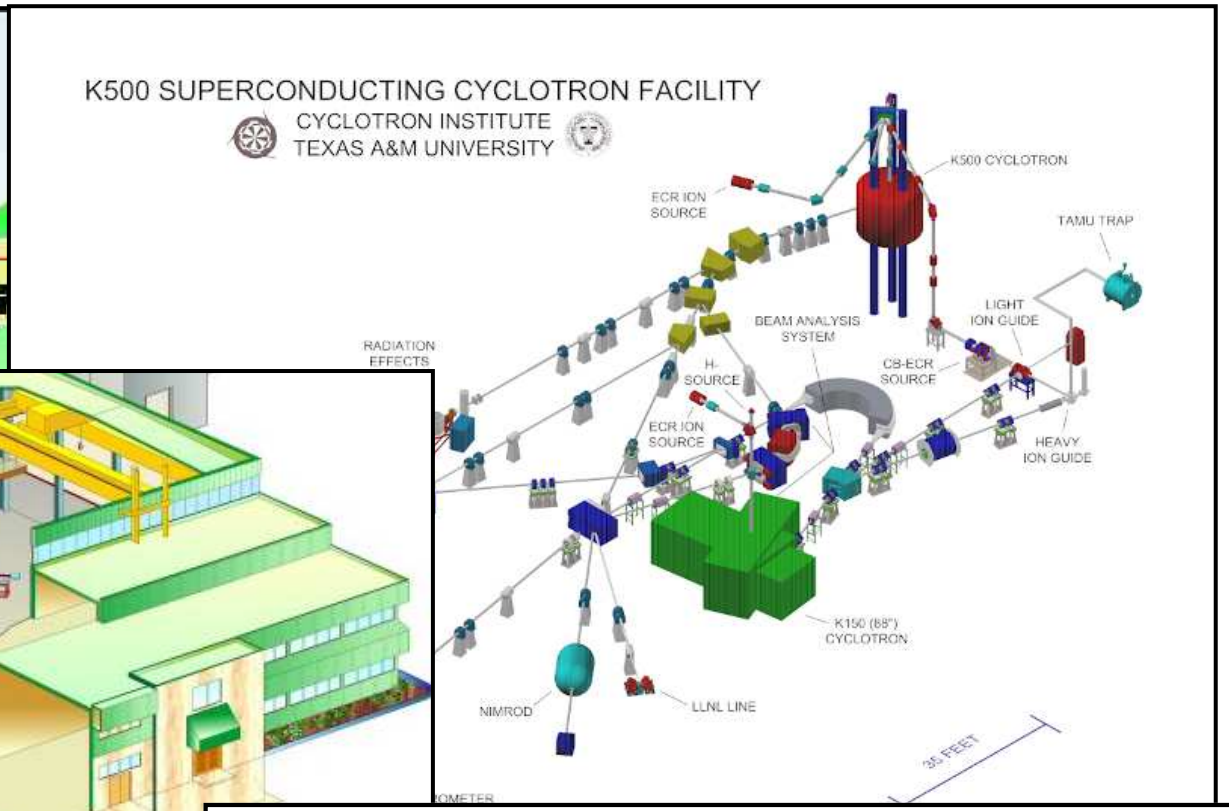


How do we test the SM?

nuclear physics: radioactive ion beam facilities

indirect search via precision measurements





- ✔ smaller collaborations
- ✔ contribute to all aspects
- ✔ "table-top" physics

How specifically do I plan to test the SM?

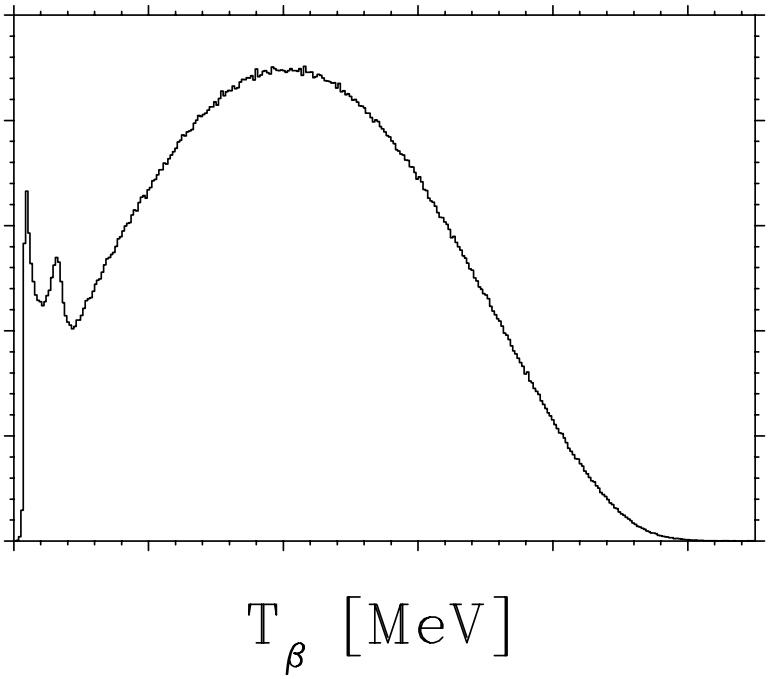
- Begin by looking at the rate for β decay

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

How specifically do I plan to test the SM?

- Begin by looking at the rate for β decay

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



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)

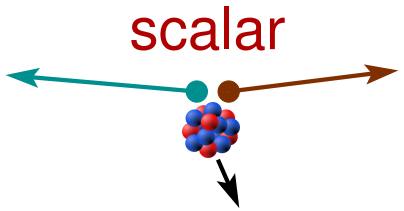
$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \overbrace{\frac{G_F^2 |V_{ud}|^2}{(2\pi)^5} p_e E_e (A_\circ - E_e)^2 \xi}^{\text{basic decay rate}} \left(1 + \overbrace{a_{\beta\nu} \frac{\vec{p}_e \cdot \vec{p}_{\nu_e}}{E_e E_{\nu_e}}}^{\beta-\nu \text{ correlation}} + \overbrace{b \frac{\Gamma m_e}{E_e}}^{\text{Fierz term}} \right.$$

How specifically do I plan to test the SM?

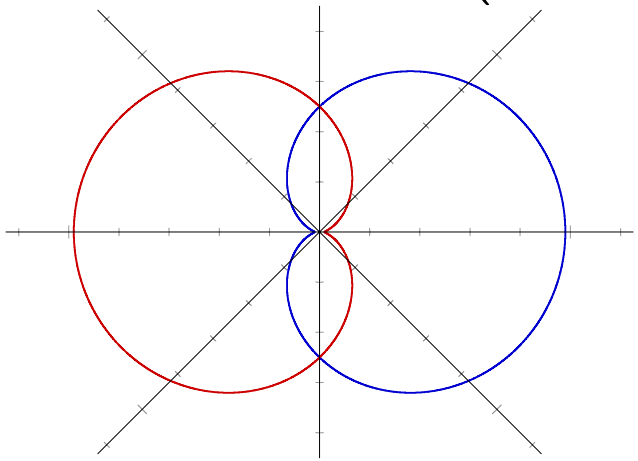
- Expand to the often-quoted **angular distribution** of the decay:
  (Jackson, Treiman and Wyld, Phys Rev **106** and Nucl Phys **4**, 1957)

$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \overbrace{\frac{G_F^2 |V_{ud}|^2}{(2\pi)^5} p_e E_e (A_\circ - E_e)^2 \xi}^{\text{basic decay rate}} \left(1 + \overbrace{a_{\beta\nu} \frac{\vec{p}_e \cdot \vec{p}_{\nu_e}}{E_e E_{\nu_e}}}^{\beta-\nu \text{ correlation}} + \overbrace{b \frac{\Gamma m_e}{E_e}}^{\text{Fierz term}} \right)$$

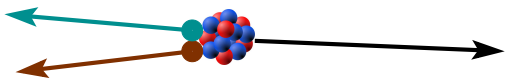
scalar



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



vector



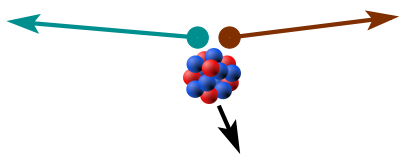
$$a_{\beta\nu} = \frac{|C_V|^2 + |C'_V|^2}{|C_V|^2 + |C'_V|^2}$$

How specifically do I plan to test the SM?

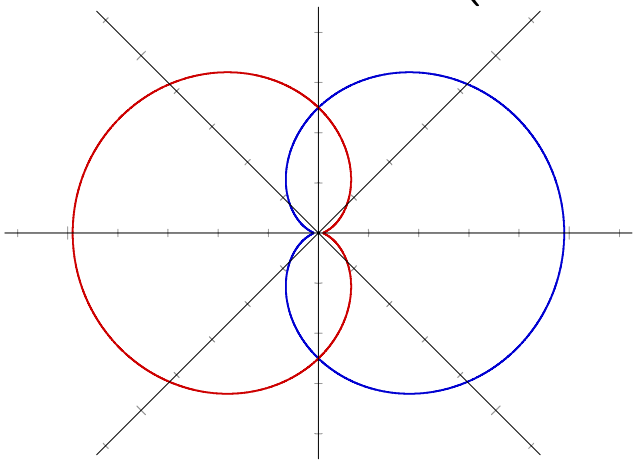
- Expand to the often-quoted **angular distribution** of the decay:
  (Jackson, Treiman and Wyld, Phys Rev **106** and Nucl Phys **4**, 1957)

$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \overbrace{\frac{G_F^2 |V_{ud}|^2}{(2\pi)^5} p_e E_e (A_\circ - E_e)^2 \xi}^{\text{basic decay rate}} \left(1 + \overbrace{a_{\beta\nu} \frac{\vec{p}_e \cdot \vec{p}_{\nu_e}}{E_e E_{\nu_e}}}^{\beta-\nu \text{ correlation}} + \overbrace{b \frac{\Gamma m_e}{E_e}}^{\text{Fierz term}} \right)$$

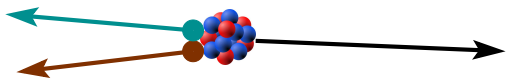
scalar



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



vector



$$a_{\beta\nu} = \frac{|C_V|^2 + |C'_V|^2}{|C_V|^2 + |C'_V|^2}$$

$$a_{\beta\nu} = \frac{|C_V|^2 + |C'_V|^2 - |C_S|^2 - |C'_S|^2}{|C_V|^2 + |C'_V|^2 + |C_S|^2 + |C'_S|^2} = 1??$$

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)

$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \overbrace{\frac{G_F^2|V_{ud}|^2}{(2\pi)^5} p_e E_e (A_\circ - E_e)^2 \xi}^{\text{basic decay rate}} \left(1 + \overbrace{a_{\beta\nu}\frac{\vec{p_e}\cdot\vec{p}_{\nu_e}}{E_e E_{\nu_e}}}^{\beta-\nu\text{ correlation}} + \overbrace{b\frac{\Gamma m_e}{E_e}}^{\text{Fierz term}}\right)$$

$$a_{\beta\nu} = \frac{|C_V|^2 + |C'_V|^2 - |C_S|^2 - |C'_S|^2}{|C_V|^2 + |C'_V|^2 + |C_S|^2 + |C'_S|^2} = 1??$$

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

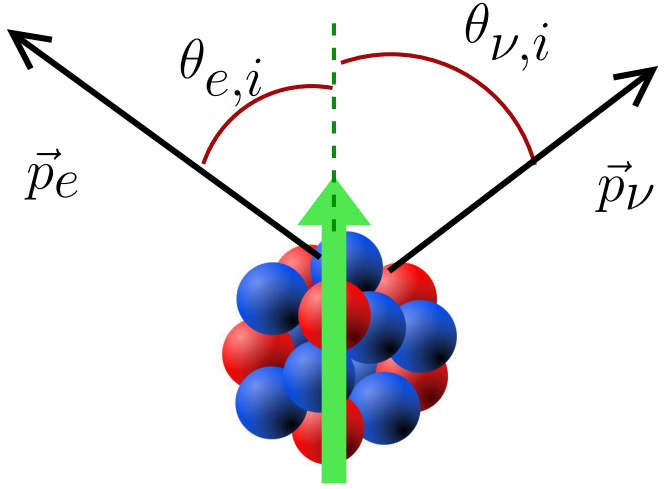
$$b_F = \frac{-2\Re e(C_S^* C_V + C_S'^* C'_V)}{|C_V|^2 + |C'_V|^2 + |C_S|^2 + |C'_S|^2} = 0??$$

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

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)

$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \overbrace{\frac{G_F^2 |V_{ud}|^2}{(2\pi)^5} p_e E_e (A_\circ - E_e)^2 \xi}^{\text{basic decay rate}} \left(1 + \overbrace{a_{\beta\nu} \frac{\vec{p_e} \cdot \vec{p}_{\nu_e}}{E_e E_{\nu_e}}}^{\beta-\nu \text{ correlation}} + \overbrace{b \frac{\Gamma m_e}{E_e}}^{\text{Fierz term}} + \frac{\langle \vec{I} \rangle}{I} \cdot \left[\underbrace{A_\beta \frac{\vec{p_e}}{E_e}}_{\beta \text{ asym}} + \underbrace{B_\nu \frac{\vec{p}_\nu}{E_\nu}}_{\nu \text{ asym}} + \underbrace{D \frac{\vec{p_e} \times \vec{p}_\nu}{E_e E_\nu}}_{T-\text{violating}} \right] + \ldots \right)$$

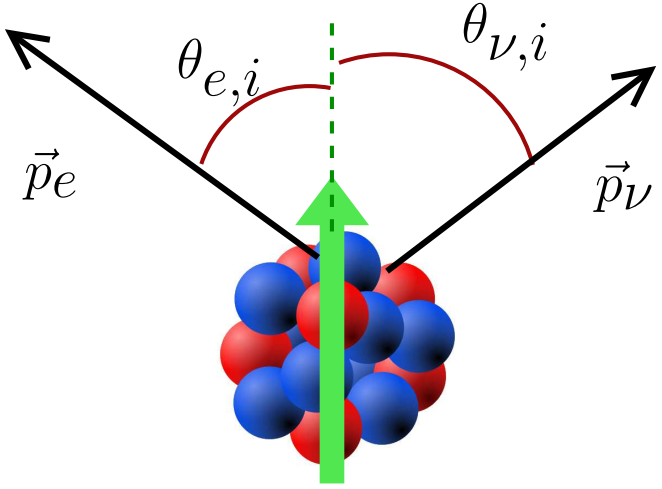


How specifically do I plan to test the SM?

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

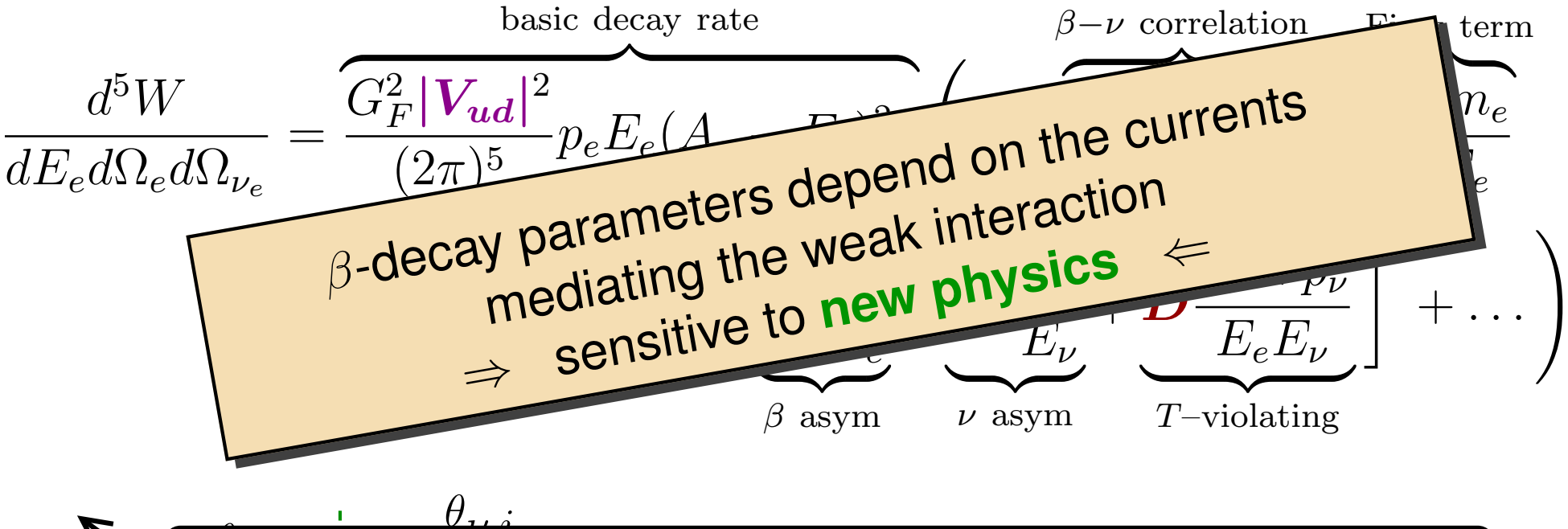
$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \overbrace{\frac{G_F^2|V_{ud}|^2}{(2\pi)^5} p_e E_e (A}^{\text{basic decay rate}} \Bigg(\overbrace{\quad}^{\beta-\nu \text{ correlation}} \overbrace{\quad}^{\text{Fierz term}} \frac{m_e}{E_e} \Bigg[\underbrace{\quad}_{\beta \text{ asym}} + \underbrace{\frac{\vec{p}_\nu}{E_\nu}}_{\nu \text{ asym}} + \underbrace{D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}}_{T-\text{violating}} \Bigg] + \ldots \Bigg)$$

β-decay parameters depend on the currents mediating the weak interaction
$\Rightarrow$ sensitive to **new physics** $\Leftarrow$



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)

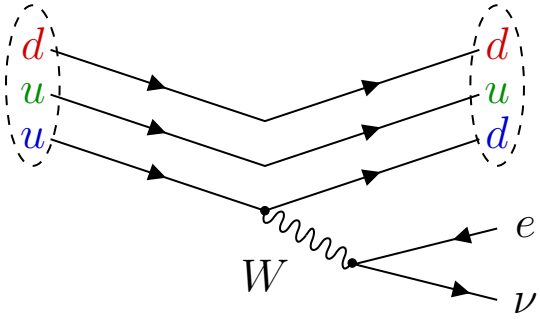


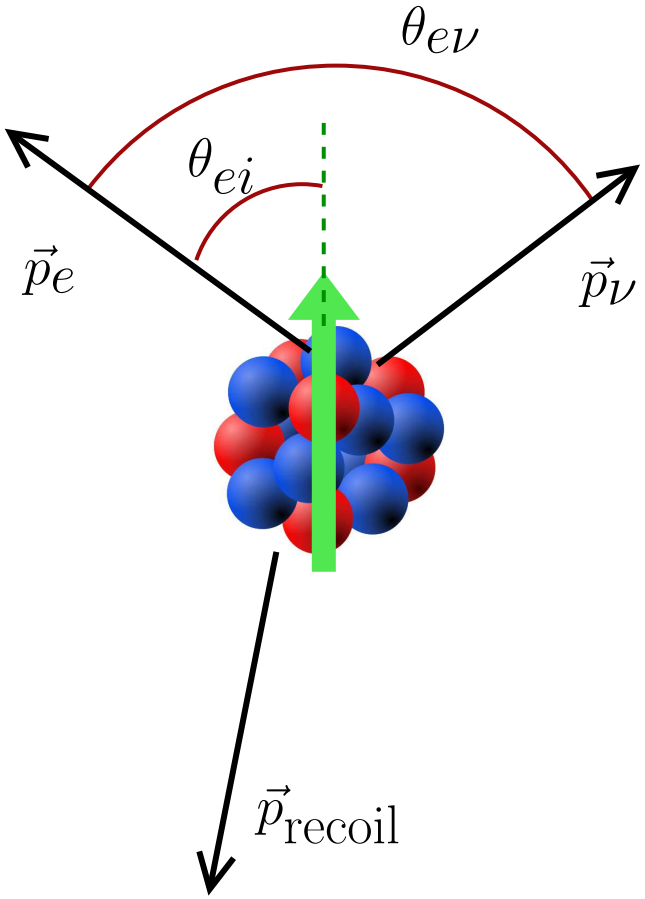
β-decay parameters depend on the currents mediating the weak interaction
$\Rightarrow$ sensitive to **new physics** $\Leftarrow$

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)

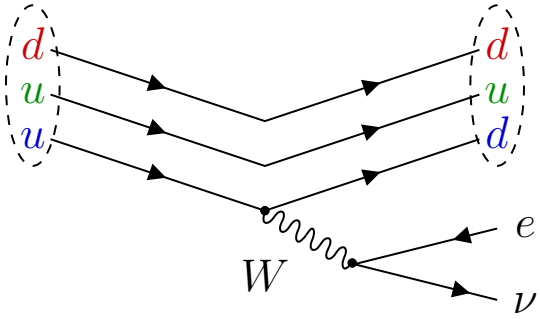
How to acheive our goal?

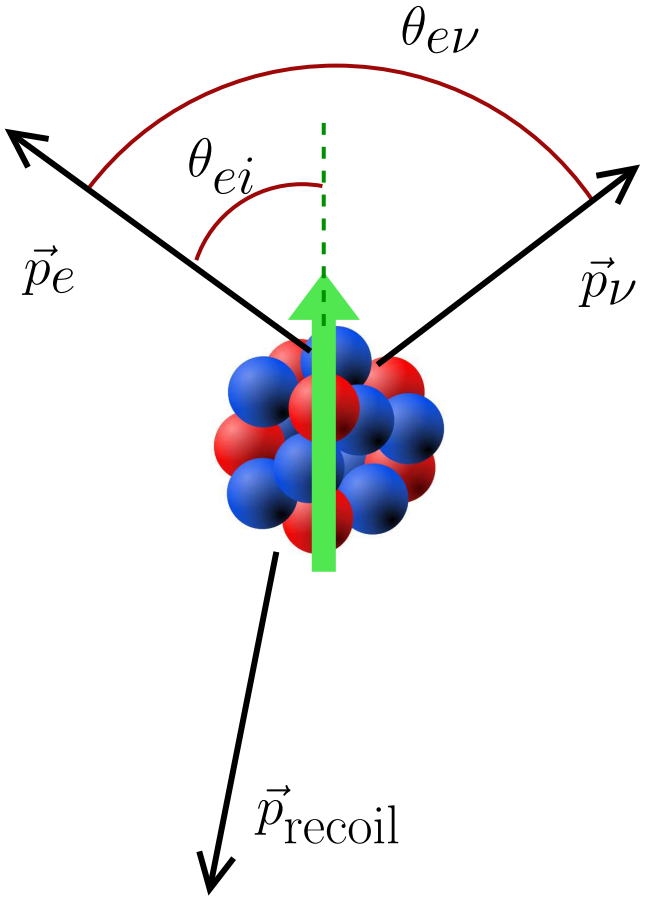




- perform a β decay experiment on **short-lived** isotopes

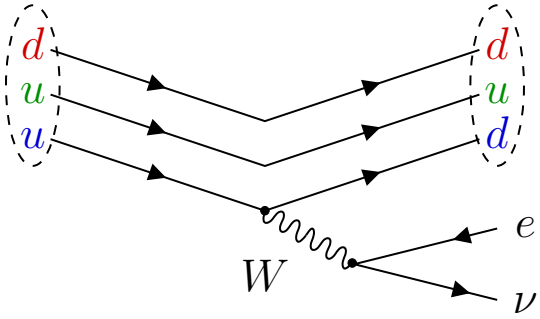
How to acheive our goal?

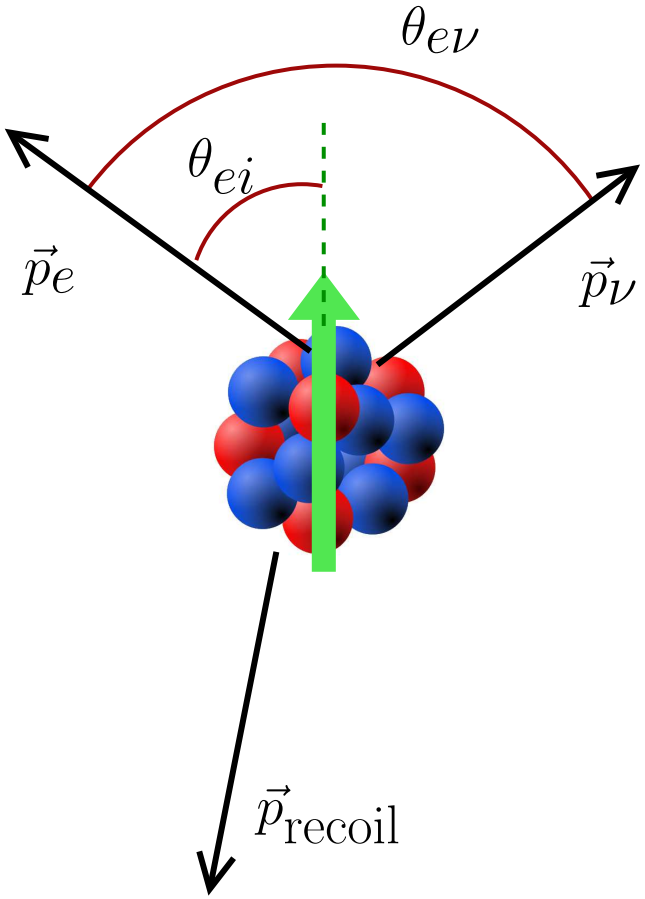




- perform a β decay experiment on **short-lived** isotopes
- make a **precision measurement** of the angular correlation parameters

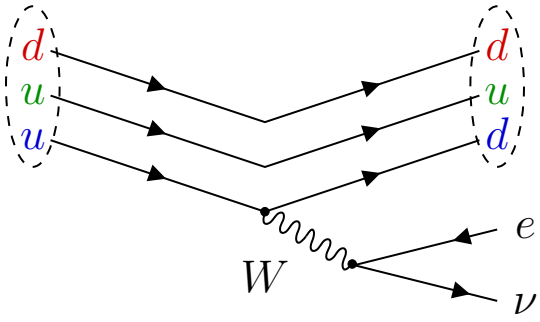
How to acheive our goal?

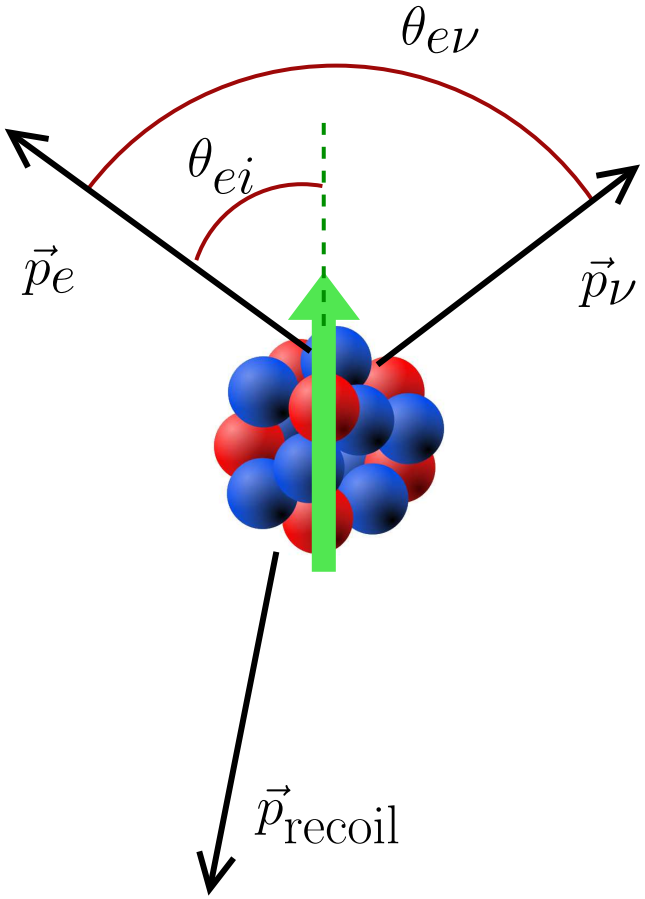




- perform a β decay experiment on **short-lived** isotopes
- make a **precision measurement** of the angular correlation parameters
- **compare** the SM predictions to observations

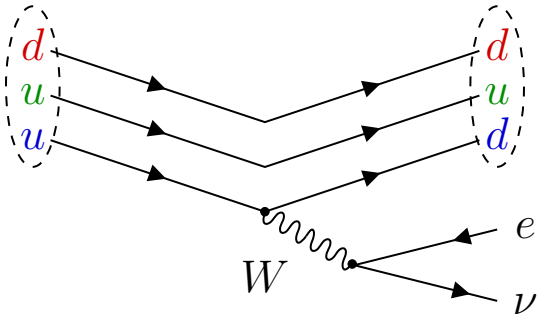
How to acheive our goal?



