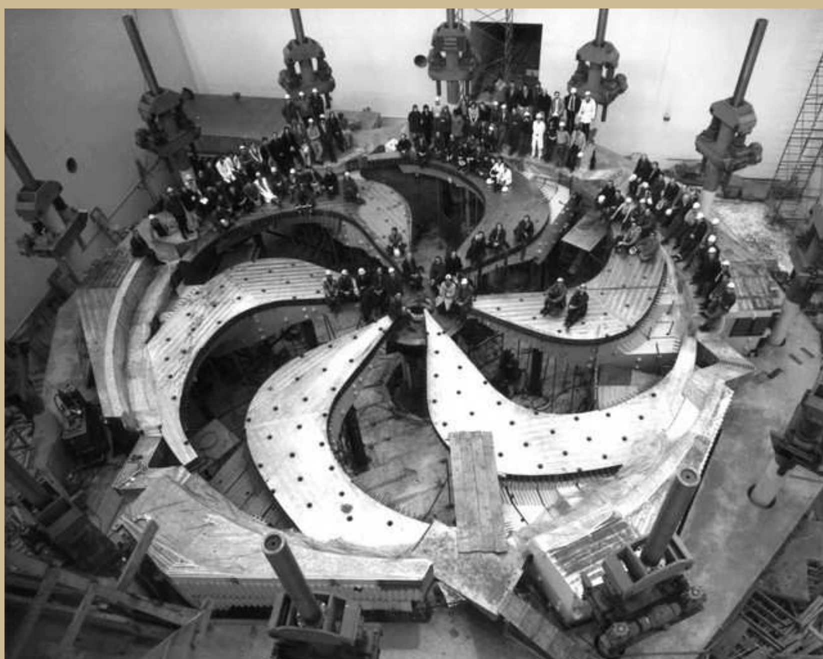
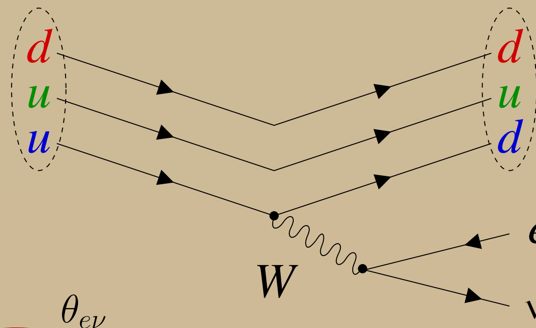