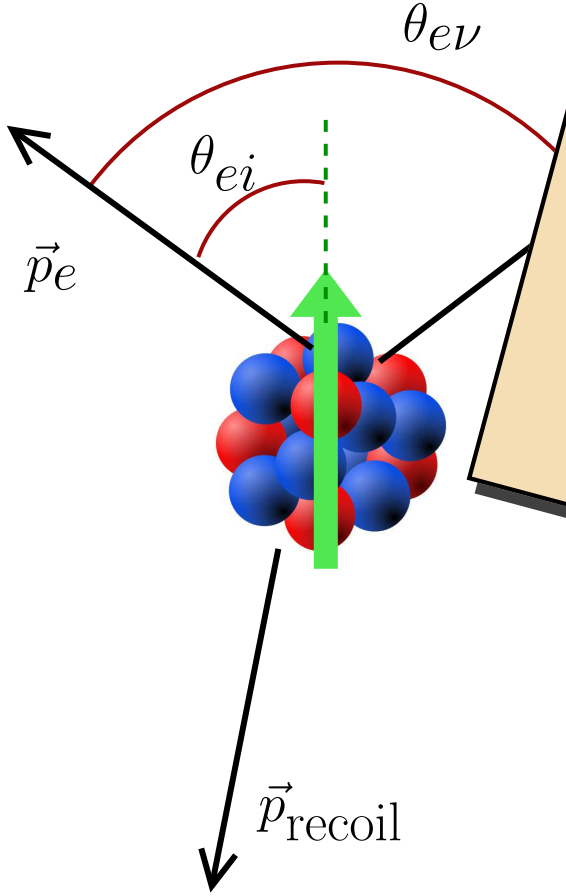


- perform a β decay experiment on **short-lived** isotopes
- make a **precision measurement** of the angular correlation parameters
- **compare** the SM predictions to observations
- look for **deviations** as an indication of **new physics**

How to acheive our goal?



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



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

CM predictions

an

indicat

C.S. Wu's experiment – Parity violation

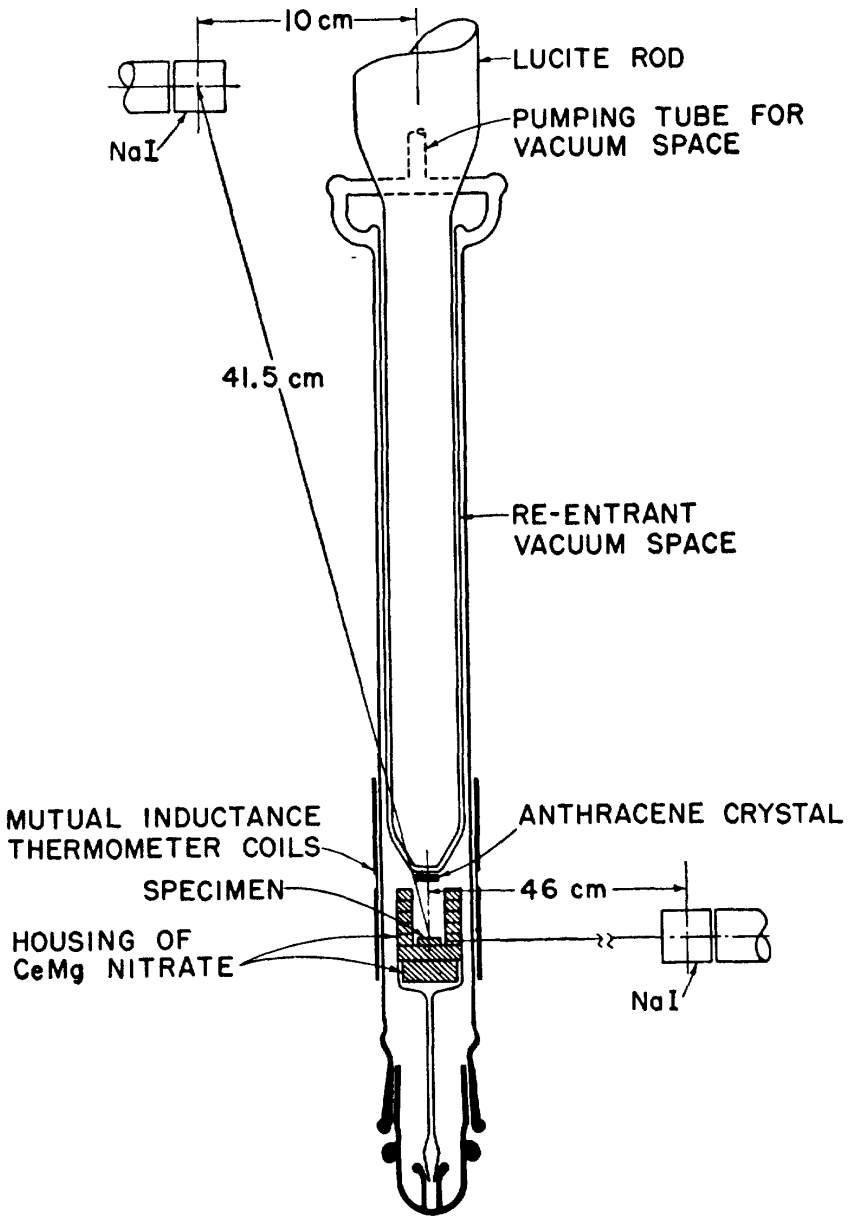
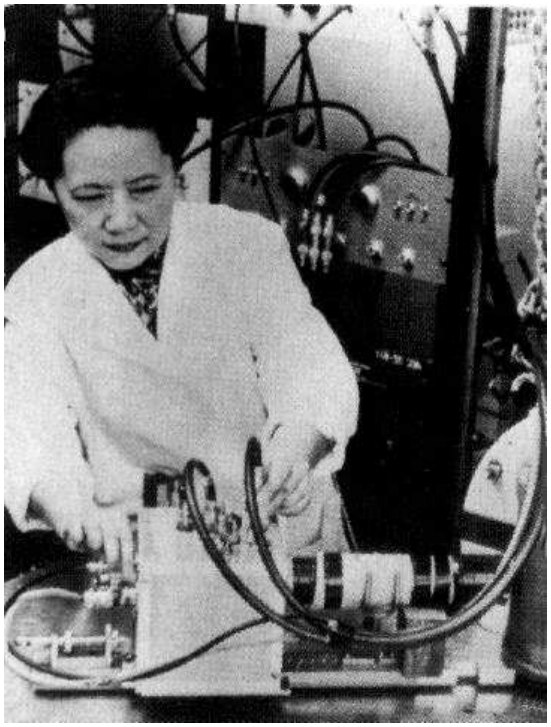
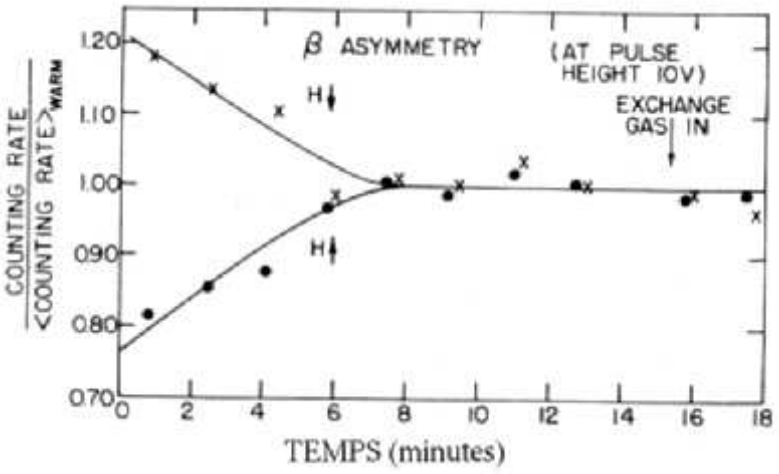


FIG. 1. Schematic drawing of the lower part of the cryostat.





C.S. Wu's experiment – Parity violation

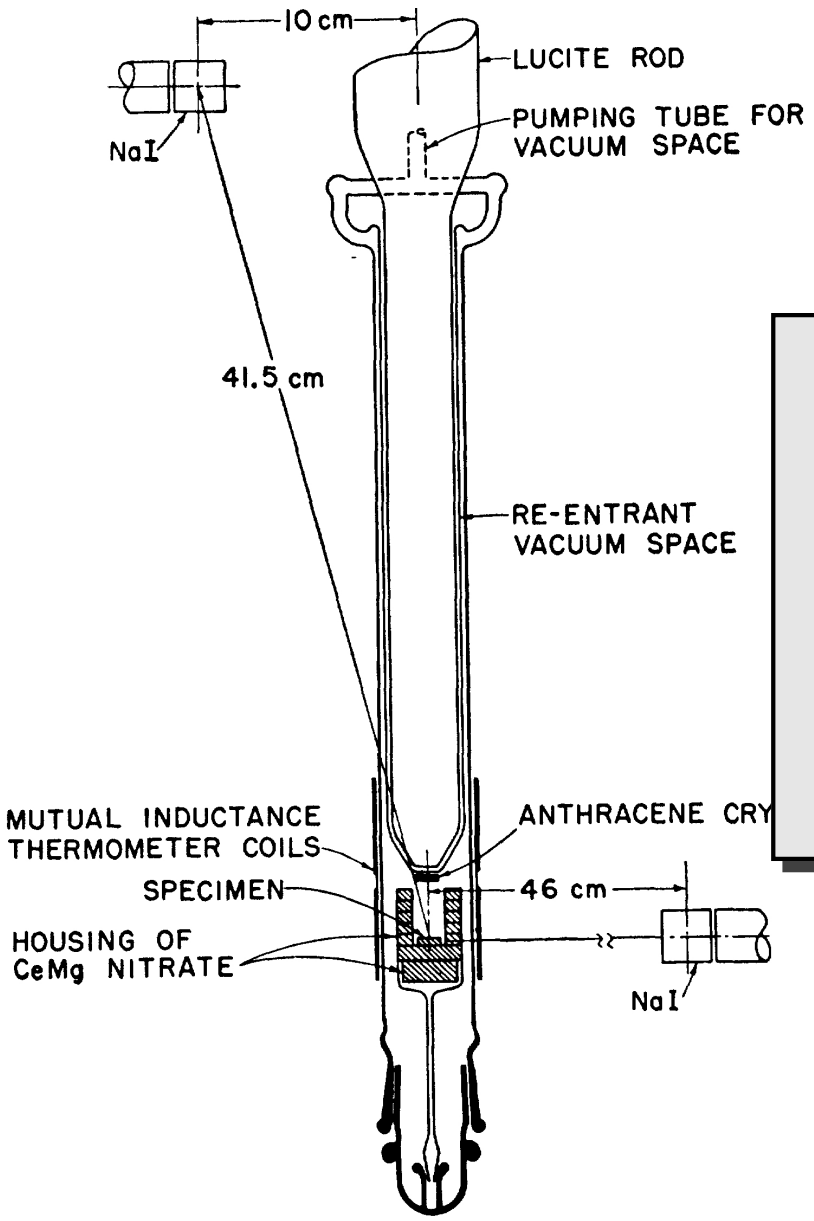
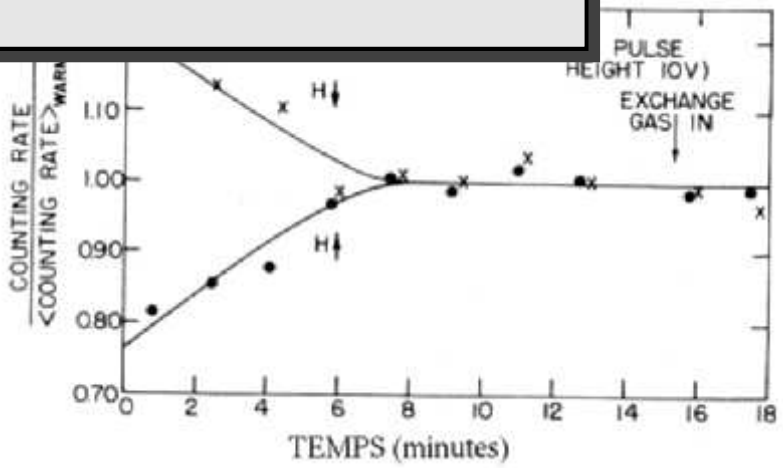


FIG. 1. Schematic drawing of the lower part of the cryostat.

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



Overview

1. Fundamental symmetries

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

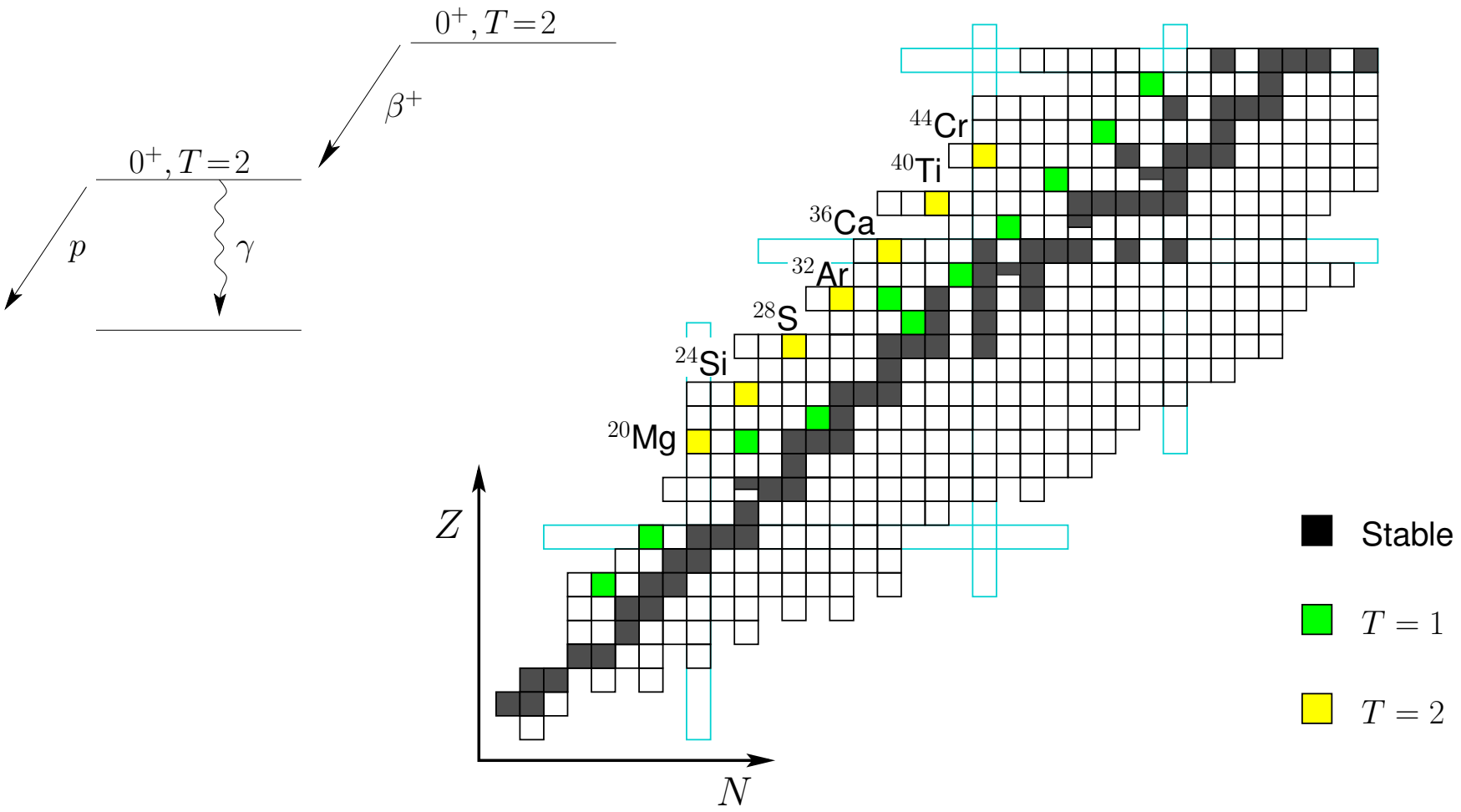
2. TAMU Penning Trap

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

3. TRIUMF Neutral Atom Trap

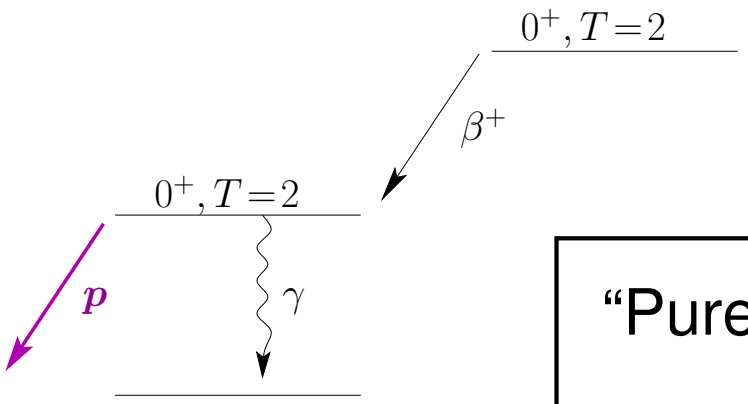
- angular correlations of **polarized ^{37}K**
- **preliminary results** of a recent run

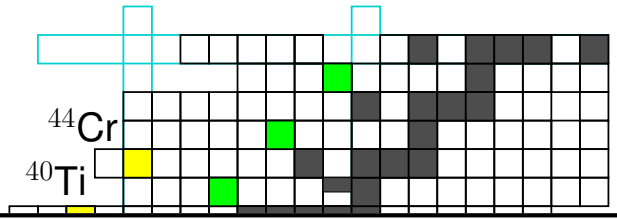
$T = 2$ superallowed decays

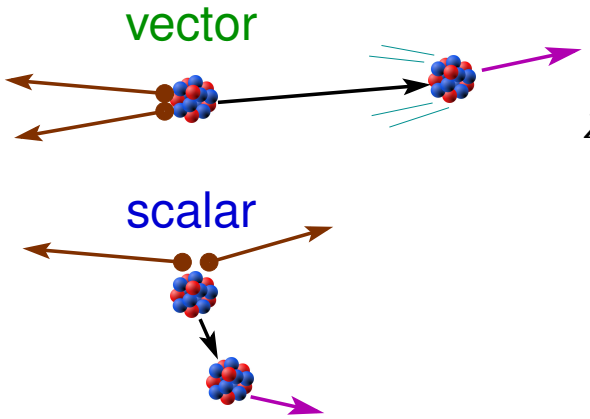


- $\beta - \nu$ correlations
- model-dependence of δ_C calcs seem to depend on T . . .
- new cases for V_{ud}

$T = 2$ superallowed decays



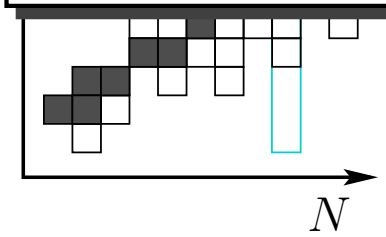




"Pure Fermi decay" $\Leftrightarrow$ minimal nuclear structure effects

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 $0^+ \rightarrow 0^+$ 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 $0^+ \rightarrow 0^+$ 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 $\vec{p}_e \cdot \vec{p}_\nu$!

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

VOLUME 83, NUMBER 7 PHYSICAL REVIEW LETTERS 16 AUGUST 1999

Positron-Neutrino Correlation in the $0^+ \rightarrow 0^+$ 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*

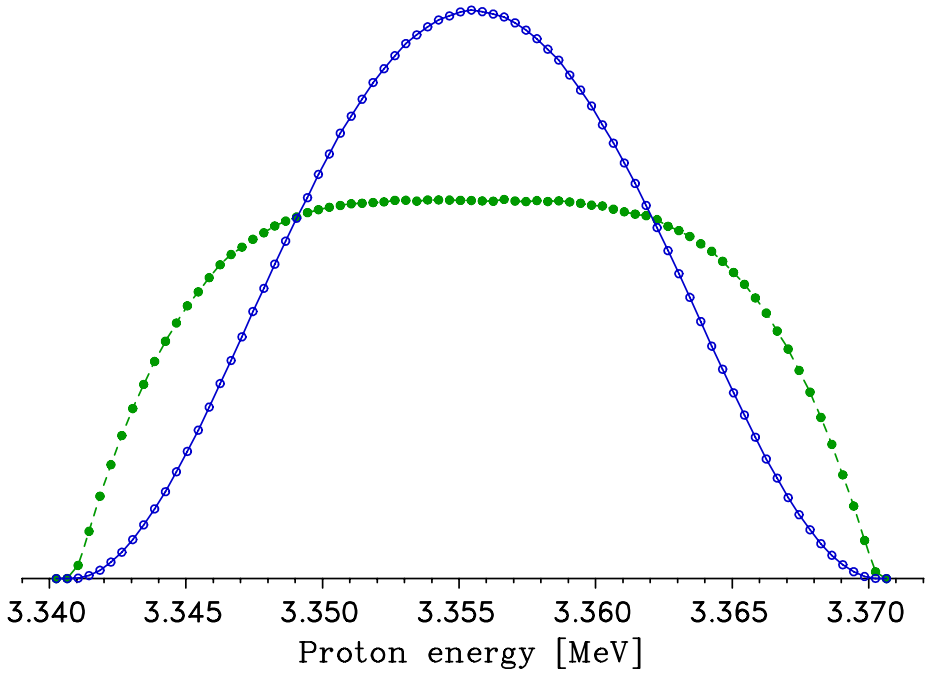
[3]*Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain*

[4]*EP Division, CERN, Geneva, Switzerland CH-1211*

(Received 24 February 1999)

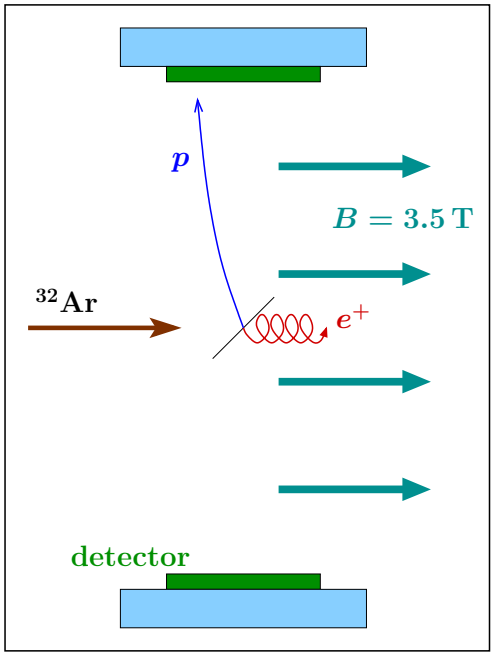
The positron-neutrino correlation in the $0^+ \rightarrow 0$ analyzing the effect of lepton recoil on the shape of decay. Our result is consistent with the standard m find $a = 0.9989 \pm 0.0052 \pm 0.0039$, which yields

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



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

VOLUME 83, NUMBER 7 PHYSICAL REVIEW LETTERS 16 AUGUST 1999

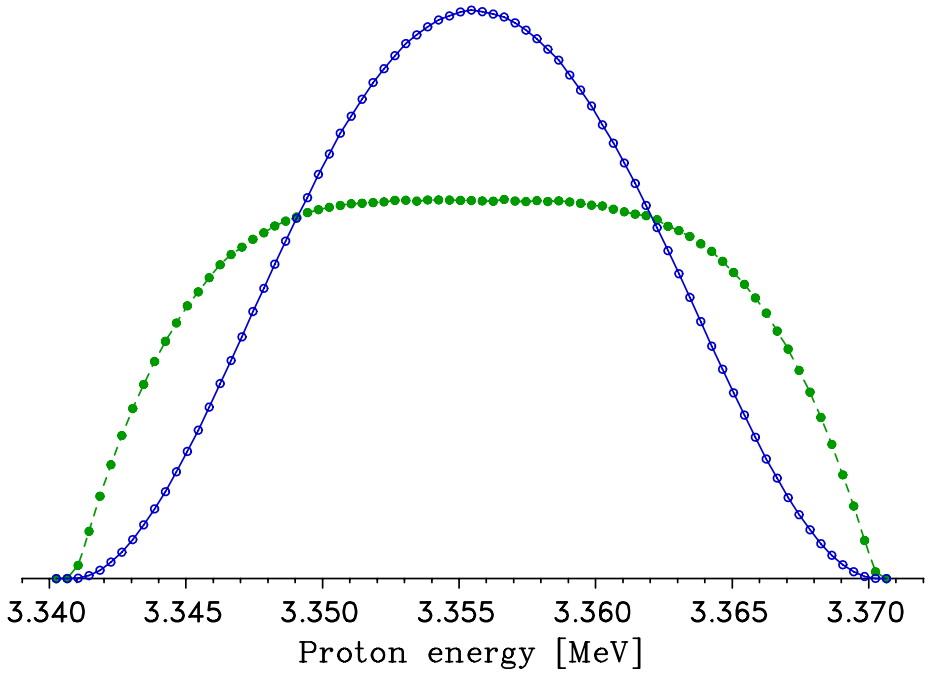


ron-Neutrino Correlation in the $0^+ \rightarrow 0^+$ Decay of ^{32}Ar

rtiz,[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]
tment of Physics, University of Washington, Seattle, Washington 98195-1560
artment 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)

neutrino correlation in the $0^+ \rightarrow 0^+$ [illegible] ^{32}[illegible] [illegible] ISOLDE [illegible]
ect of lepton recoil on the shape of
lt is consistent with the standard m
$\pm$ 0.0052 $\pm$ 0.0039, which yields

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



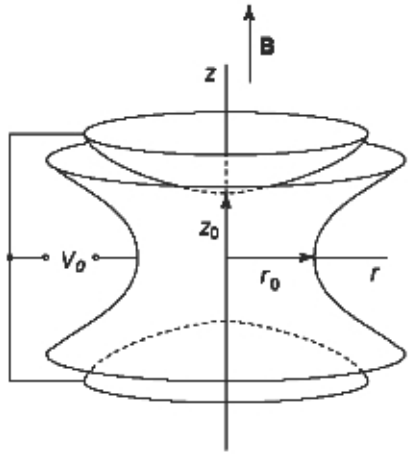
But why throw away useful information??

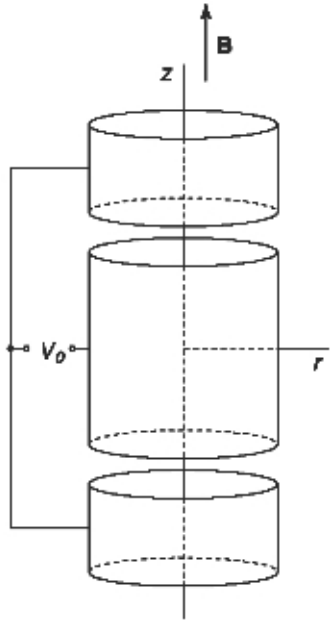
We can improve the correlation measurement by retaining information about the β

But why throw away useful information??

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

utilize technology of Penning traps to provide a **backing-free** source of localized radioactive ions!!

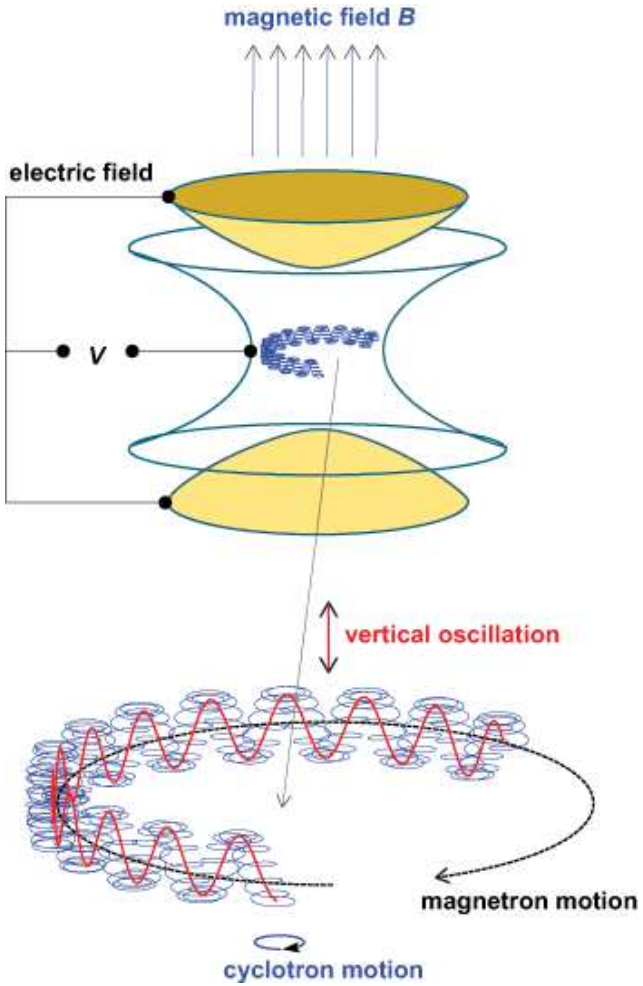


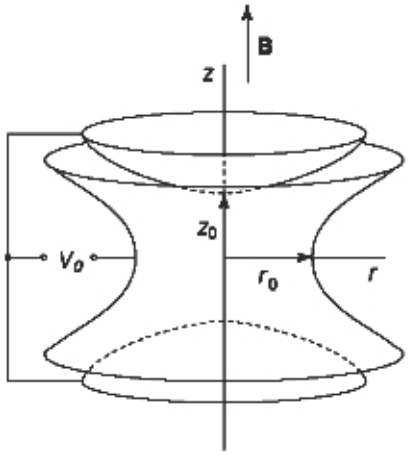


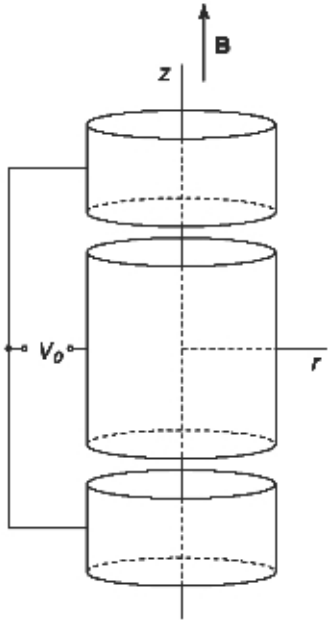
But why throw away useful information??

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

utilize technology of Penning traps to provide a **backing-free** source of localized radioactive ions!!



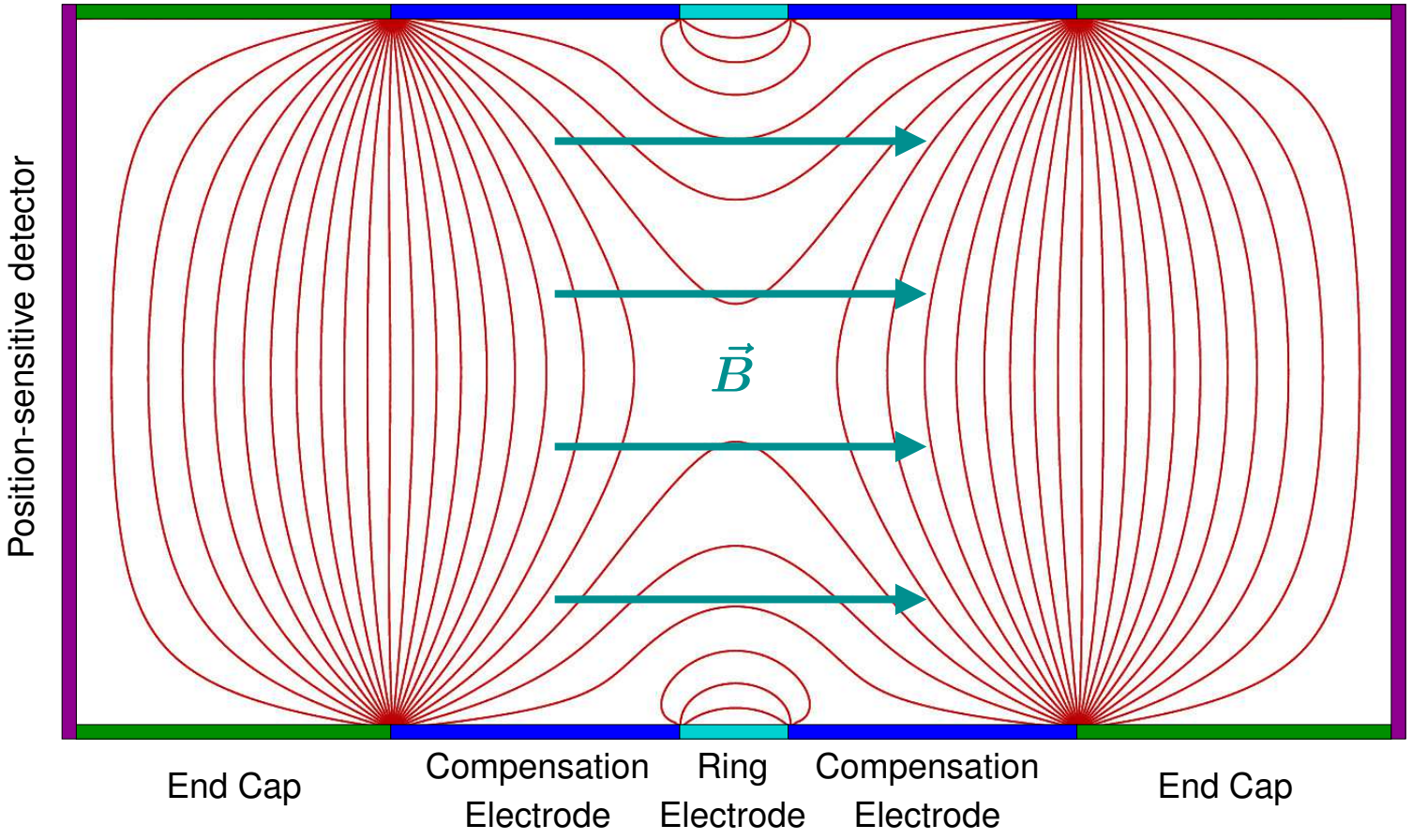


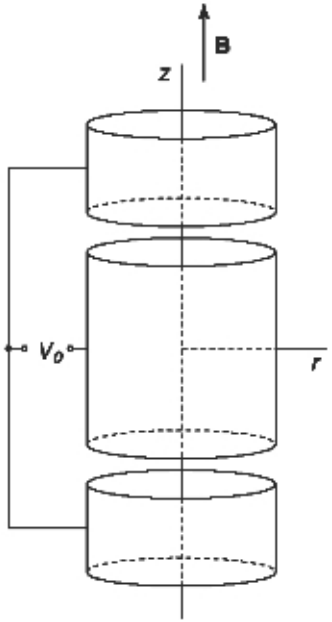


But why throw away useful information??

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

utilize technology of Penning traps to provide a **backing-free** source of localized radioactive ions!!

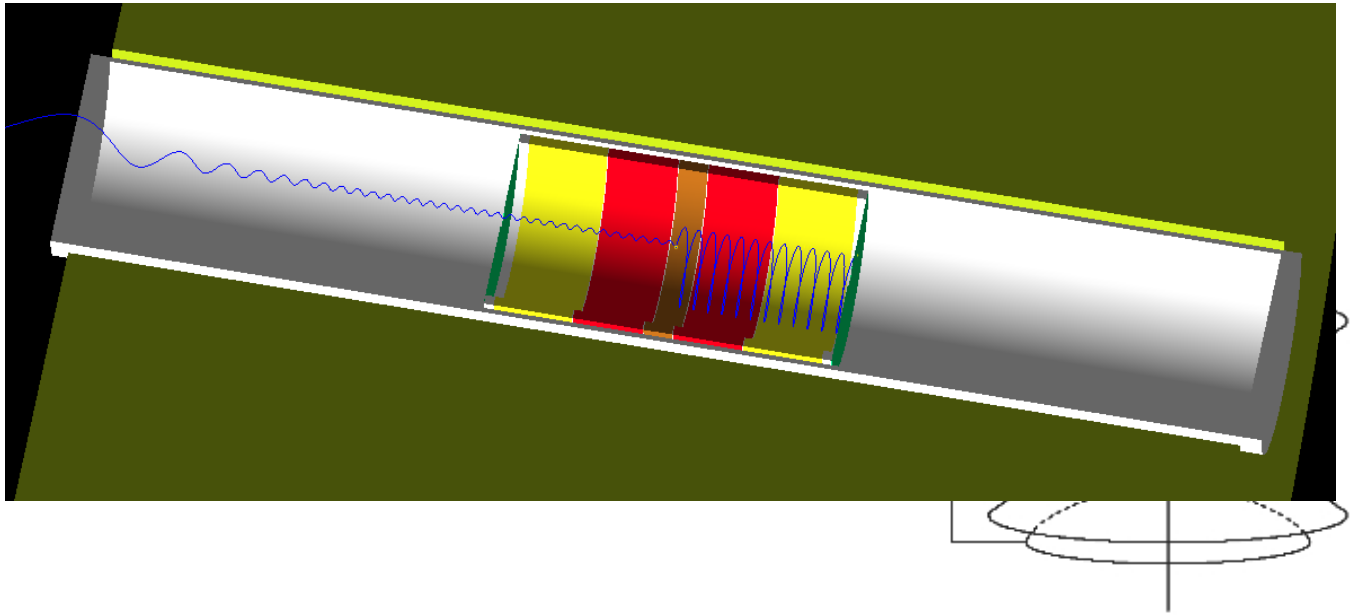


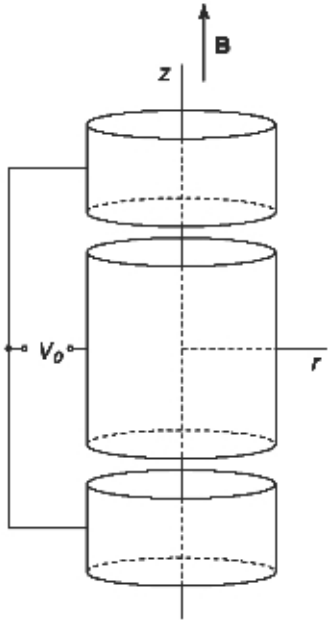


But why throw away useful information??

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

utilize technology of Penning traps to provide a **backing-free** source of localized radioactive ions!!

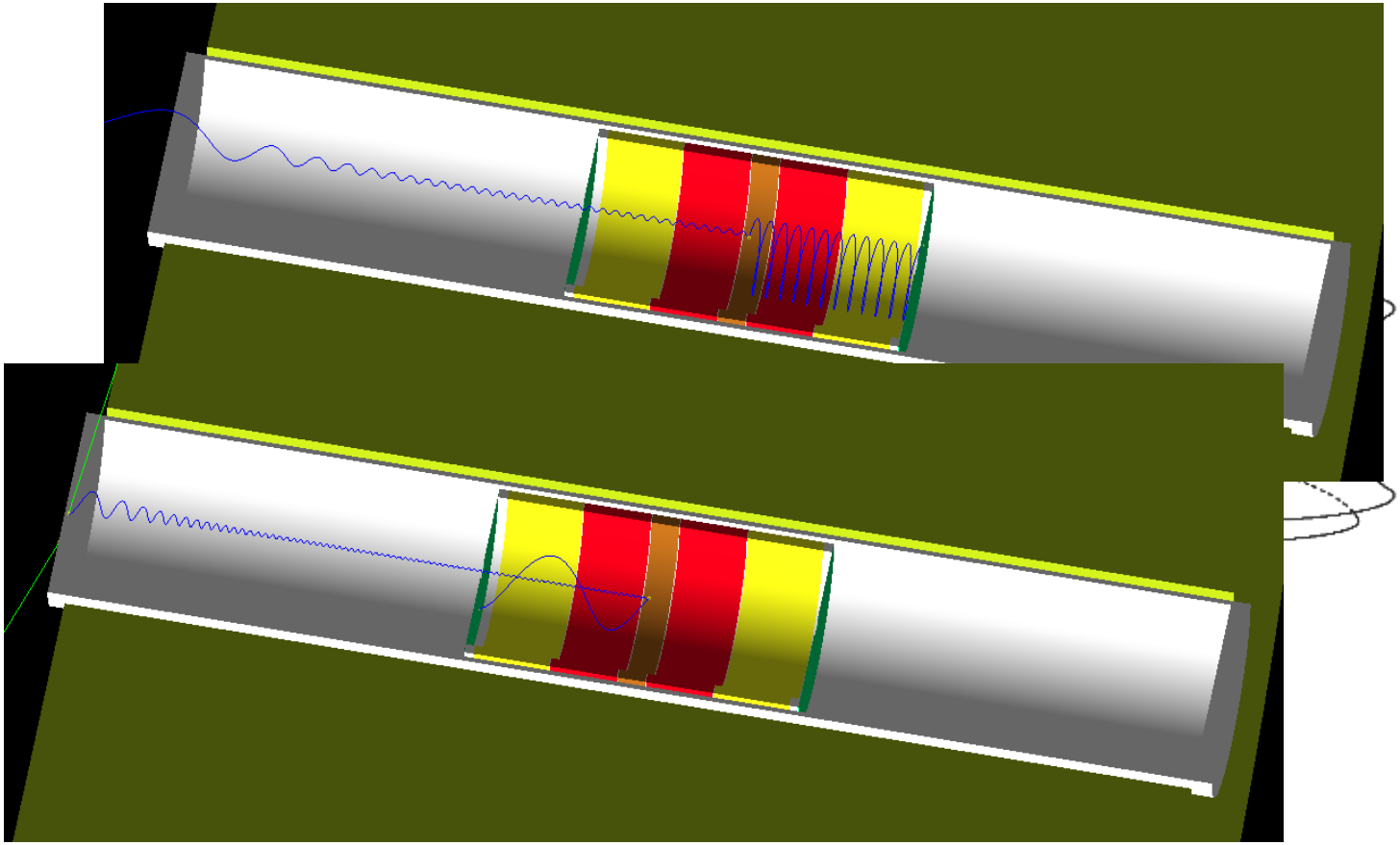


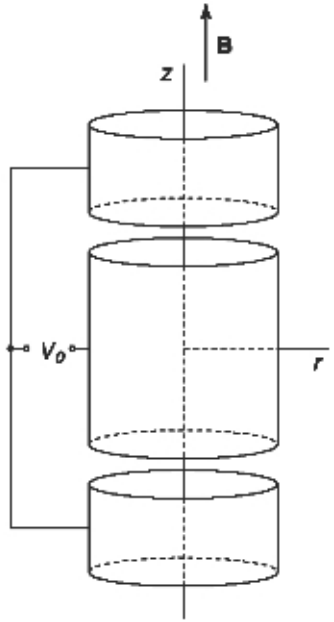


But why throw away useful information??

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

utilize technology of Penning traps to provide a **backing-free** source of localized radioactive ions!!

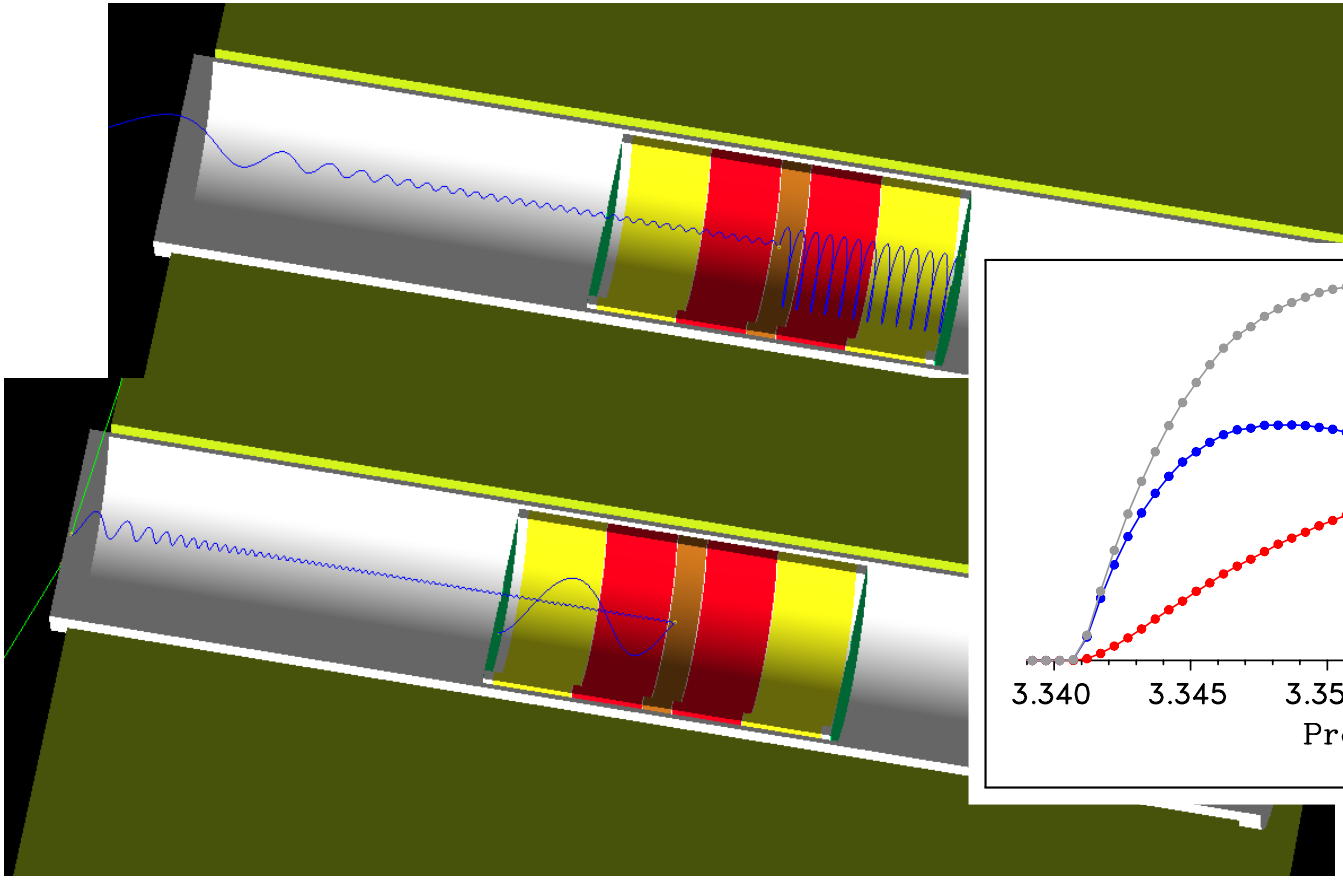


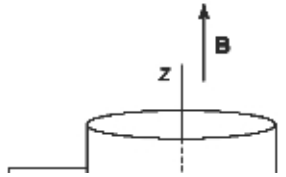


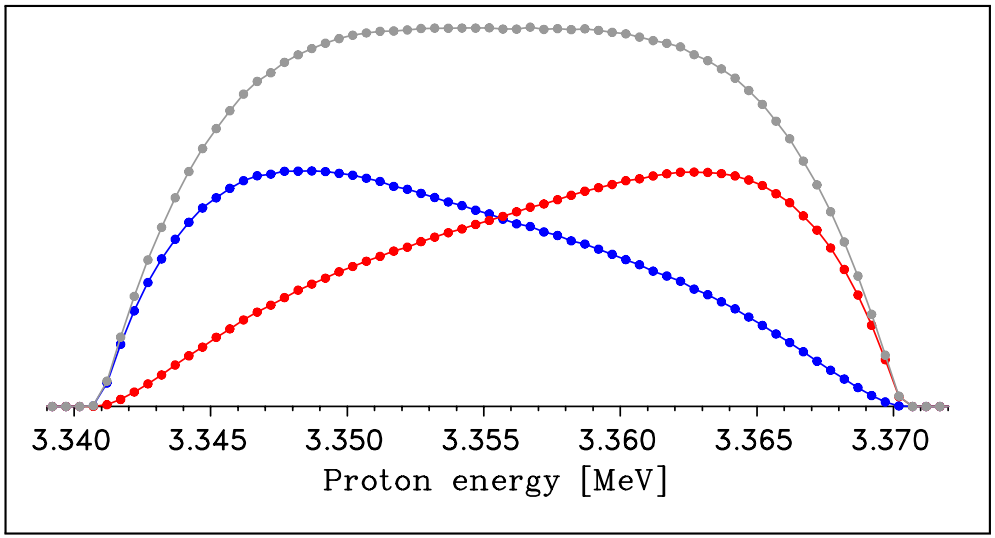
But why throw away useful information??

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

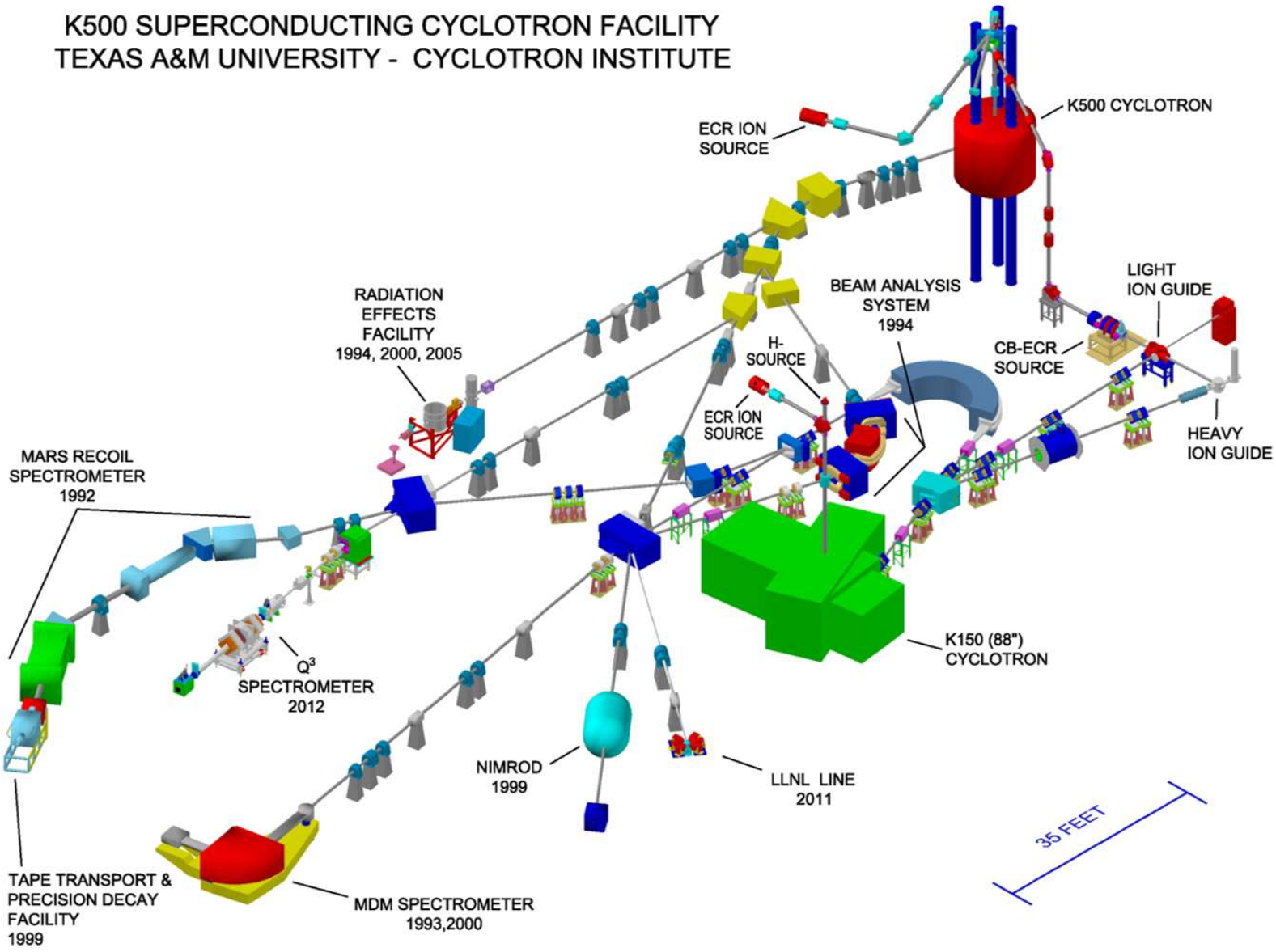
utilize technology of Penning traps to provide a **backing-free** source of localized radioactive ions!!





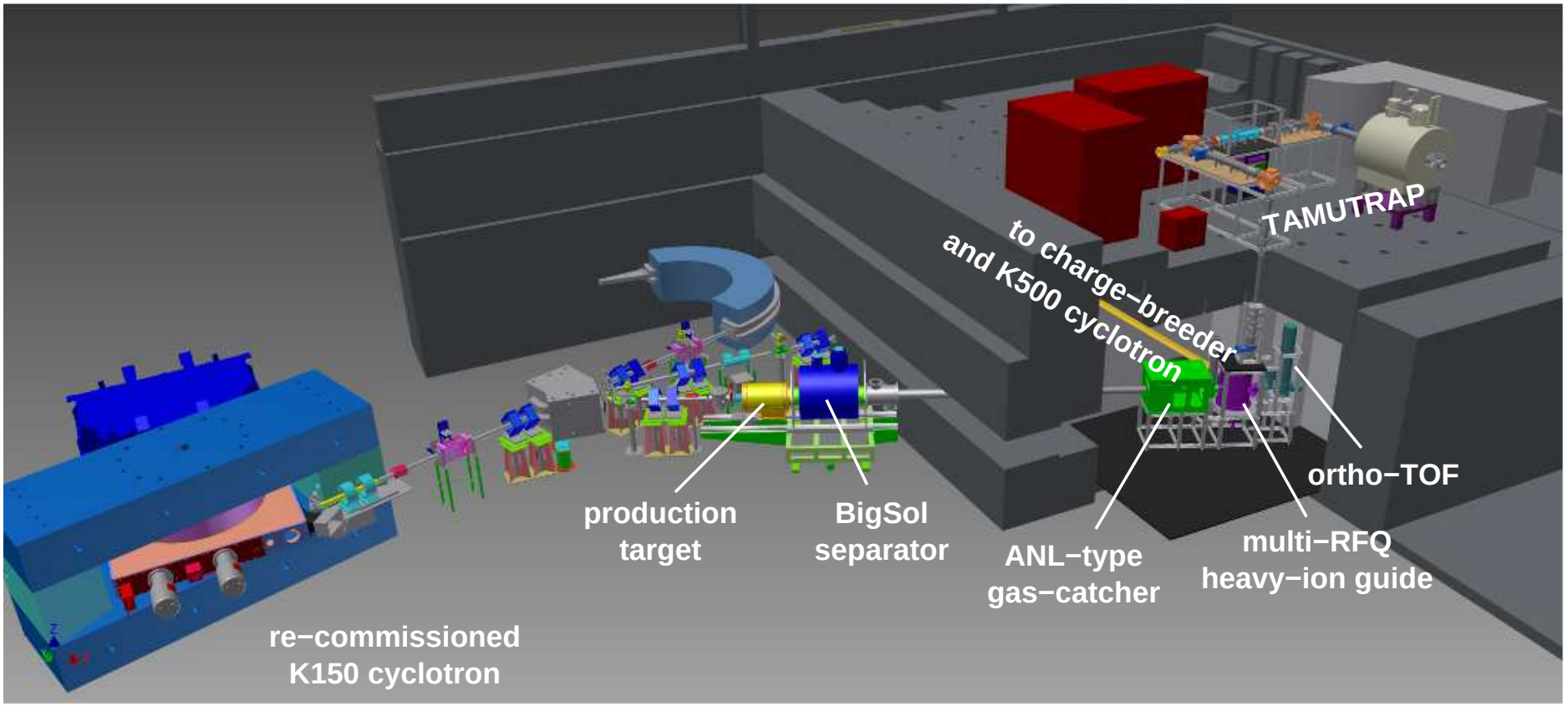


A Penning trap at T-REX CI/TAMU



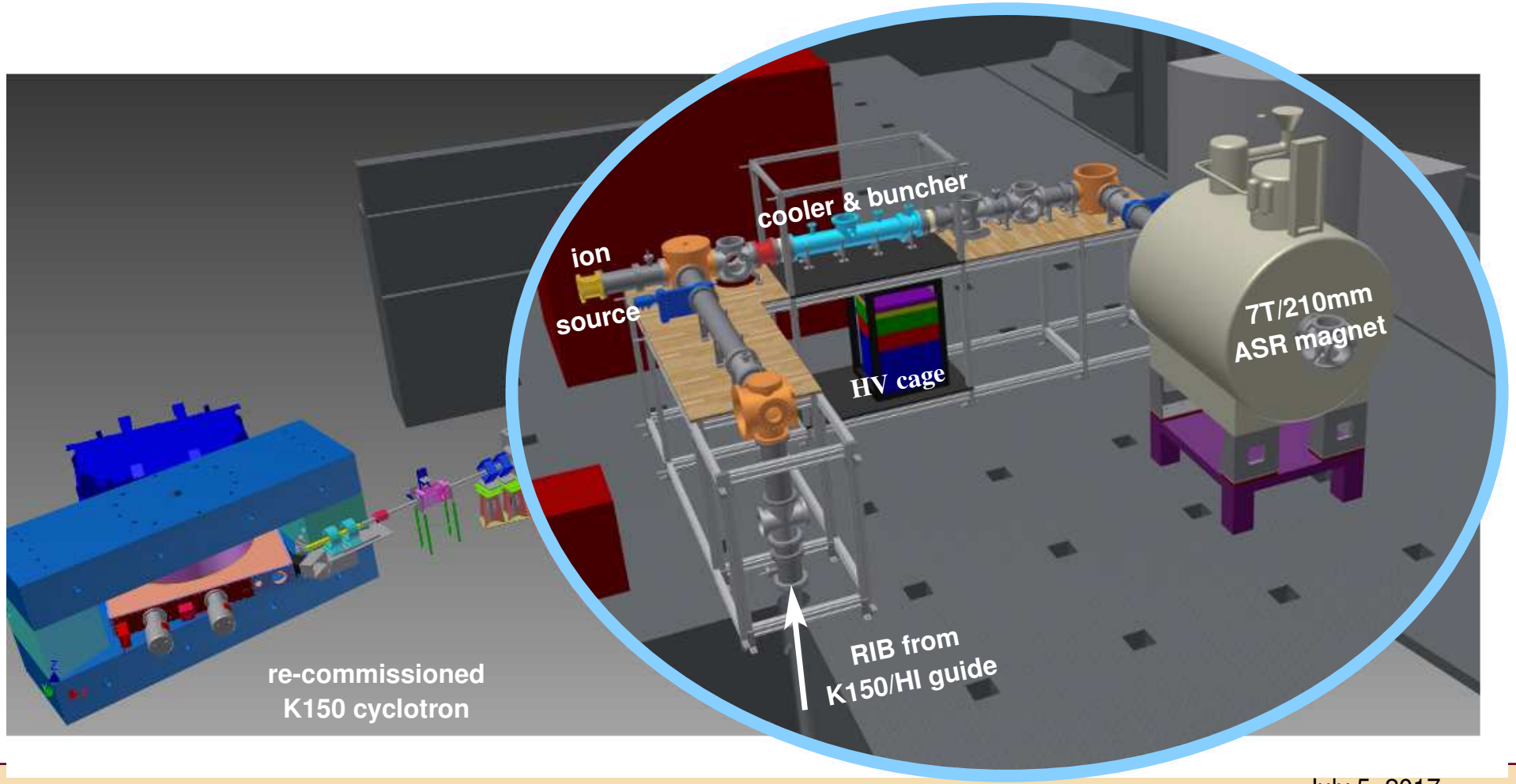
The Texas A&M University Penning Trap

- 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, . . .

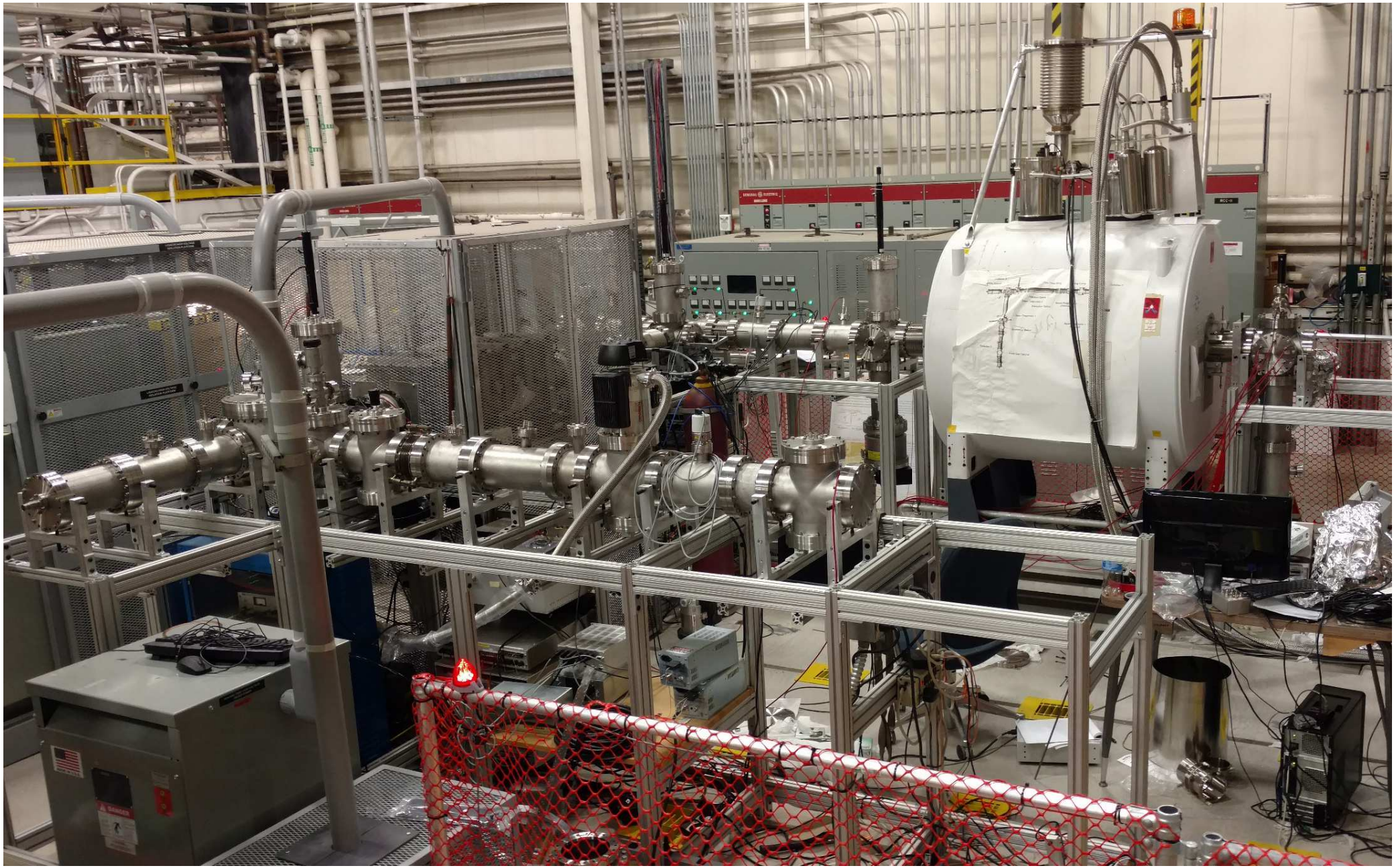


The Texas A&M University Penning Trap

- 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, . . .



Current Status



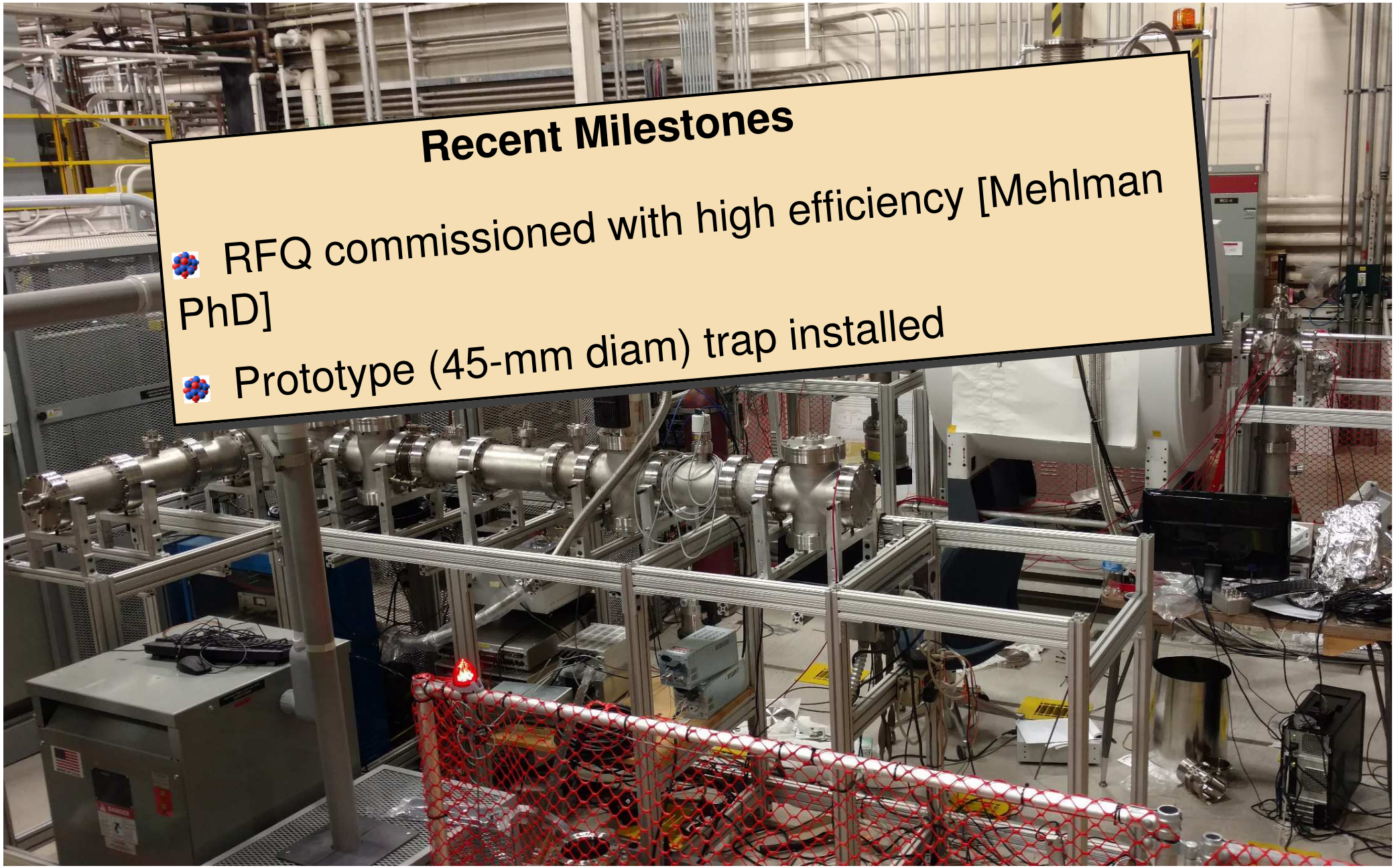
Current Status

Recent Milestones

- RFQ commissioned with high efficiency [Mehlman PhD]

Current Status

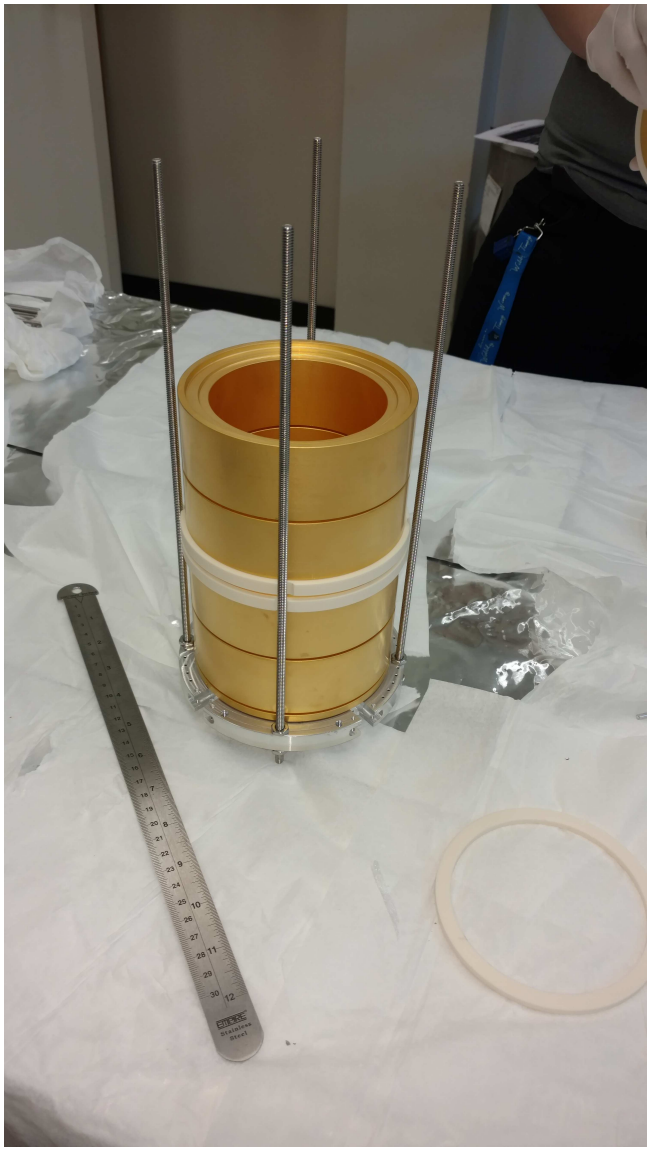
Current Status



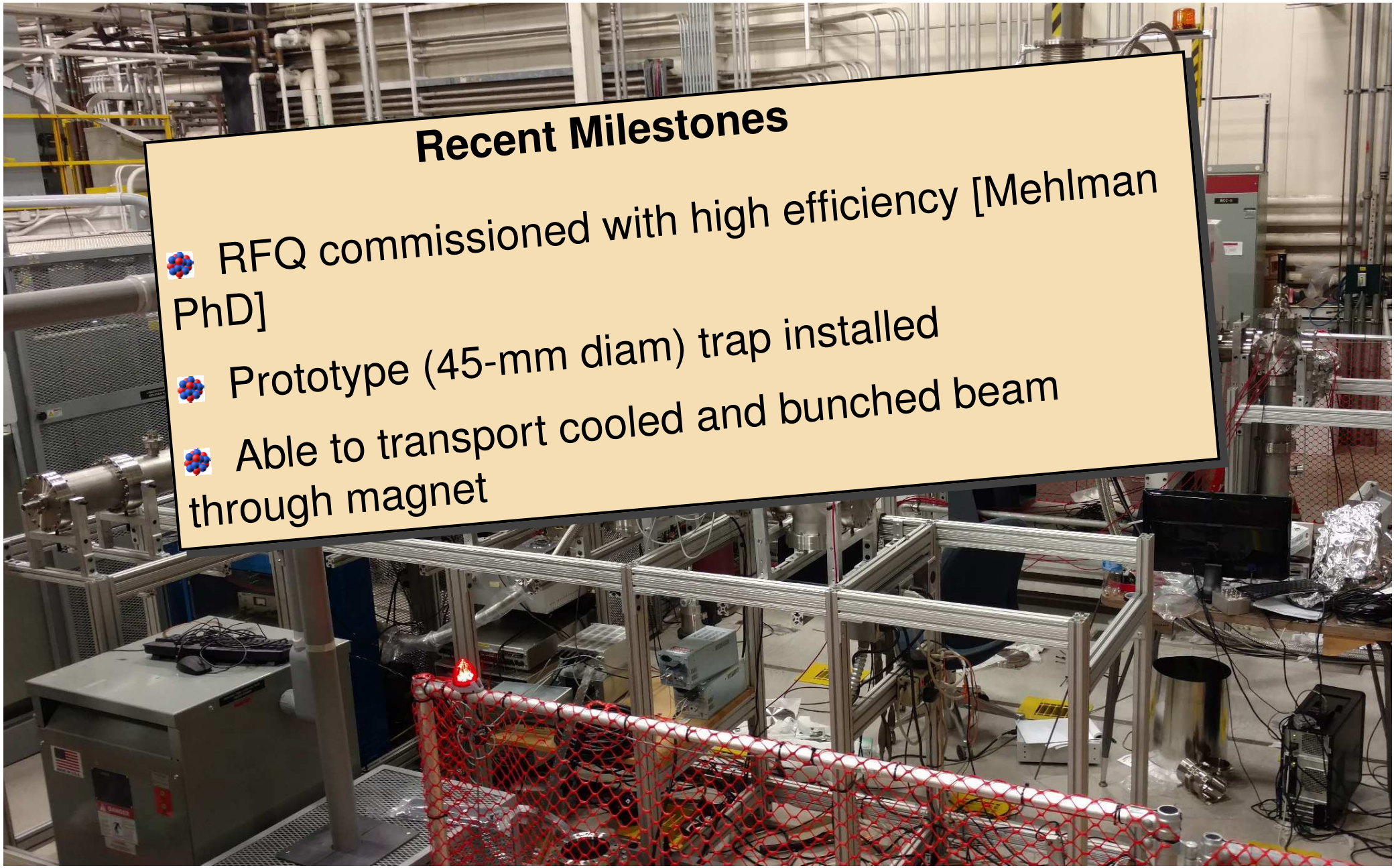
Recent Milestones

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

Current Status



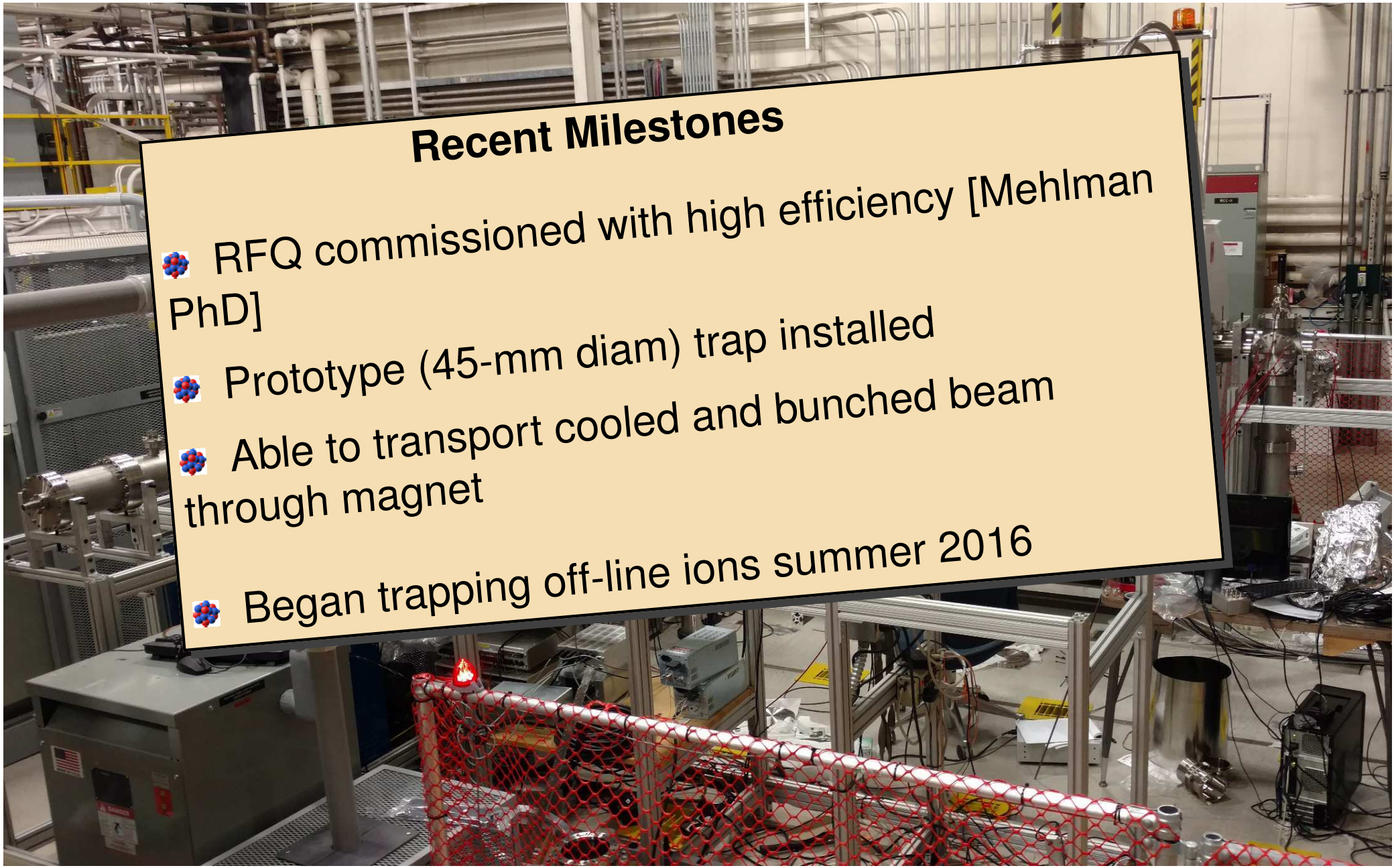
Current Status



Recent Milestones

- RFQ commissioned with high efficiency [Mehlman PhD]
- Prototype (45-mm diam) trap installed
- Able to transport cooled and bunched beam through magnet

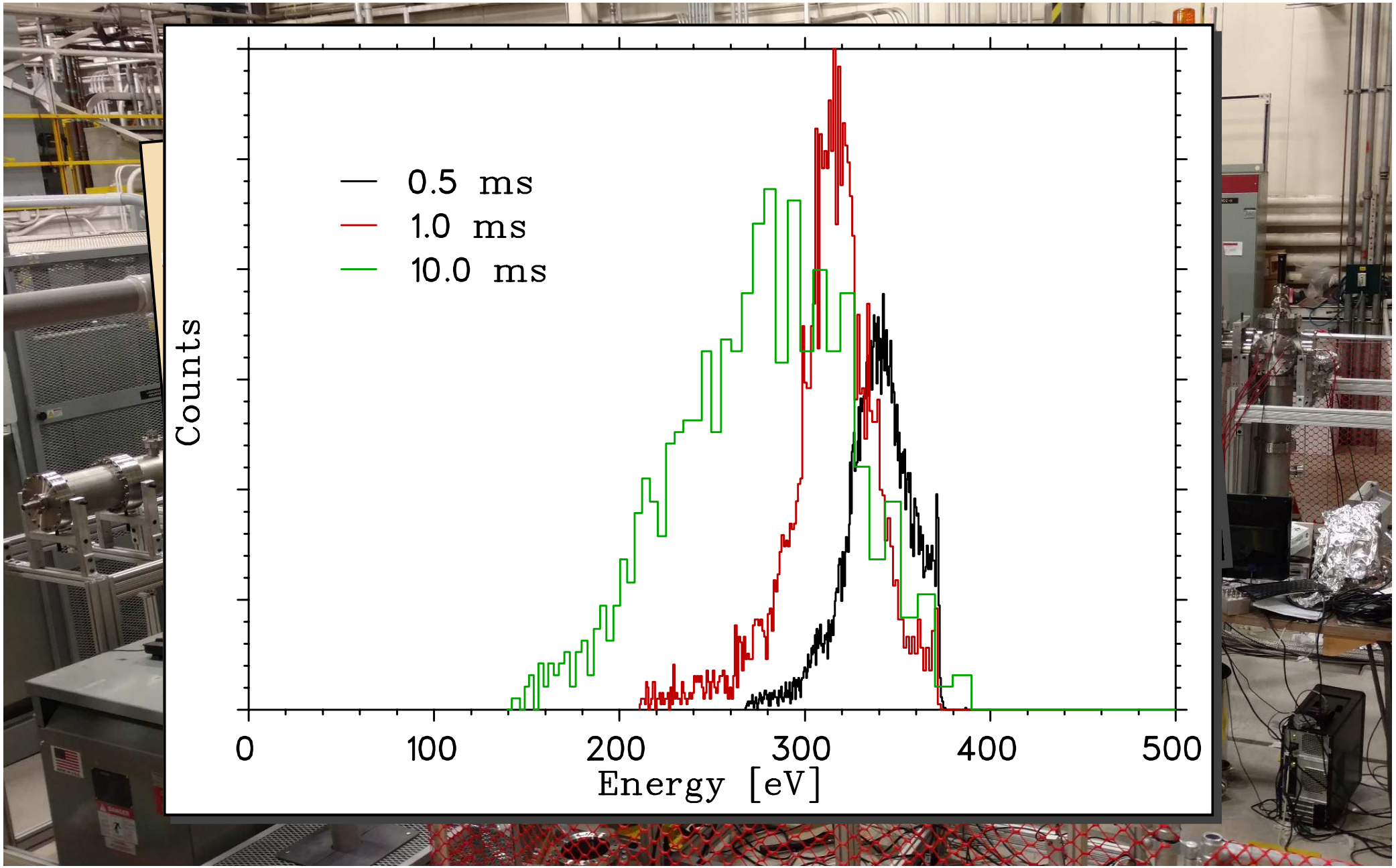
Current Status



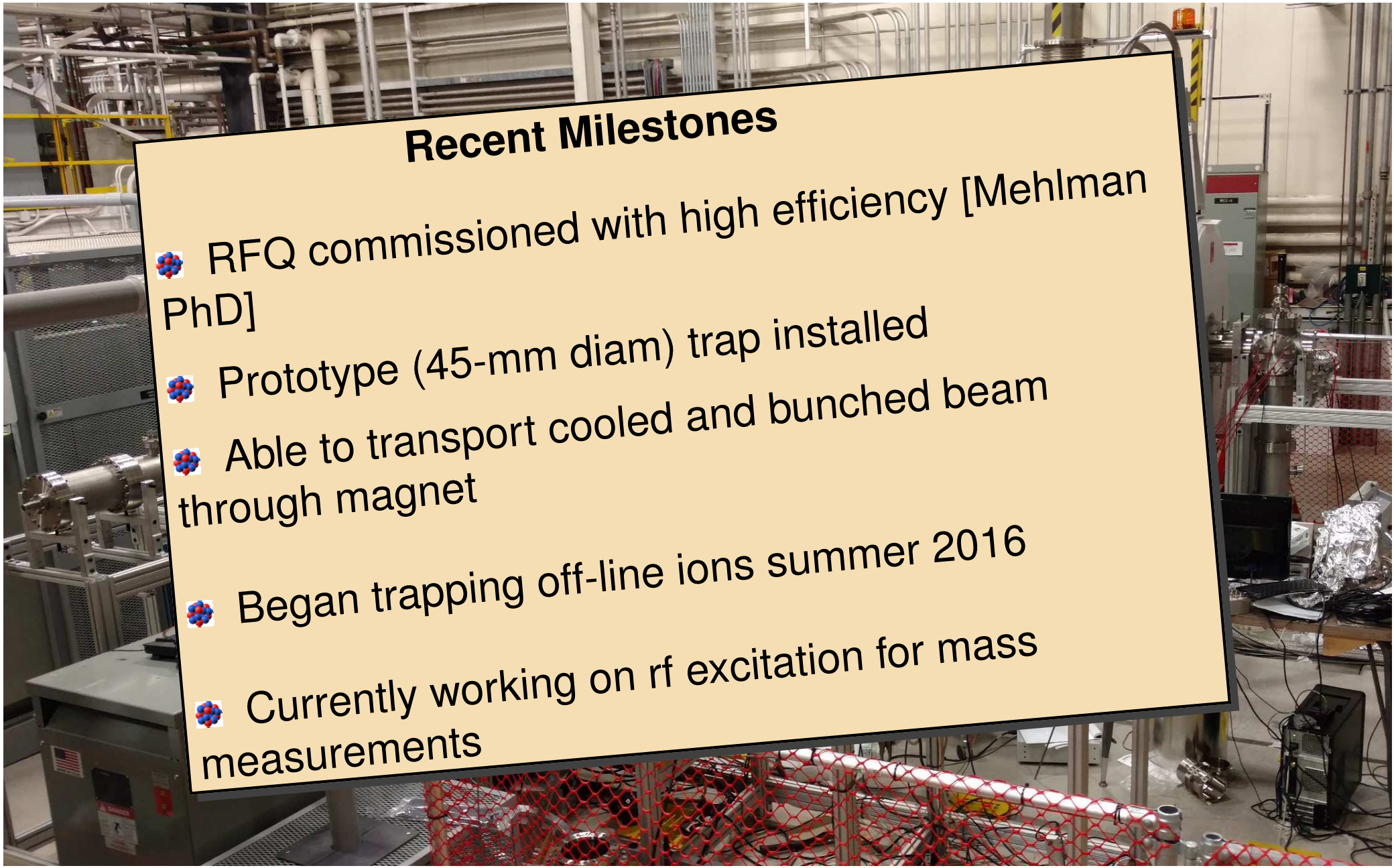
Recent Milestones

- RFQ commissioned with high efficiency [Mehlman PhD]
- Prototype (45-mm diam) trap installed
- Able to transport cooled and bunched beam through magnet
- Began trapping off-line ions summer 2016

Current Status



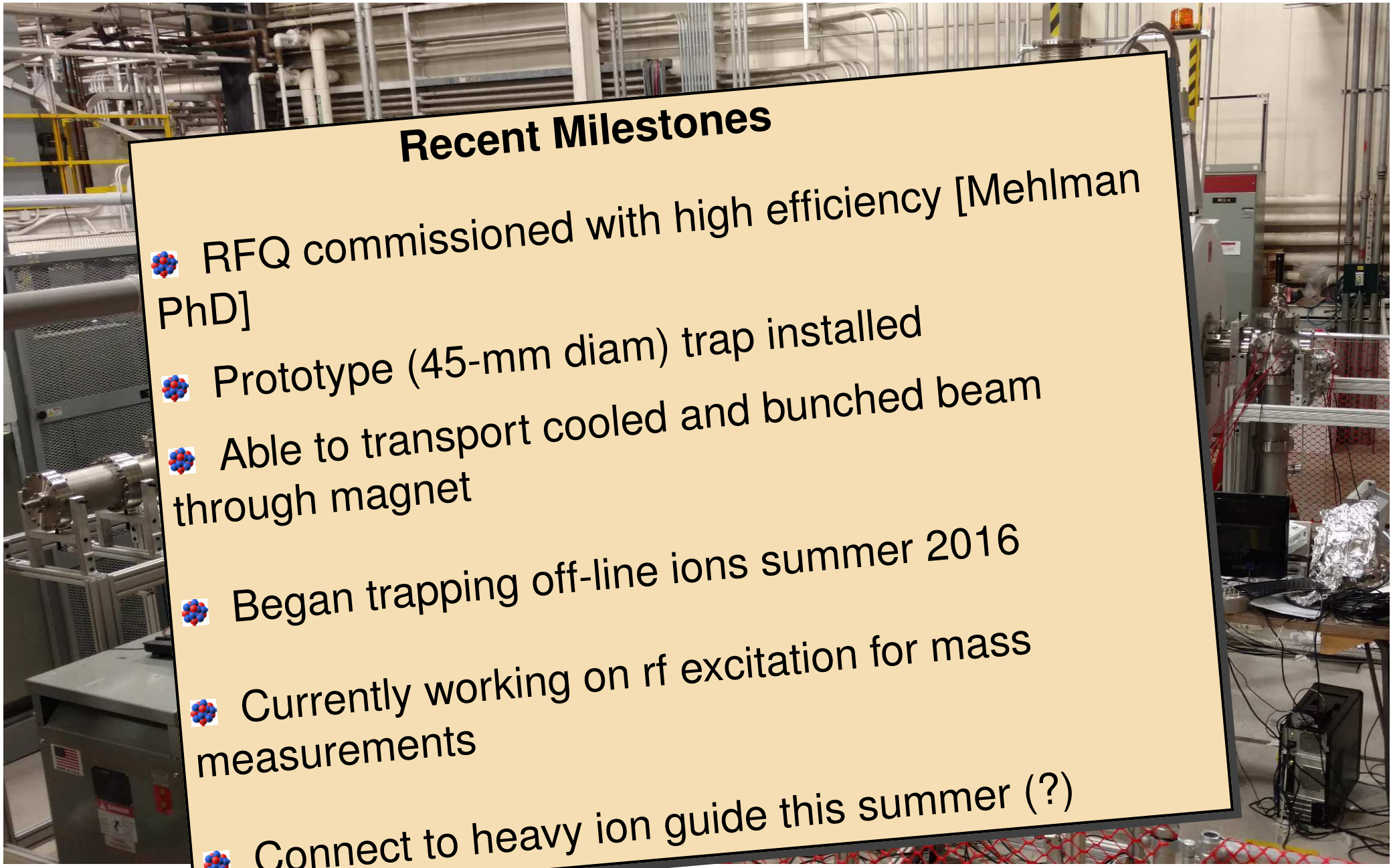
Current Status



Recent Milestones

- RFQ commissioned with high efficiency [Mehlman PhD]
- Prototype (45-mm diam) trap installed
- Able to transport cooled and bunched beam through magnet
- Began trapping off-line ions summer 2016
- Currently working on rf excitation for mass measurements

Current Status



Recent Milestones

- RFQ commissioned with high efficiency [Mehlman PhD]
- Prototype (45-mm diam) trap installed
- Able to transport cooled and bunched beam through magnet
- Began trapping off-line ions summer 2016
- Currently working on rf excitation for mass measurements
- 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

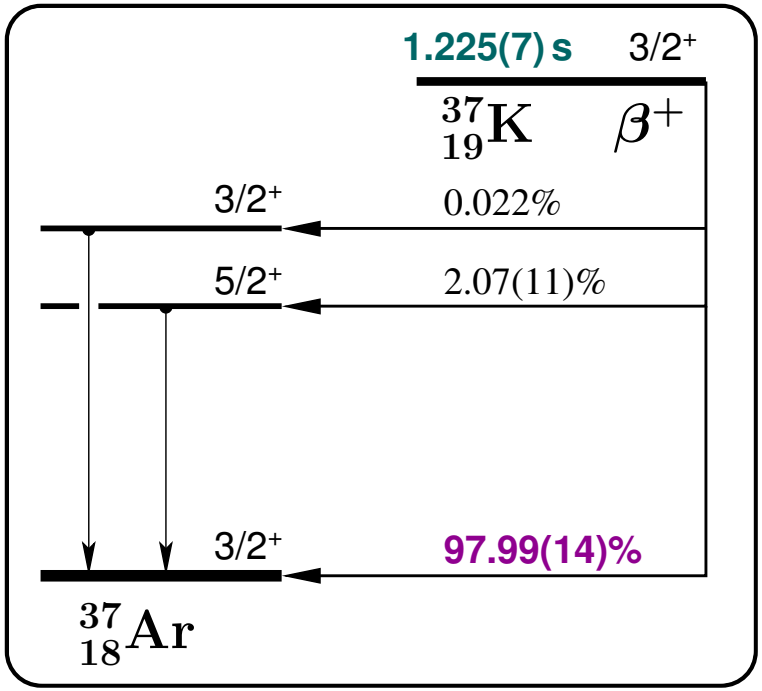
- **physics** of superallowed β decay
- **ion trapping** of proton-rich nuclei at T-REX

3. TRIUMF Neutral Atom Trap

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

The β^+-decay of ^{37}K

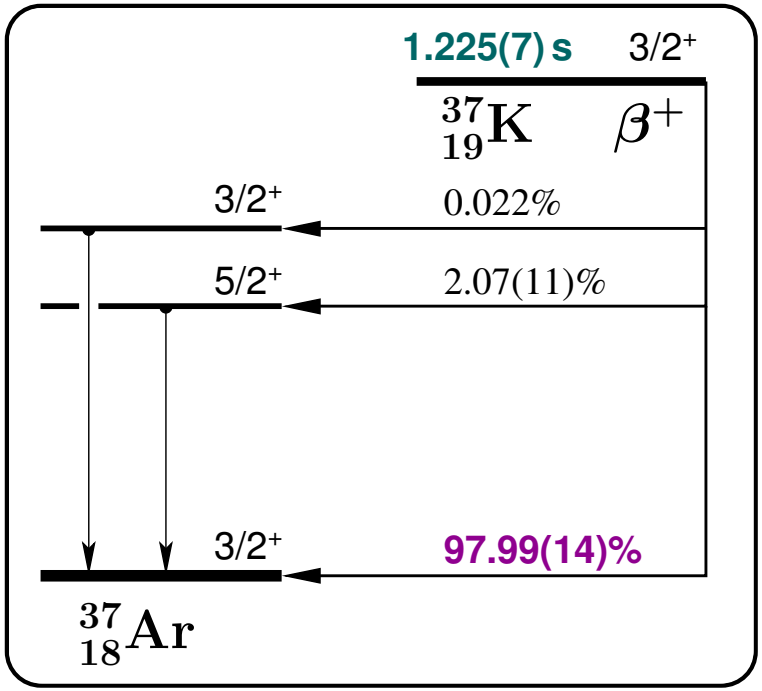
Almost as simple as $0^+ \rightarrow 0^+$:



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

The β^+-decay of ^{37}K

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

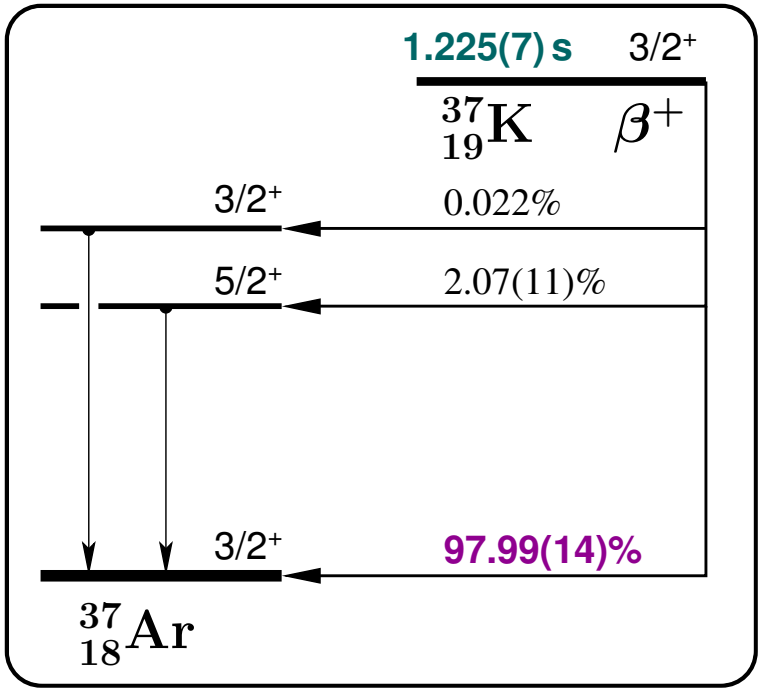


- **isobaric analogue** decay
- **strong** branch to g.s.
- **polarization/alignment**
- **mixed** Fermi/Gamow-Teller

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

The β^+-decay of ^{37}K

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



- **isobaric analogue** decay
- **strong** branch to g.s.
- **polarization/alignment**
- **mixed** Fermi/Gamow-Teller

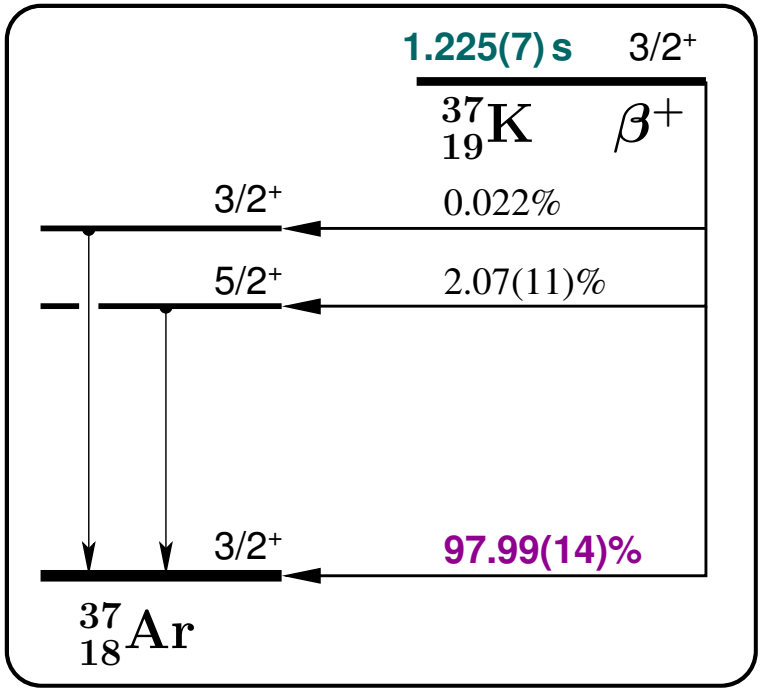
$\Rightarrow$ need $\rho \equiv G_A M_{GT} / G_V M_F$ to get SM prediction for correlation parameters

get ρ from the comparative half-life:

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

The β^+-decay of ^{37}K

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



- **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:

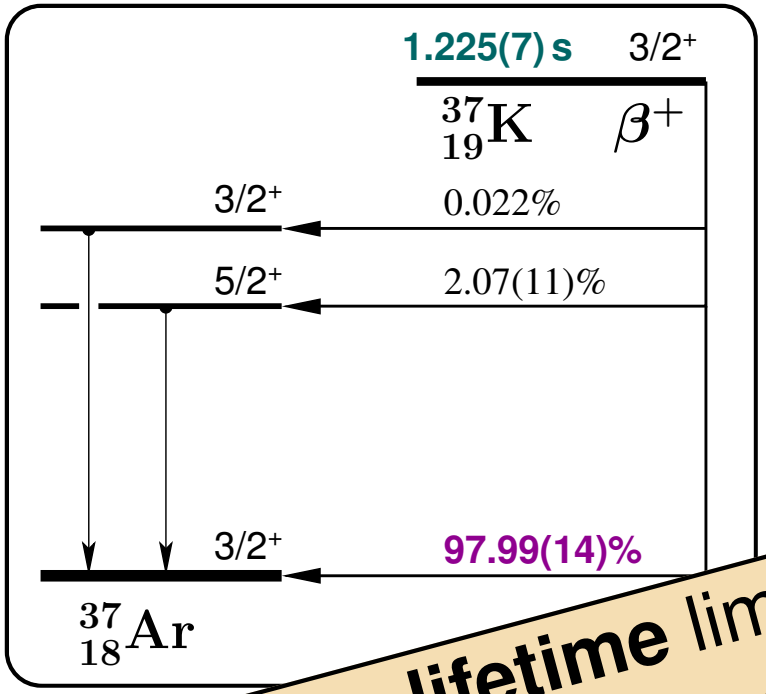
$$\rho^2 = \frac{2\mathcal{F}t^{0^+\rightarrow 0^+}}{\mathcal{F}t} - 1$$

Q_{EC}: $\pm 0.003\%$
BR: $\pm 0.14\%$
$t_{1/2}$: $\pm \mathbf{0.57\%}$

$\mathcal{F}t = 4562(28)$ $\Rightarrow$ $\rho = 0.5874(\mathbf{71})$

The β^+-decay of ^{37}K

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



- **isobaric analogue** decay
- **strong** branch to g.s.
- **polarization/alignment**
- **mixed** Fermi/Gamow-Teller

$\Rightarrow$ nee... $M_{GT}/G_V M_F$ for correla-

The **lifetime** limits the $\mathcal{F}t$ value
- and hence precision of ρ
- and hence the SM predictions of the correlation parameters

get ρ

$$\frac{\mathcal{F}t}{} - 1$$

Q_{EC}:

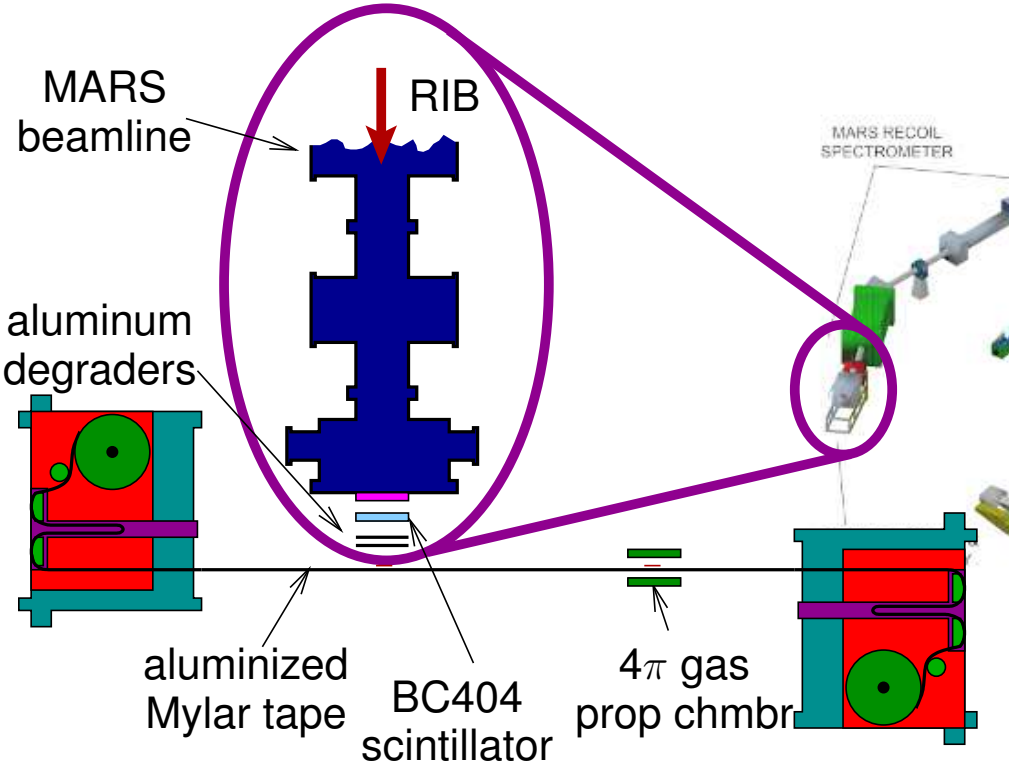
BR: ...%

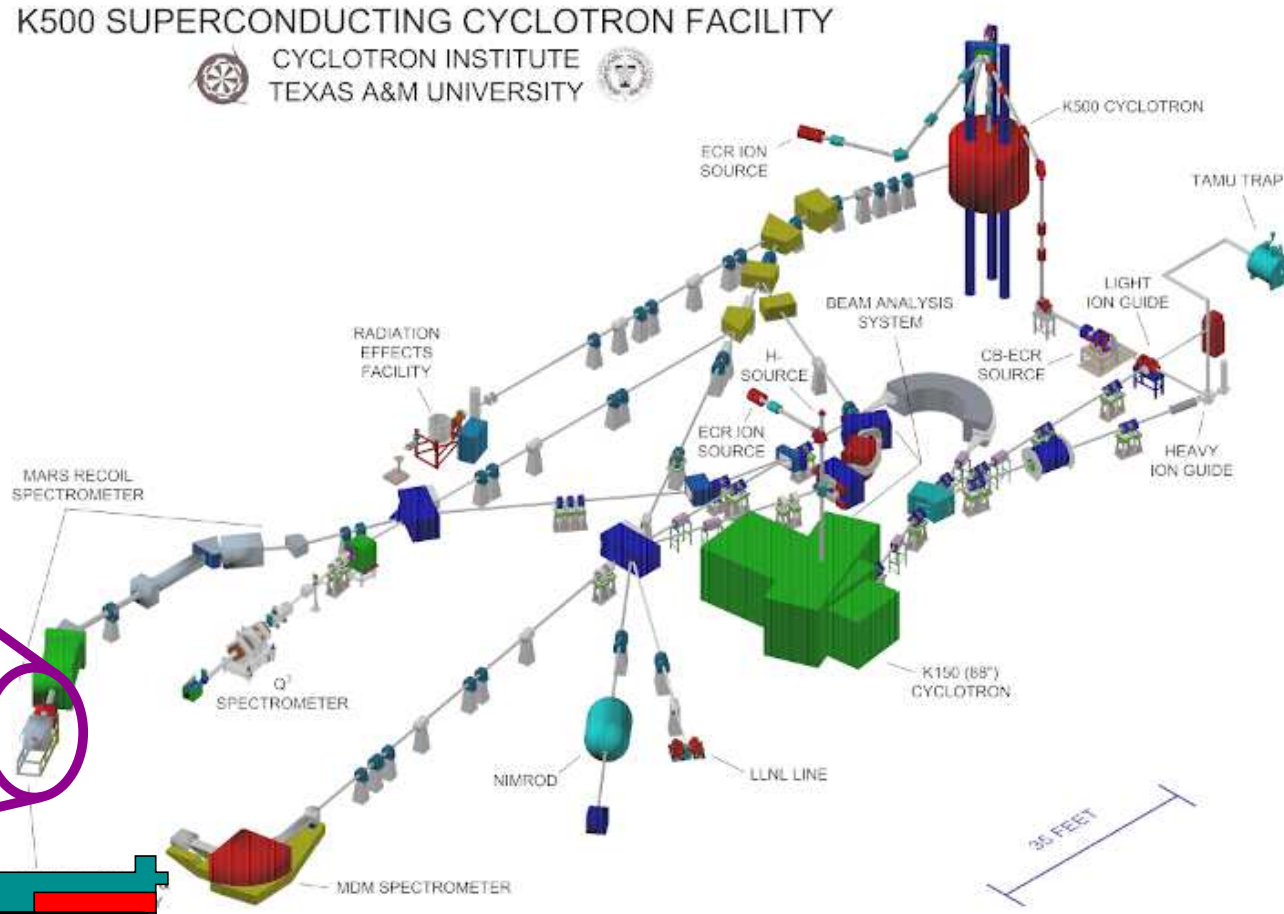
$t_{1/2}$: **±0.57%**

$$\mathcal{F}t = 4562(28) \Rightarrow \boxed{\rho = 0.5874(\mathbf{71})}$$

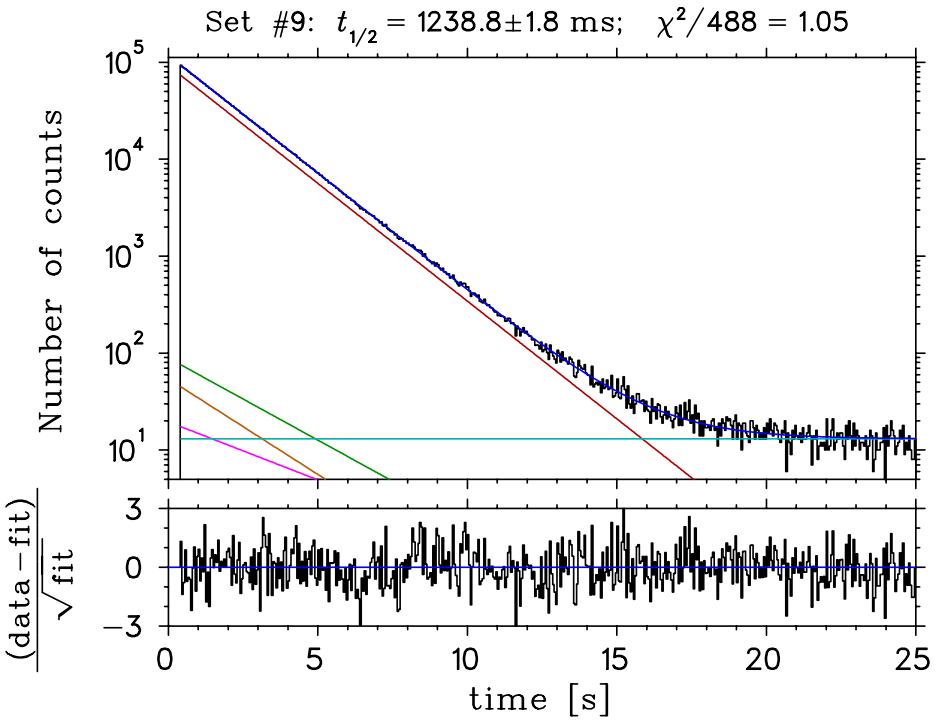
Measuring the lifetime at the CI

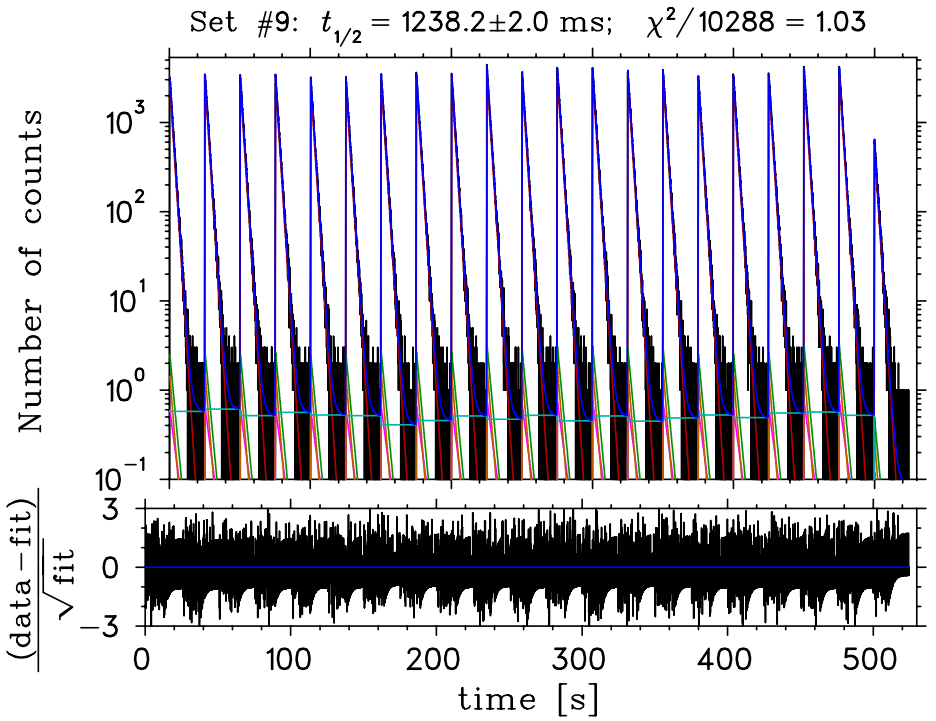
$^{38}\mathrm{Ar}\,(p, 2n)^{37}\mathrm{K}$



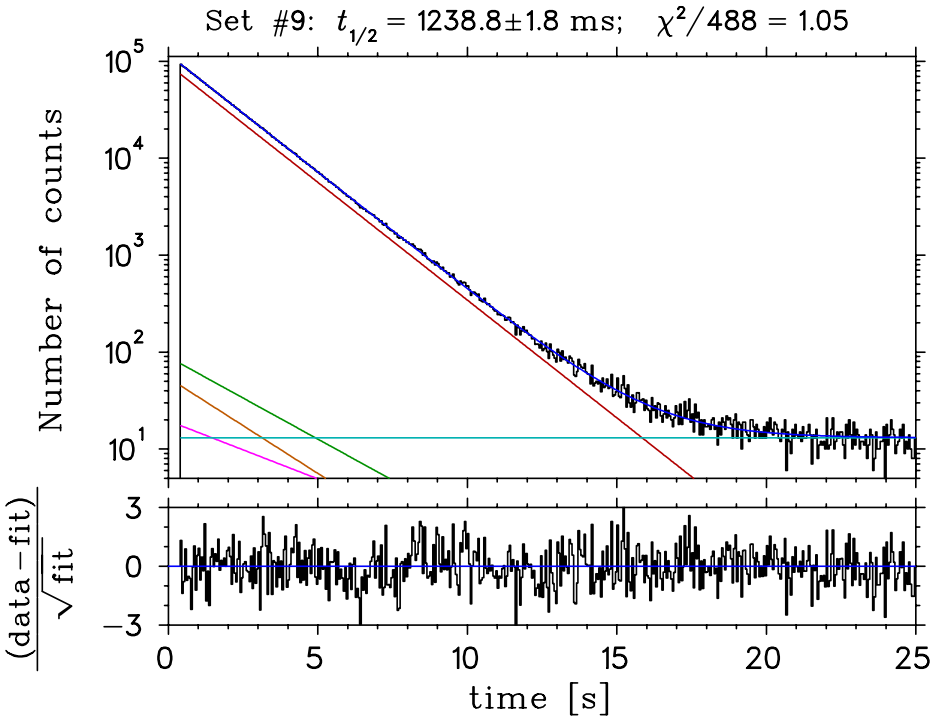


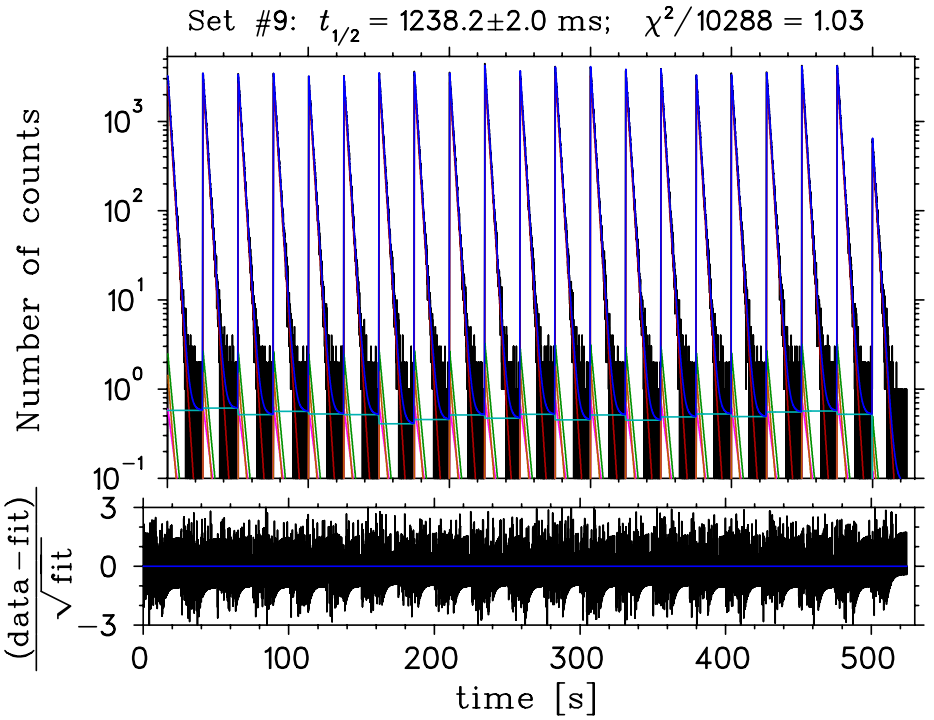
Improving the lifetime





Improving the lifetime





nearly a $10\times$ improvement: $t_{1/2} = 1236.51 \pm 0.47 \pm 0.83$ ms

$$\Rightarrow \quad \Delta\mathcal{F}t = 0.62\% \quad \longrightarrow \quad 0.18\%$$

$$\text{and} \quad \Delta\rho = 1.2\% \quad \longrightarrow \quad 0.4\%$$

P. Shidling *et al.*, PRC **90** (2014) 032501(R)

Thank you, AMO physicists!!

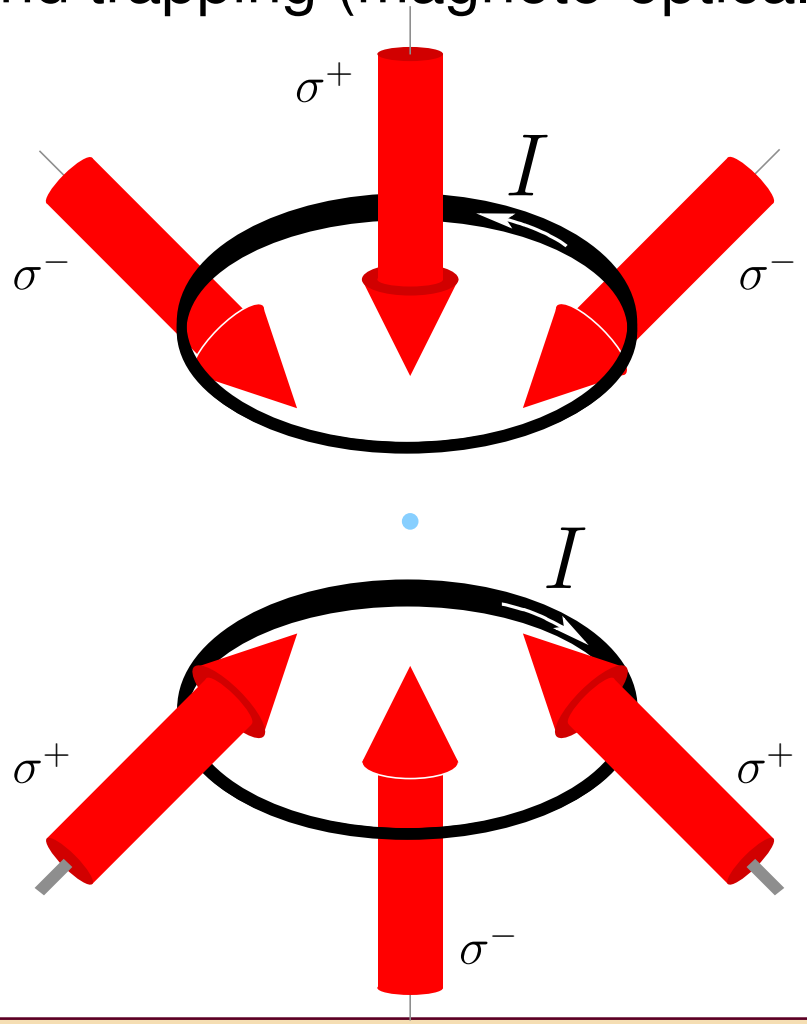
Atomic methods have opened up a new vista in precision work and provide the ability to push β decay measurements to $\lesssim 0.1\%$

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

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 $\lesssim 0.1\%$

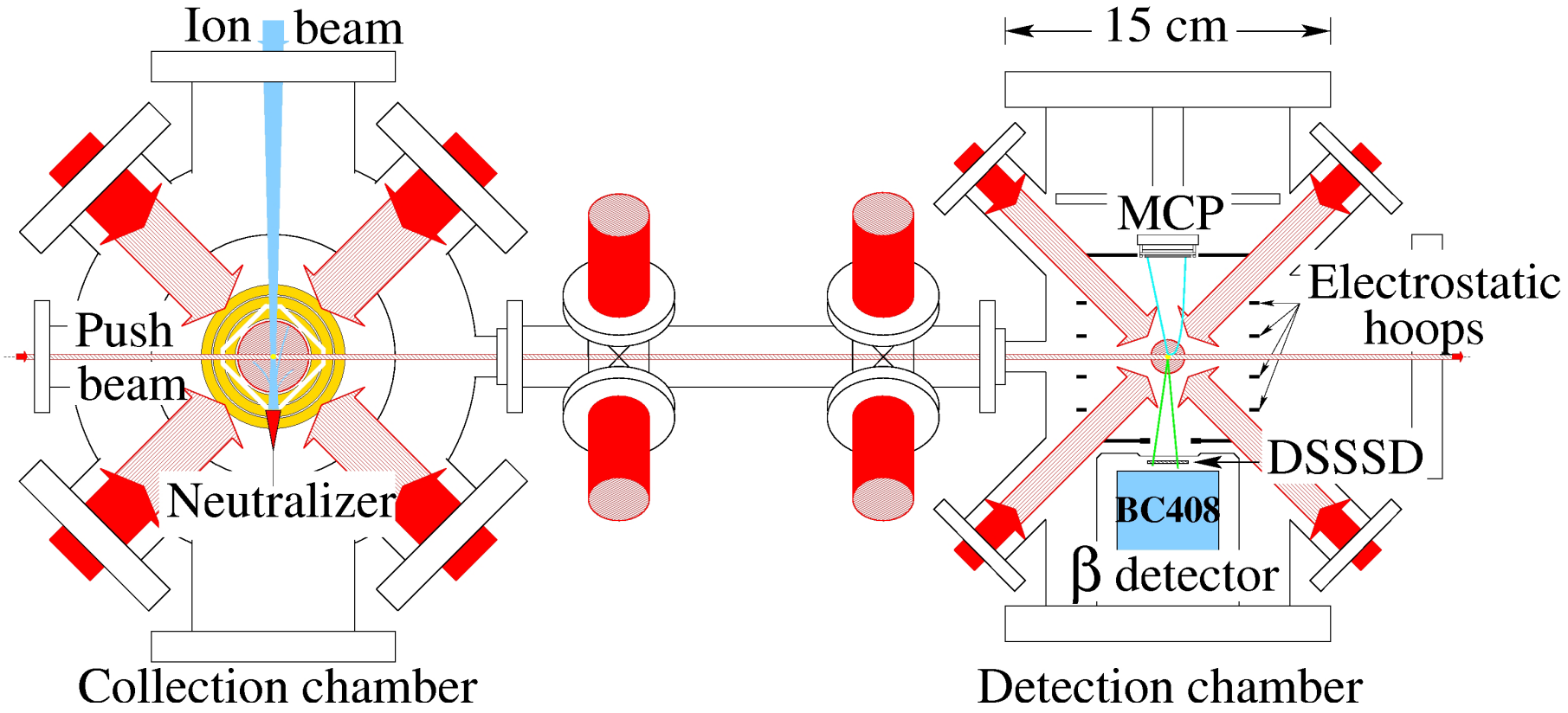
- laser-cooling and trapping (magneto-optical traps)



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 $\lesssim 0.1\%$

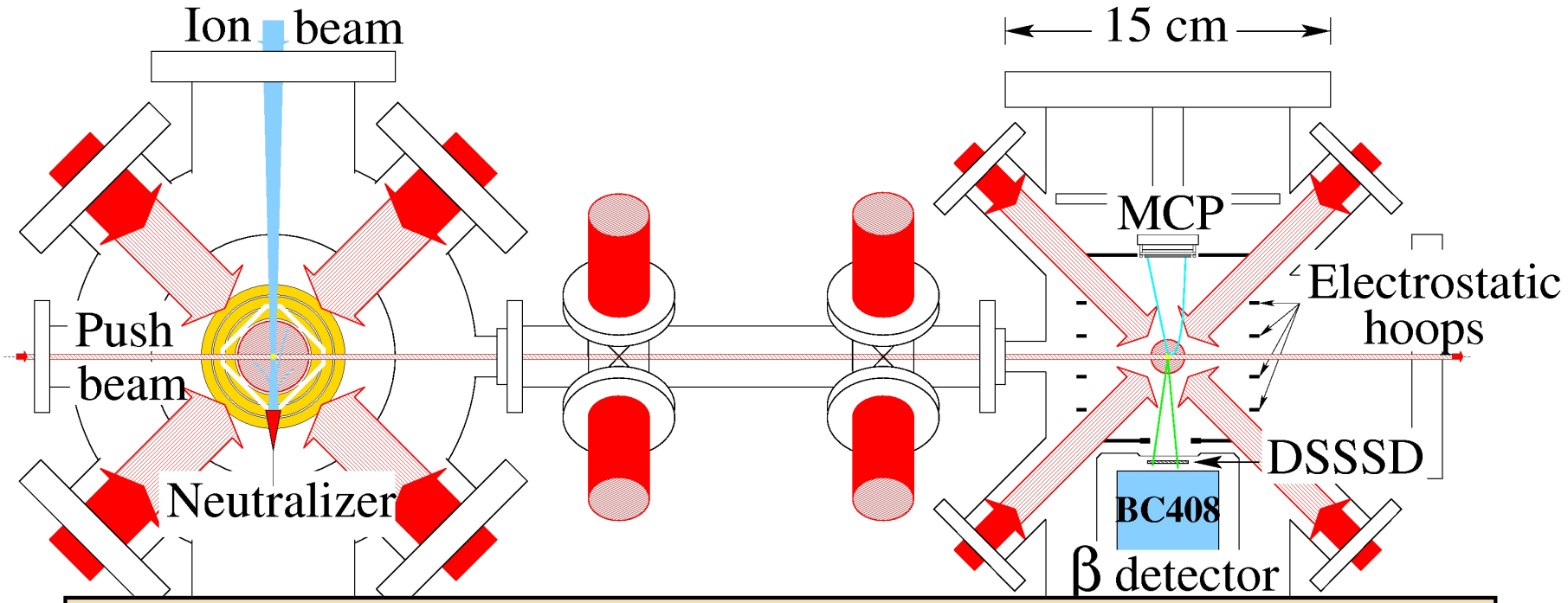
- laser-cooling and trapping (magneto-optical traps)



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)

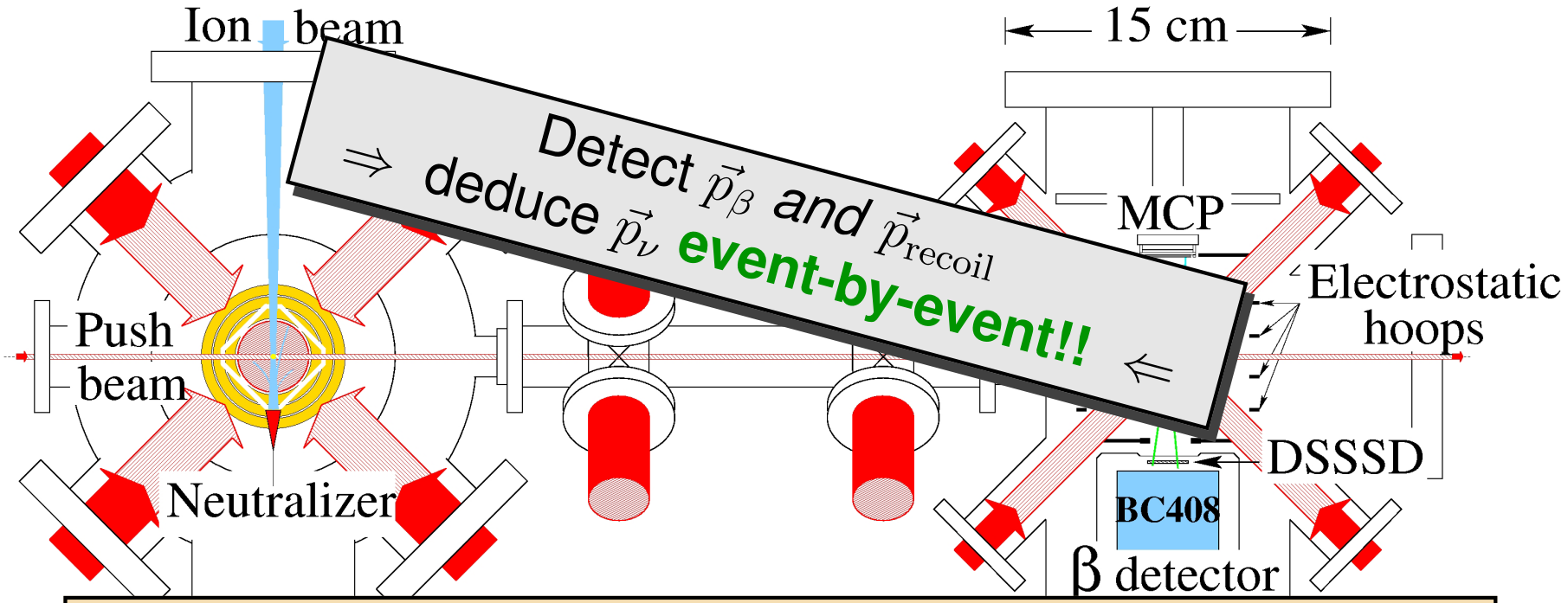


Traps provide a **backing-free**, very **cold** ($\lesssim 1$ mK), **localized** ($\sim 1\ \mathrm{mm}^3$) source of **isomerically-selective**, **short-lived** radioactive atoms

Thank you, AMO physicists!!

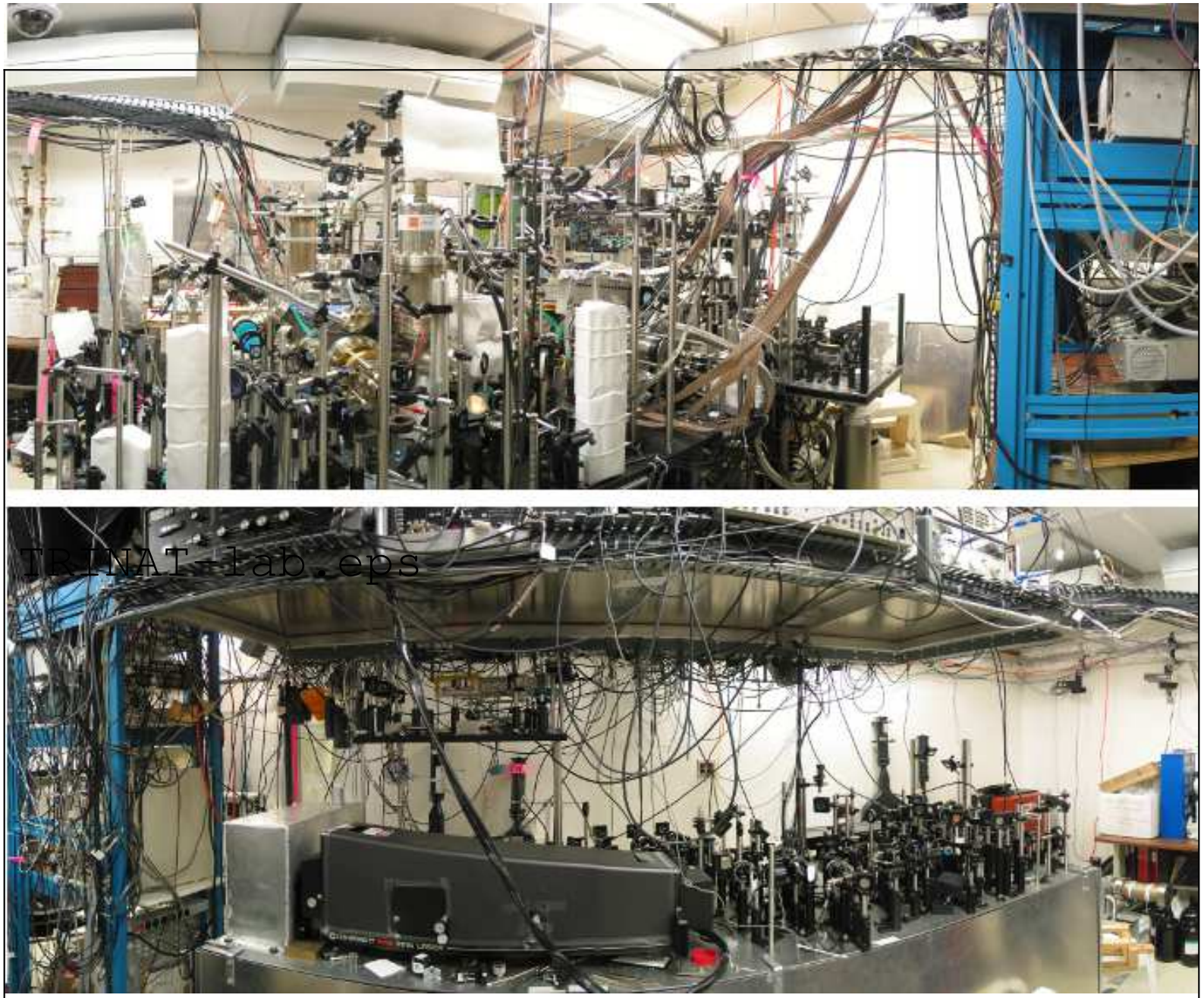
Atomic methods have opened up a new vista in precision work and provide the ability to push β decay measurements to $\lesssim 0.1\%$

- laser-cooling and trapping (magneto-optical traps)



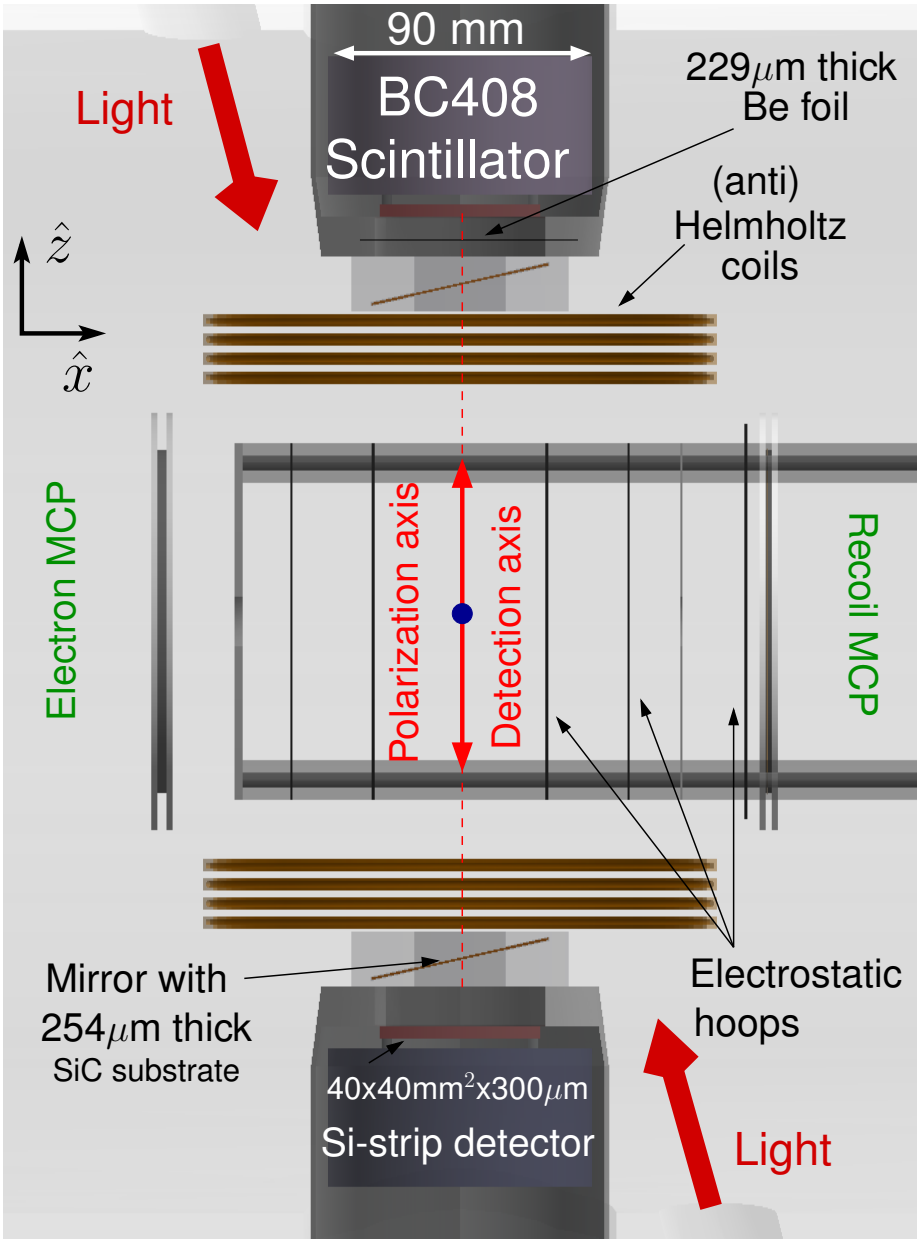
Traps provide a **backing-free**, very **cold** ($\lesssim 1$ mK), **localized** ($\sim 1\ \mathrm{mm}^3$) source of **isomerically-selective**, **short-lived** radioactive atoms

The TRINAT lab

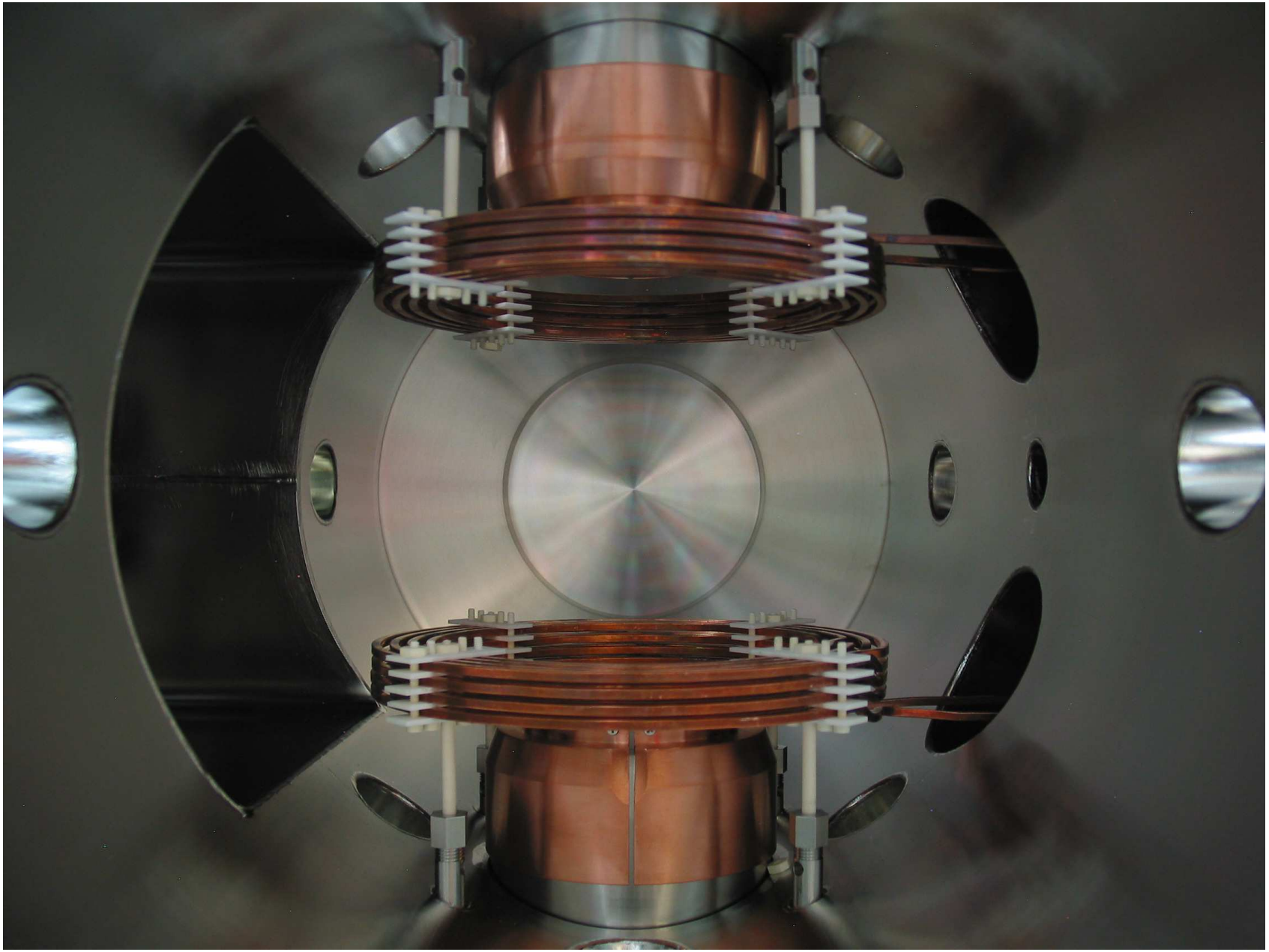


The measurement chamber

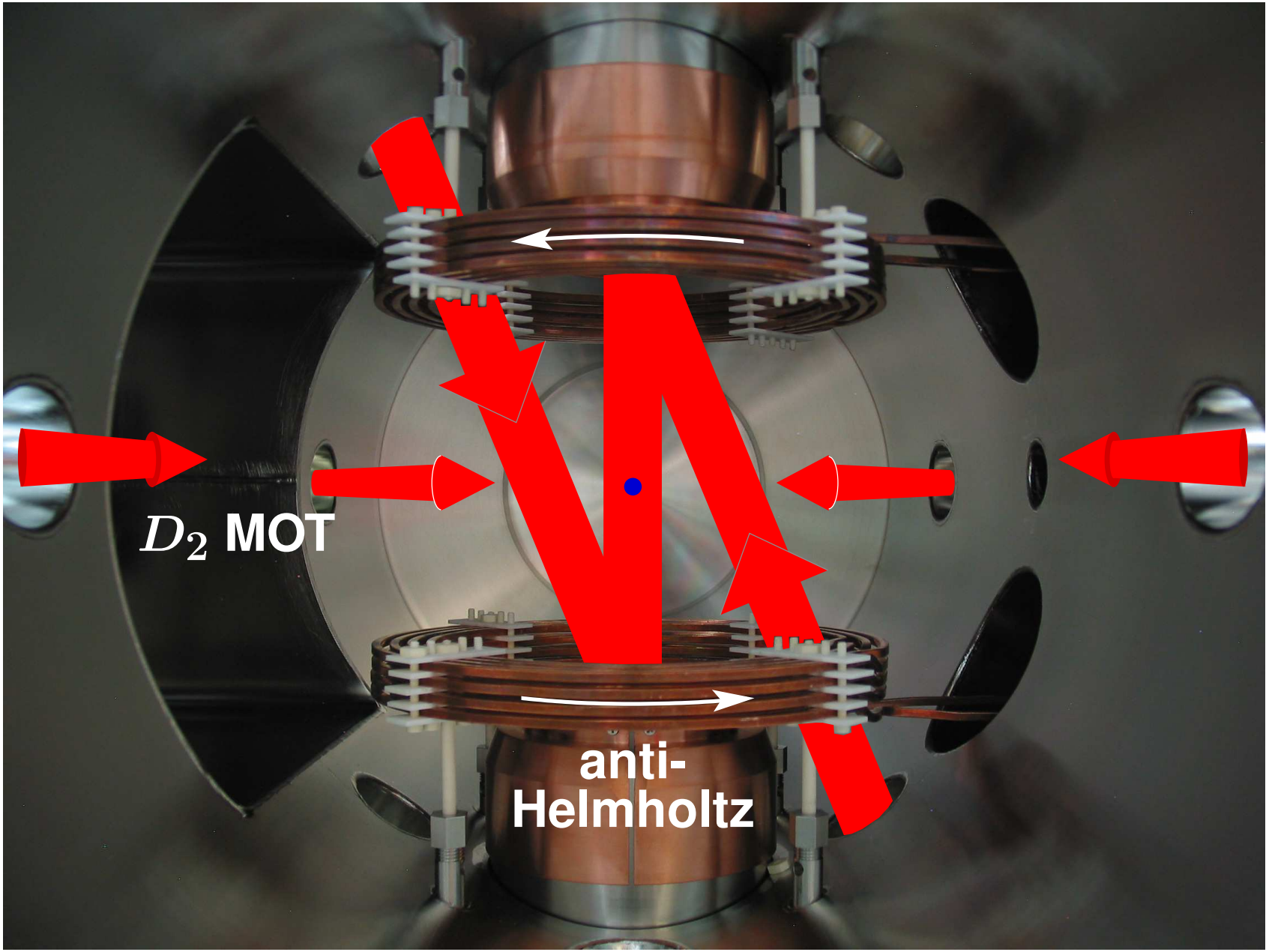
- Shake-off e^- detection
  $\rightsquigarrow$ know decay occured from trap
- Better control of OP beams
  $\rightsquigarrow$ less heating, higher P
- $B_{\mathrm{quad}} \rightarrow B_{\mathrm{OP}}$ quickly: AC-MOT
  $\rightsquigarrow$ better duty cycle, higher polarization
- Increased β/recoil solid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



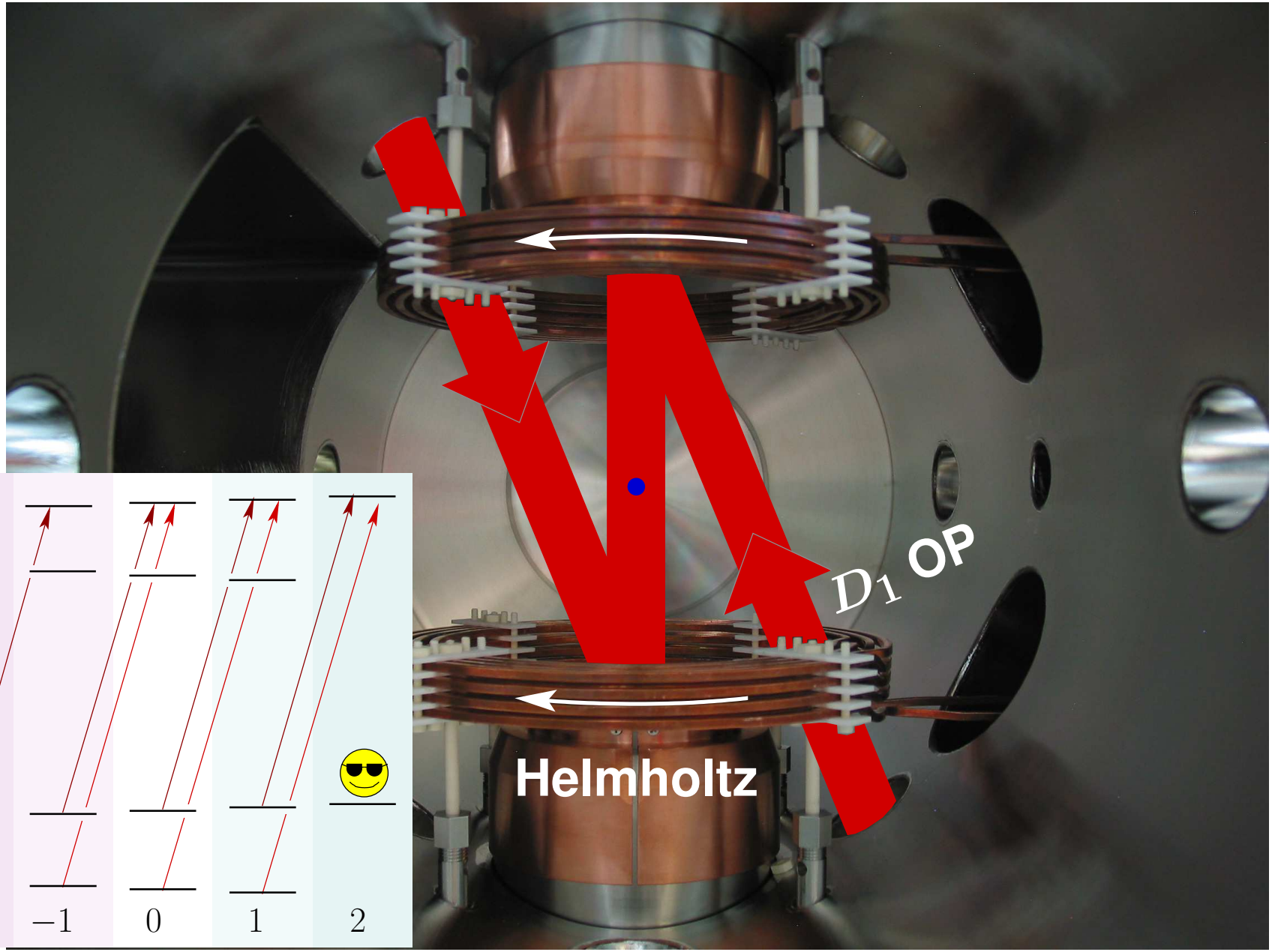
Outline of polarized experiment



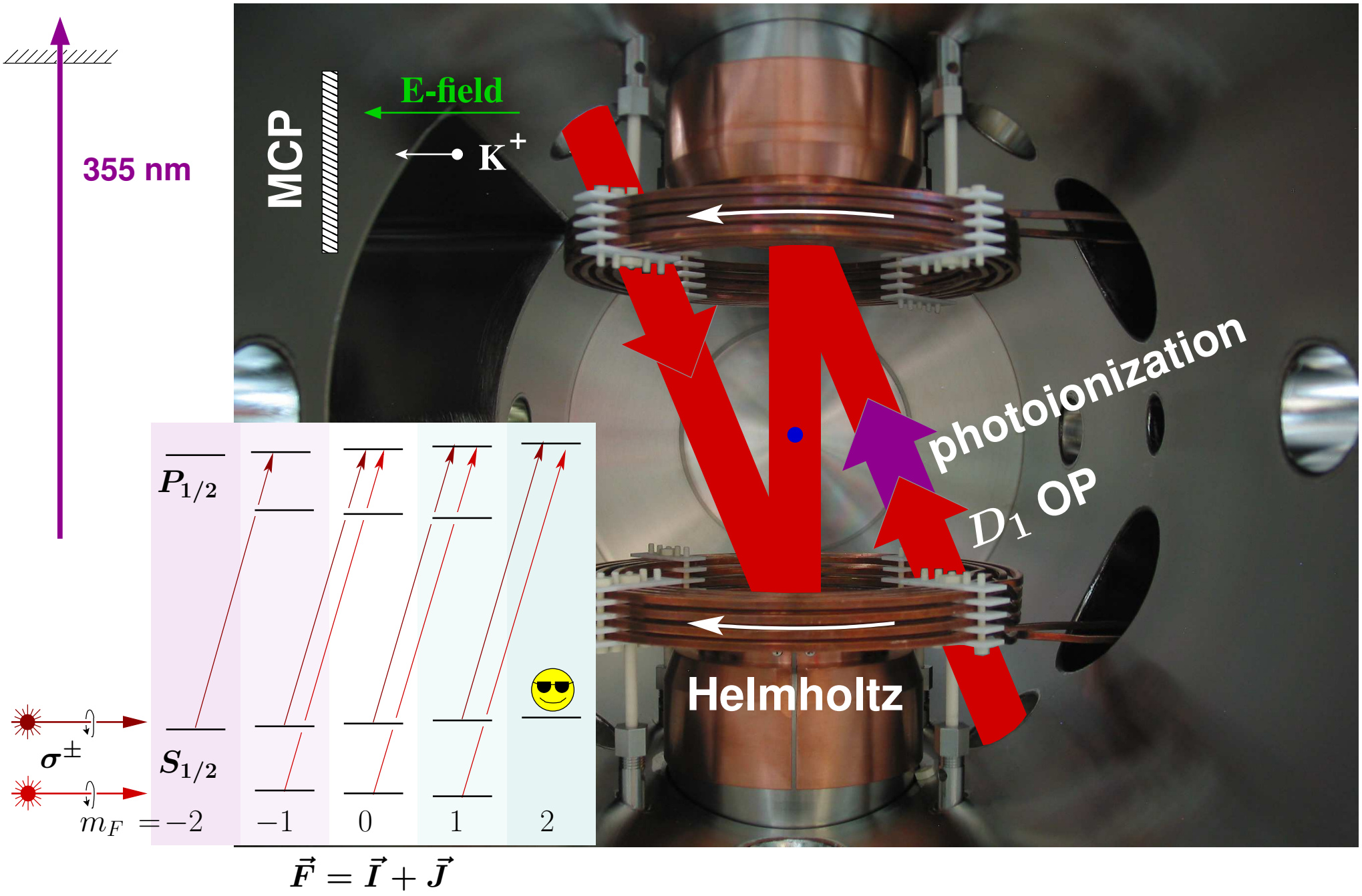
Outline of polarized experiment



Outline of polarized experiment

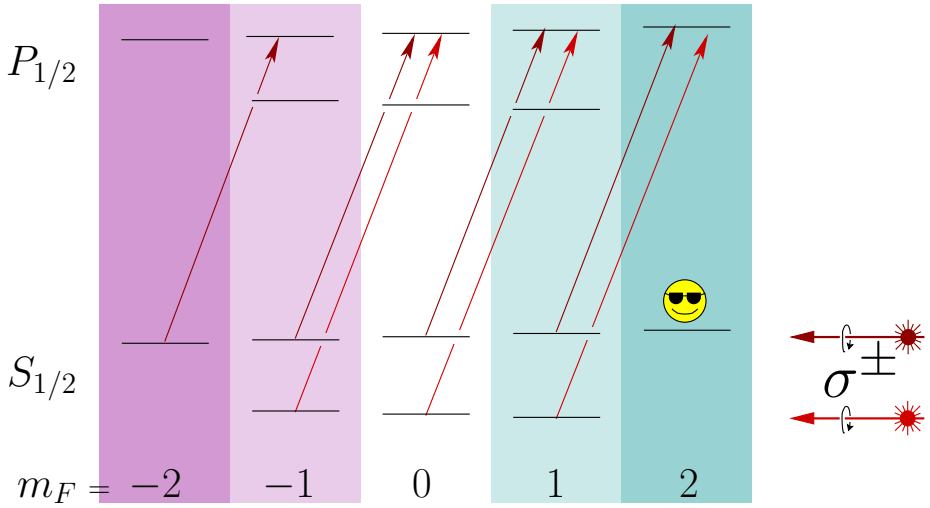


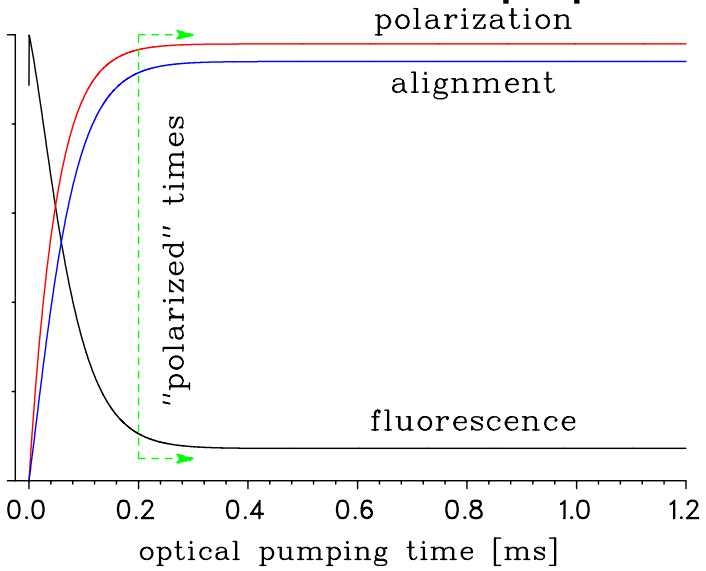
Outline of polarized experiment



Atomic measurement of P

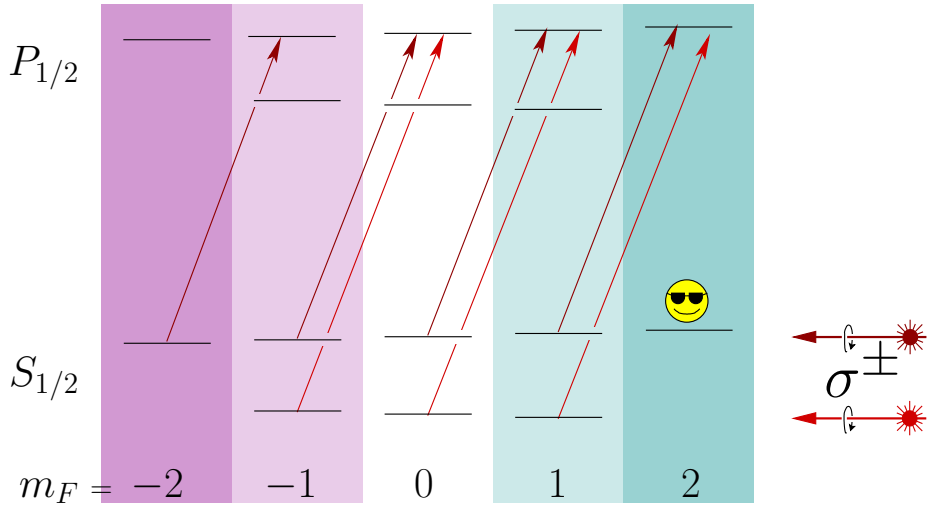
Deduce P based on a model of the excited state populations

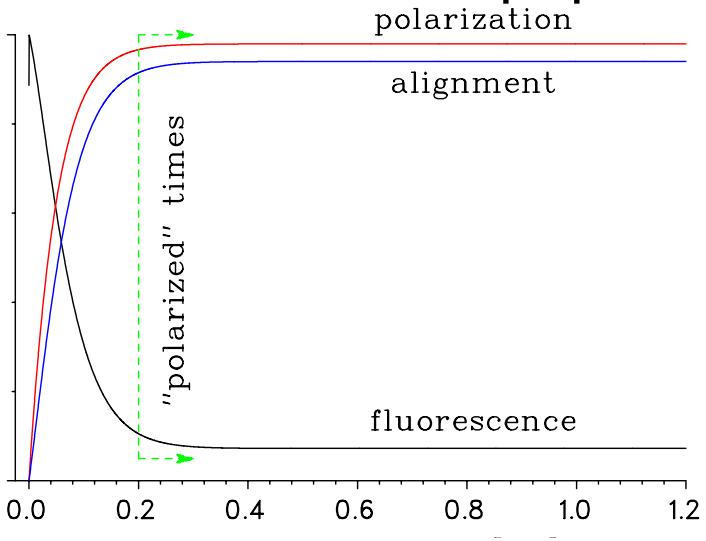


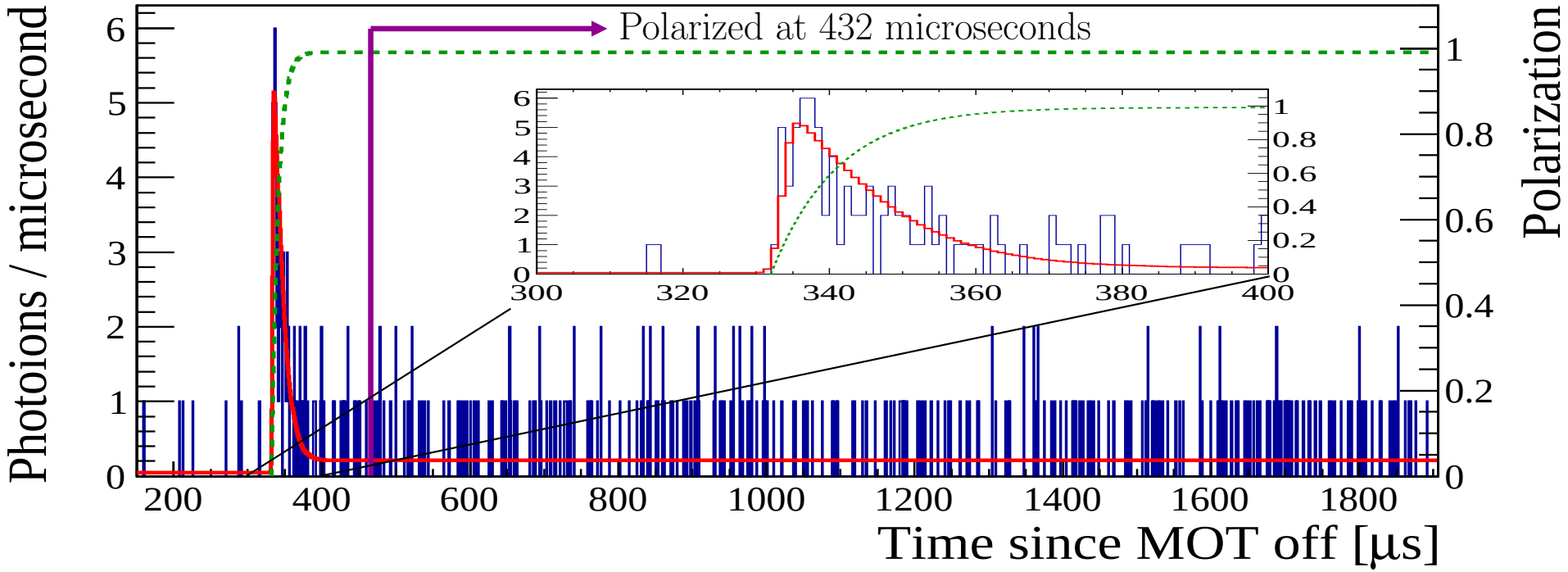


Atomic measurement of P

Deduce P based on a model of the excited state populations

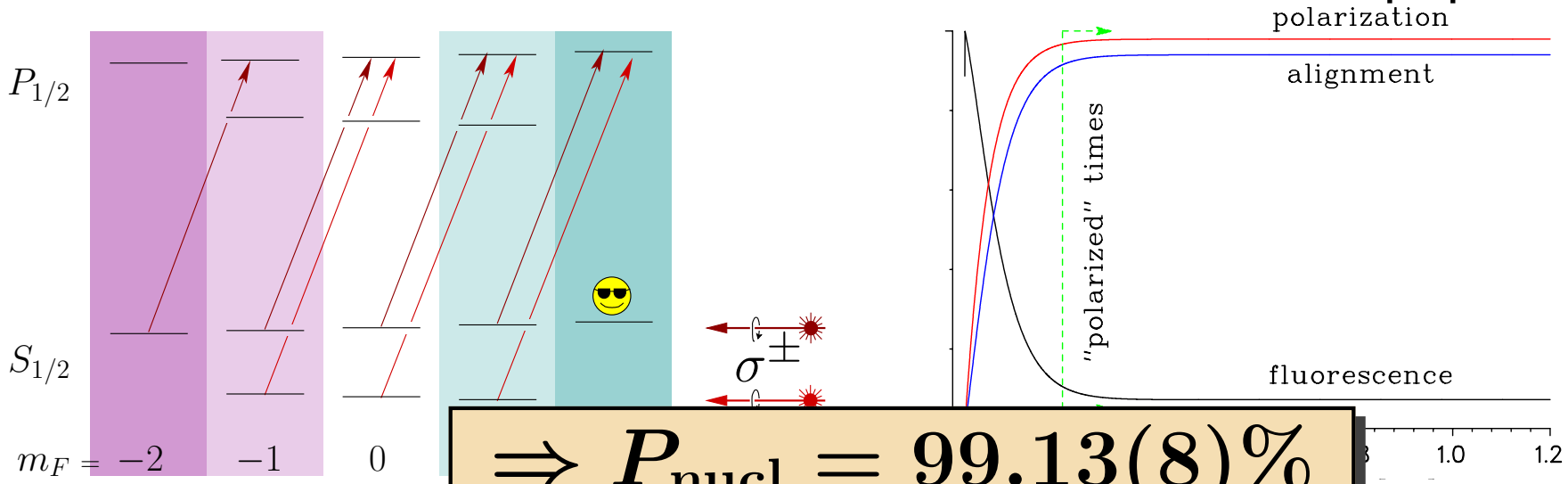




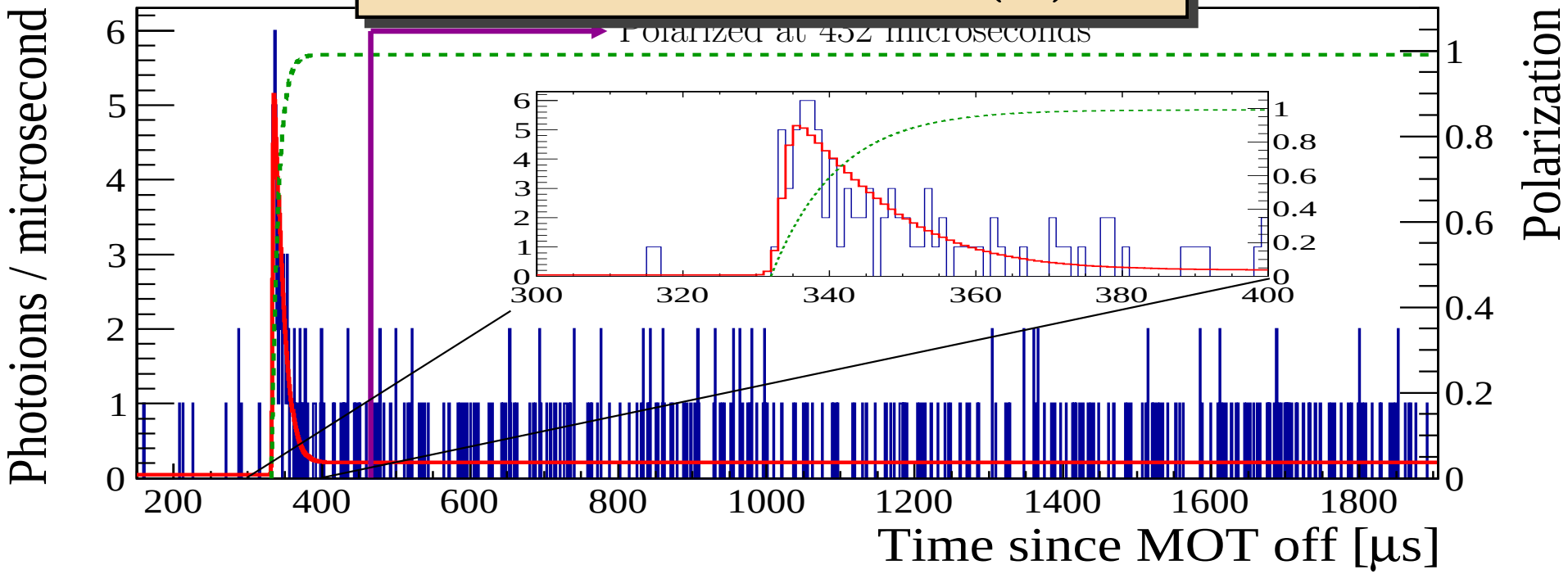


Atomic measurement of P

Deduce P based on a model of the excited state populations

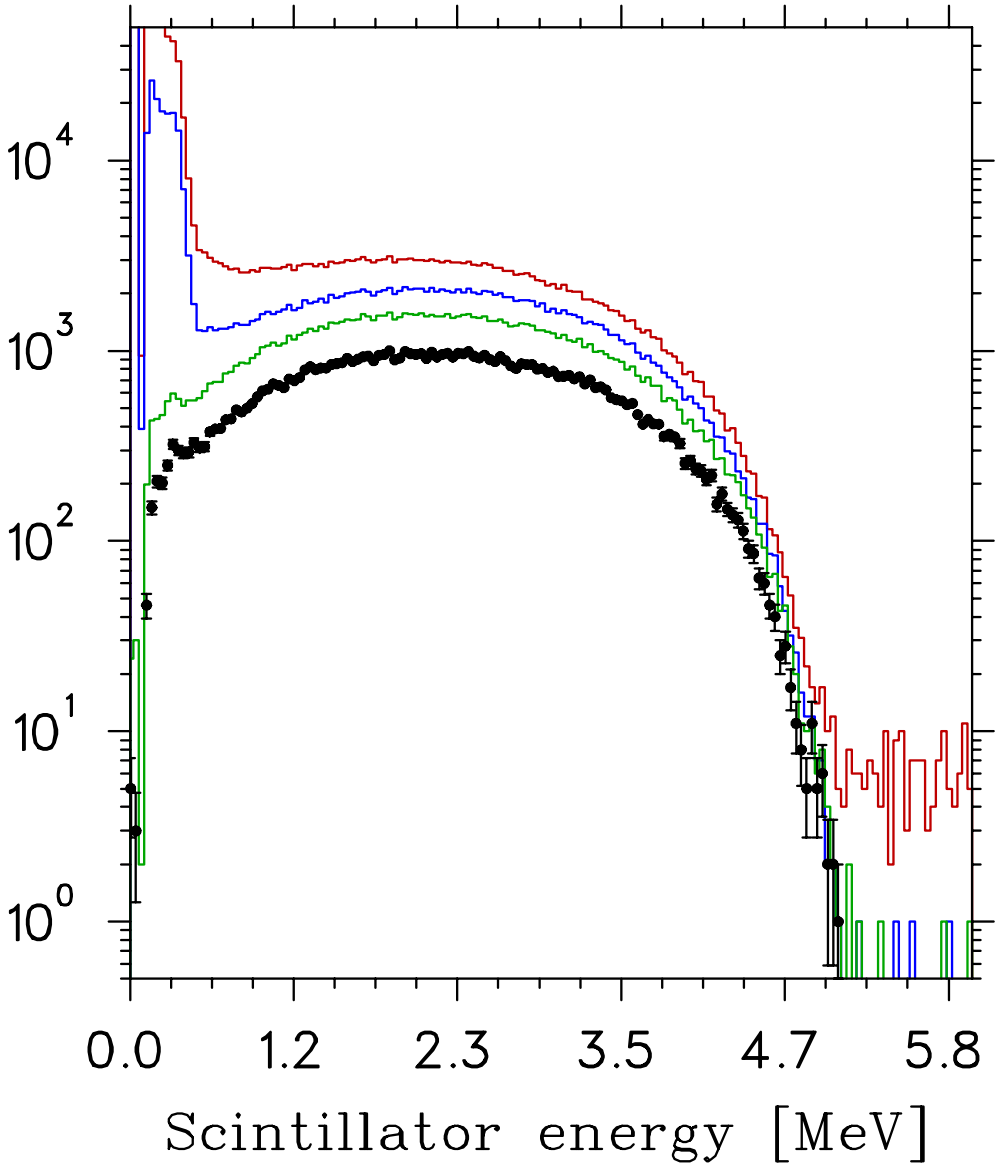


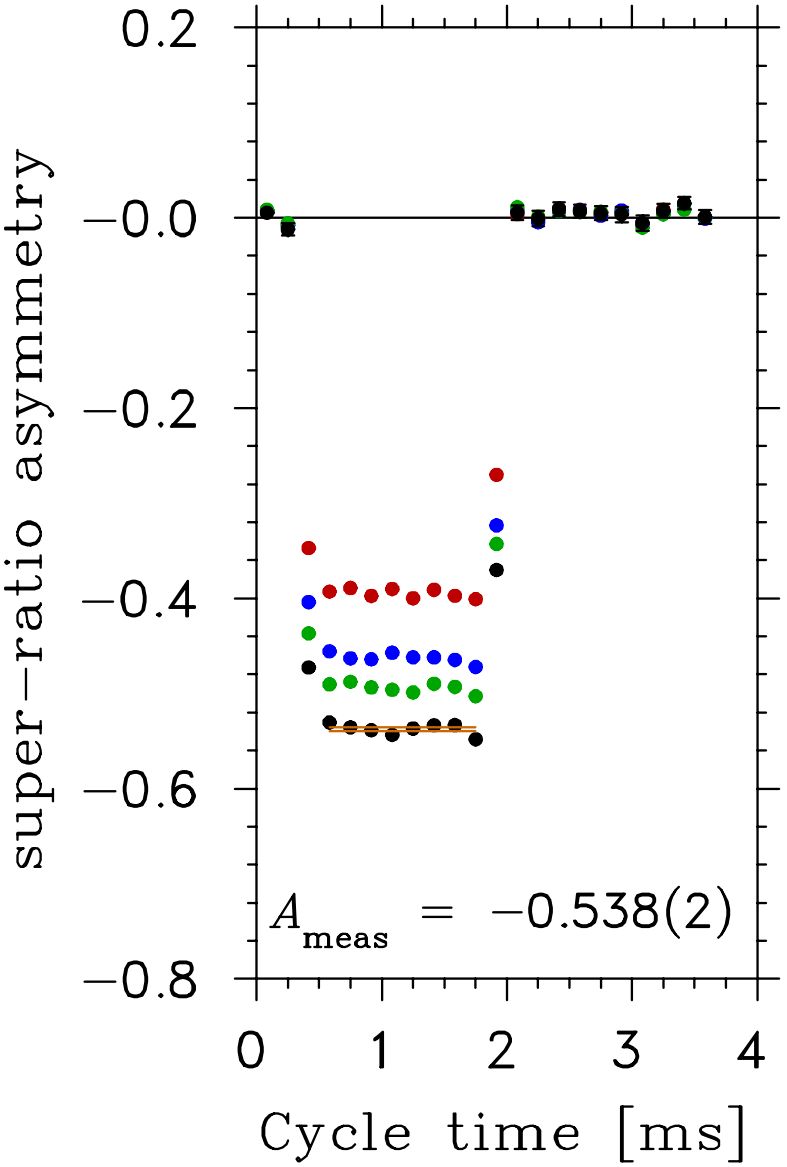
$$\Rightarrow P_{\text{nucl}} = 99.13(8)\%$$



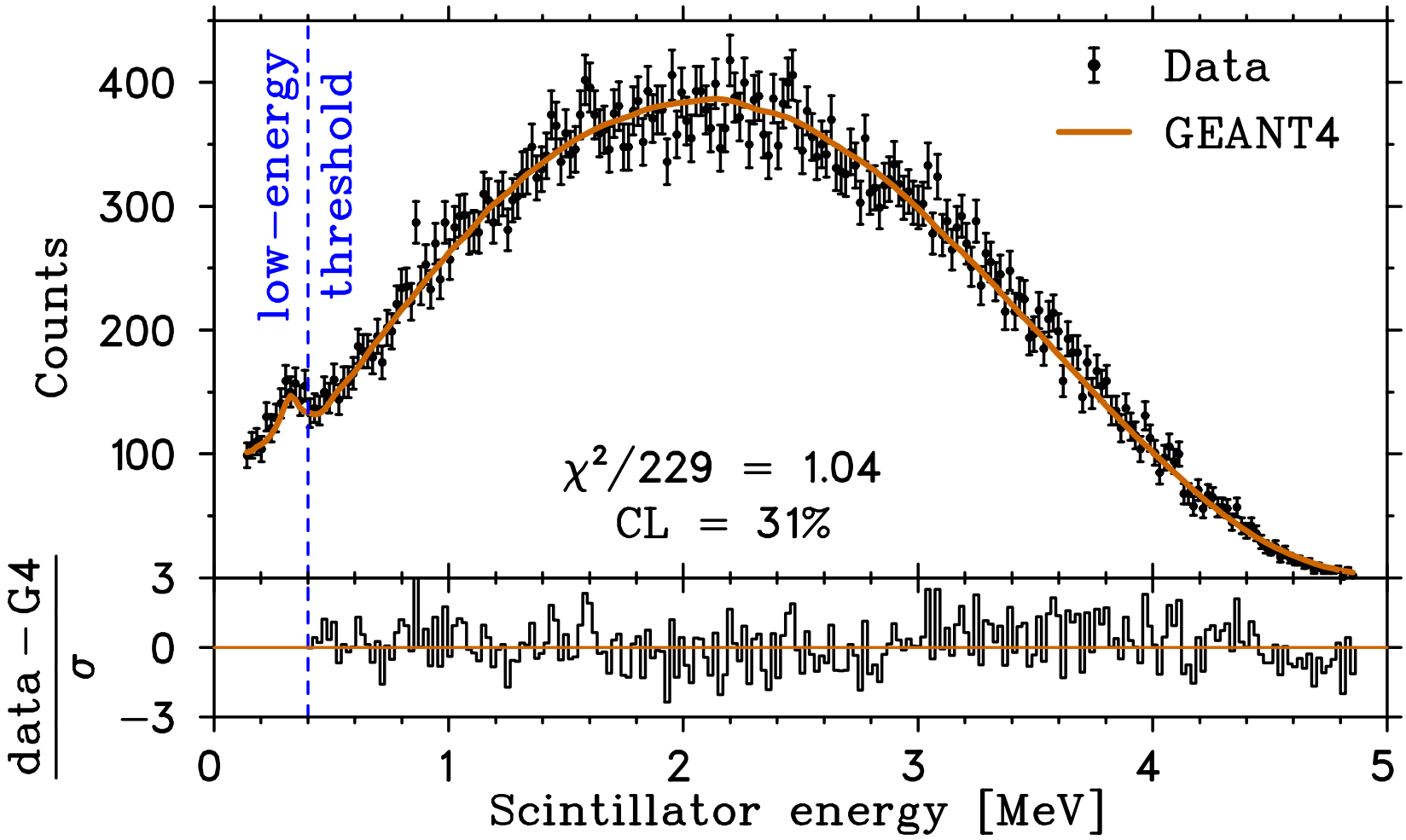
Scintillator spectrum

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

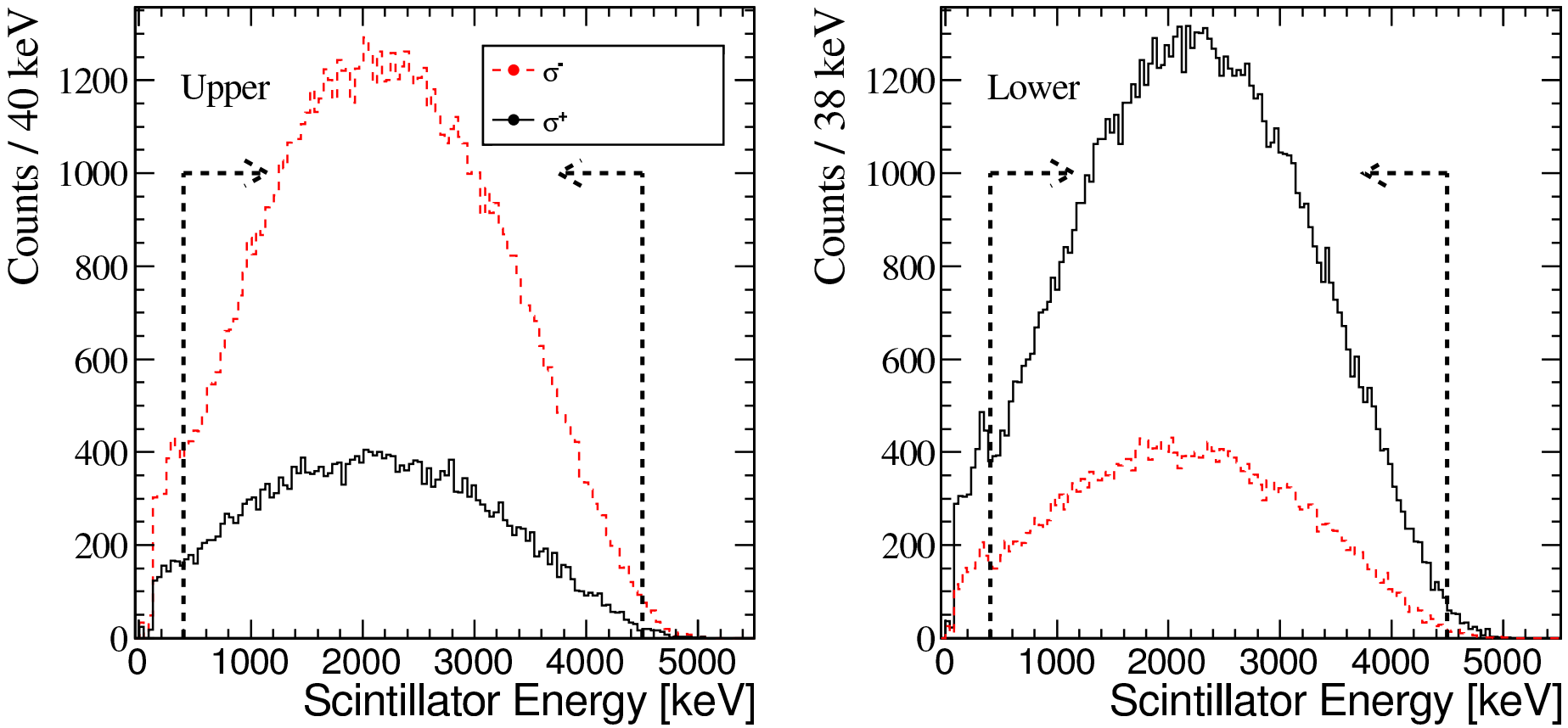




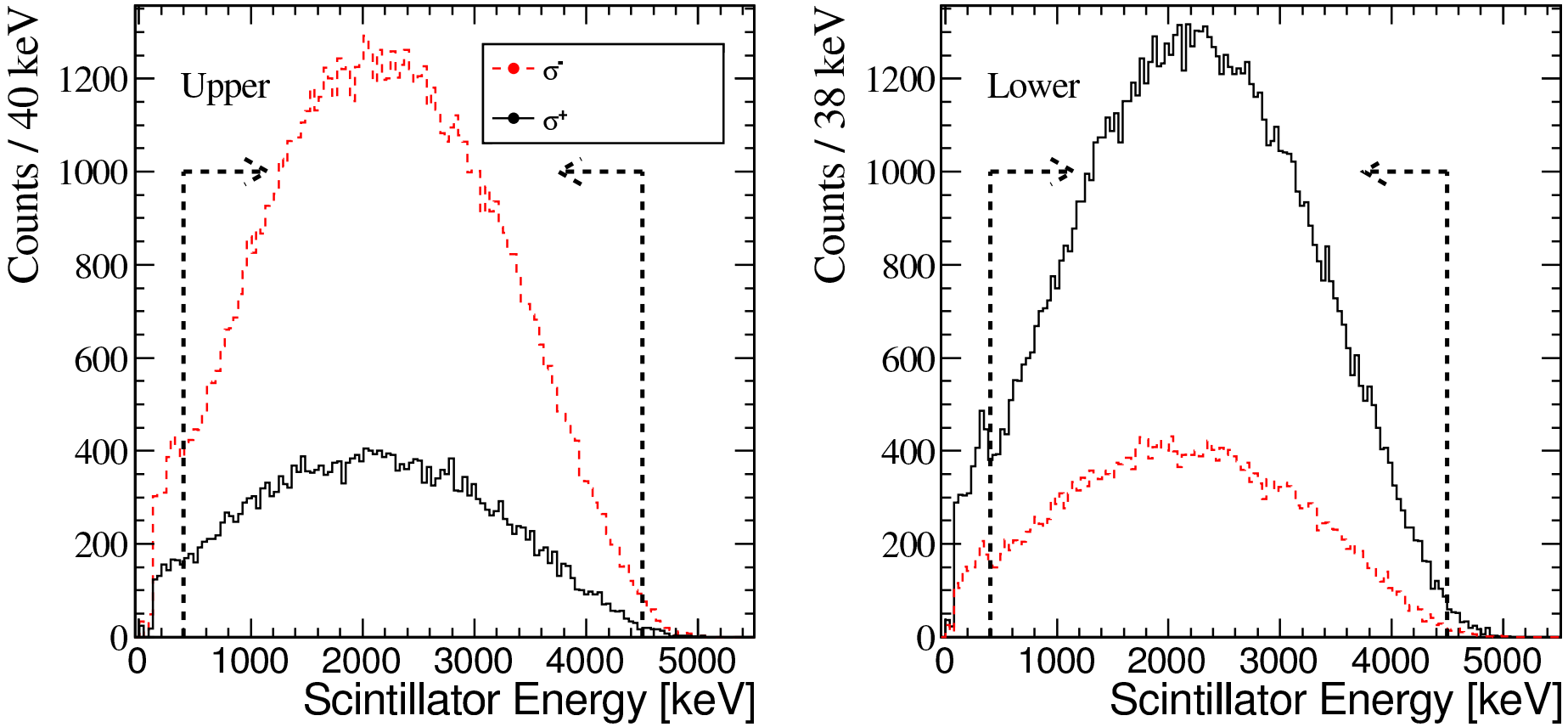
Energy Spectrum Compared to GEANT4



Asymmetry Measurement (briefly)



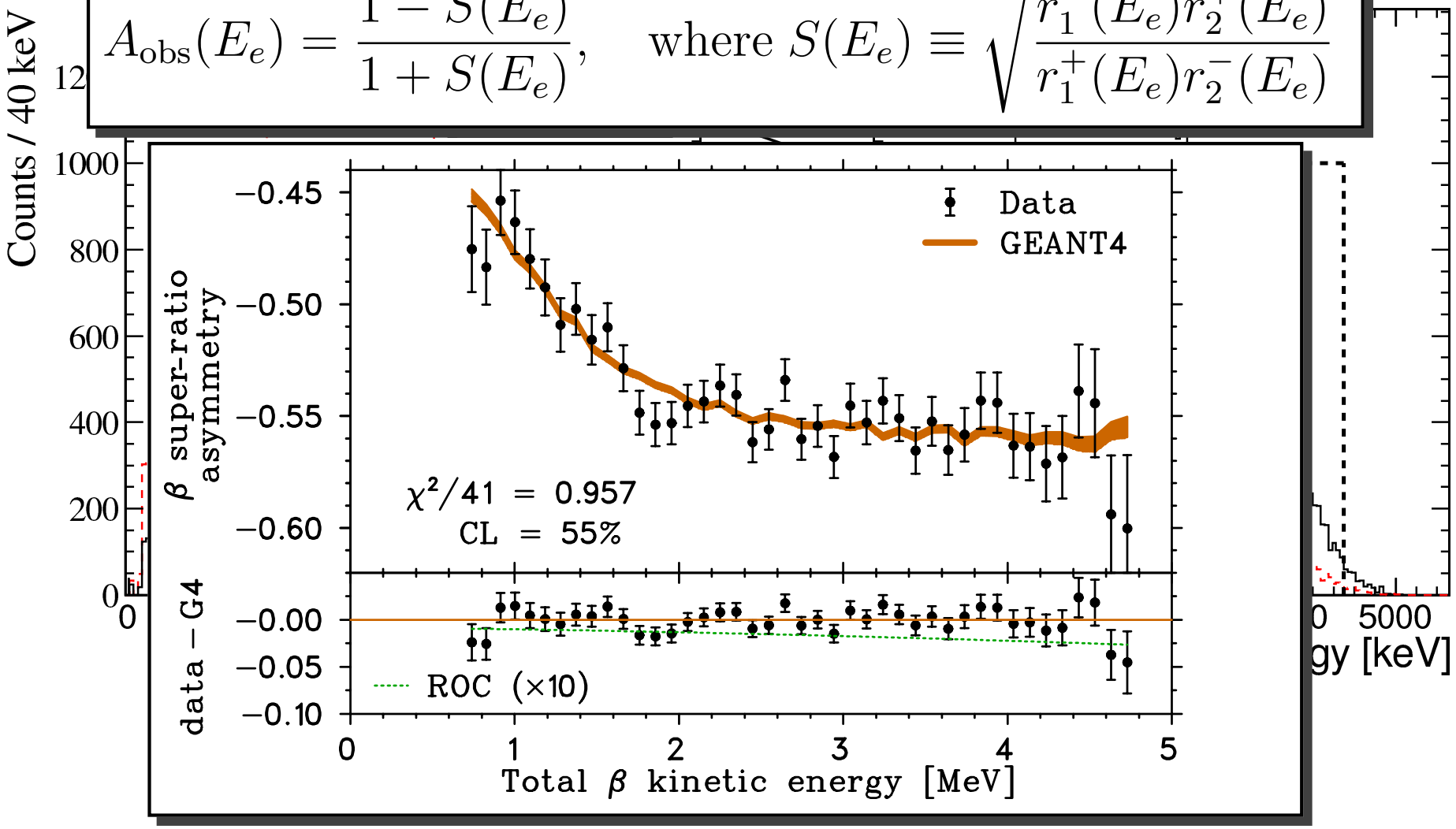
Asymmetry Measurement (briefly)



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

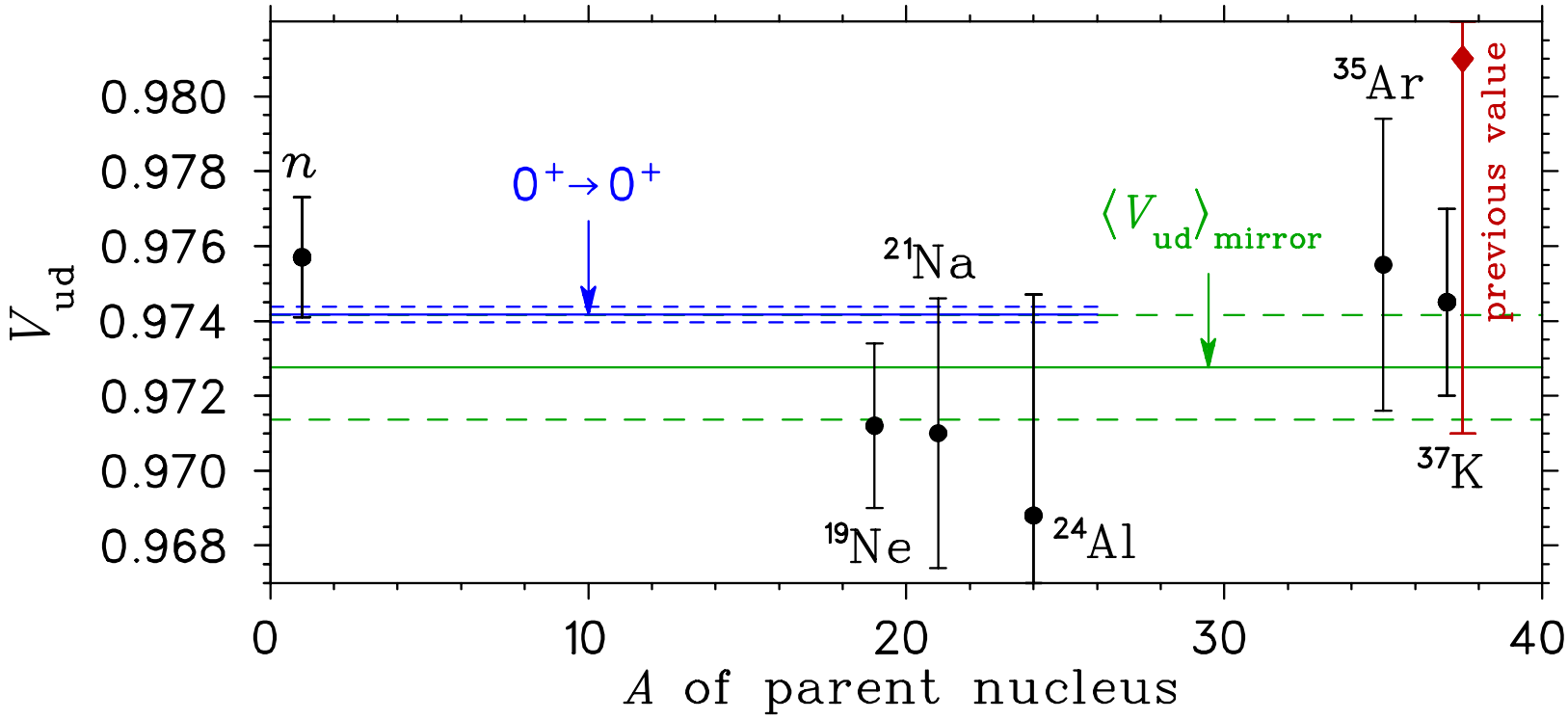
Asymmetry Measurement (briefly)

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



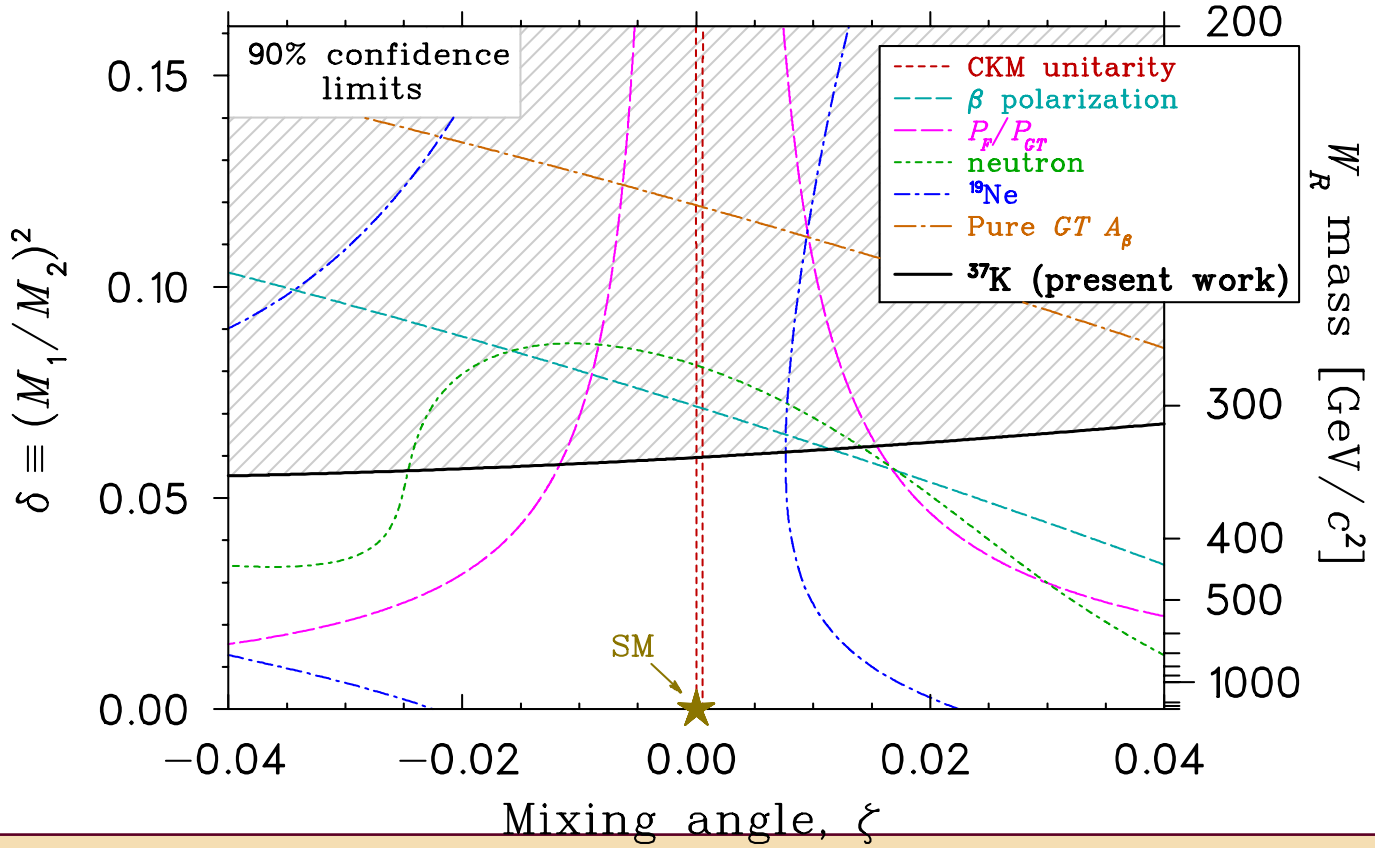
Impact of A_β Measurement

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



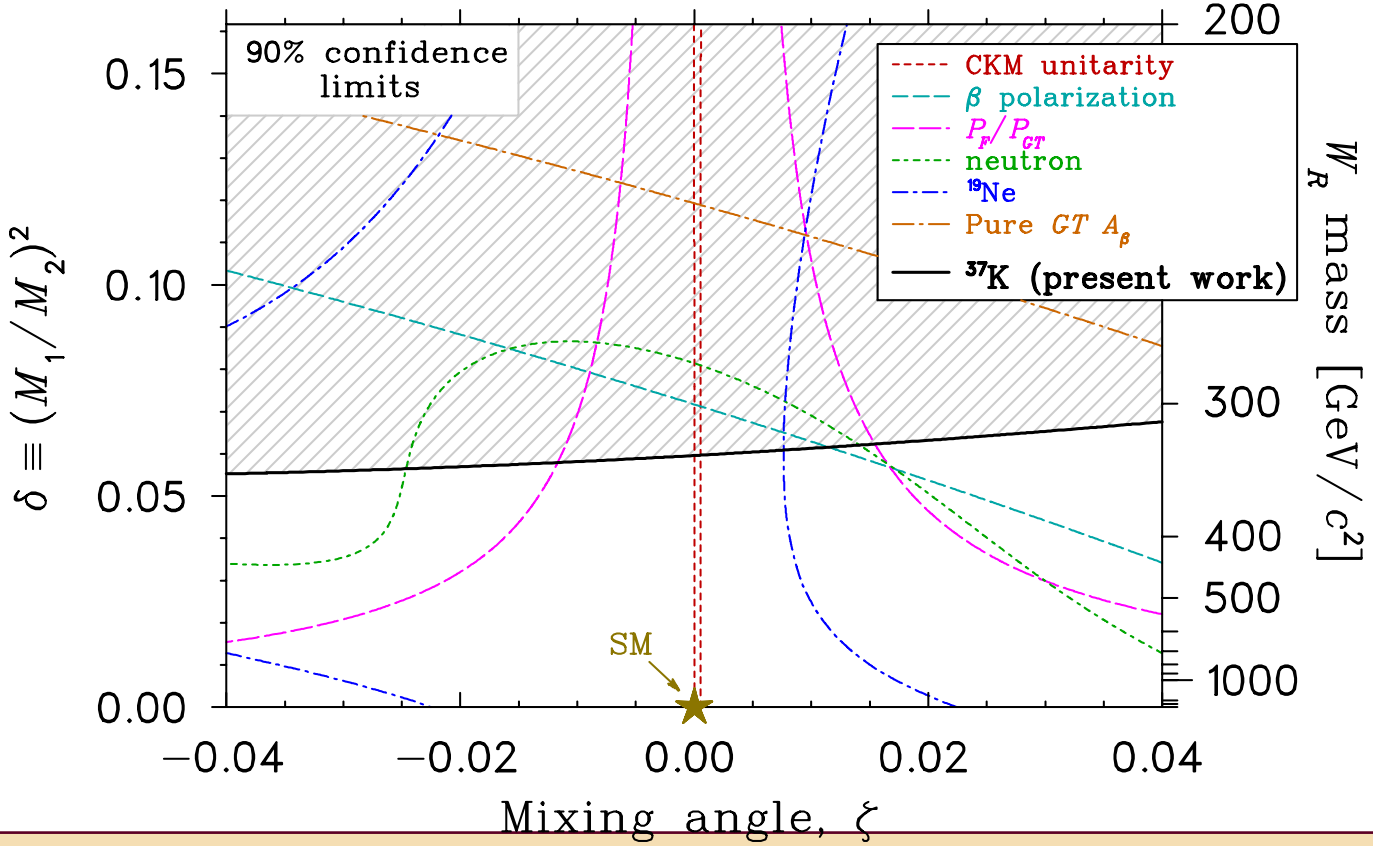
Impact of A_β Measurement

- In terms of CKM unitarity, our A_β result improved V_{ud} by nearly a factor of five: $|V_{ud}| = 0.981^{+12}_{-10} \rightarrow 0.9745(25)$.
- In terms of right-handed currents, our result is the best nuclear limit: $M_{W_R} > 351$ GeV (in minimal left-right symmetric models)



Impact of A_β Measurement

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

- SM is fantastic, but **not** our “ultimate” theory
- many exciting avenues to find more a complete model
- **nuclear approach:** precision measurement of correlation parameters
- Penning trap + RIB CI = ***cool*** physics
- (AC-)MOT + opt. pumping = ***cool*** physics

Summary

- SM is fantastic, but **not** our “ultimate” theory
- many exciting avenues to find more a complete model
- **nuclear approach:** precision measurement of correlation parameters
- Penning trap + RIB CI = ***cool*** physics
- (AC-)MOT + opt. pumping = ***cool*** physics

Thank you for your attention!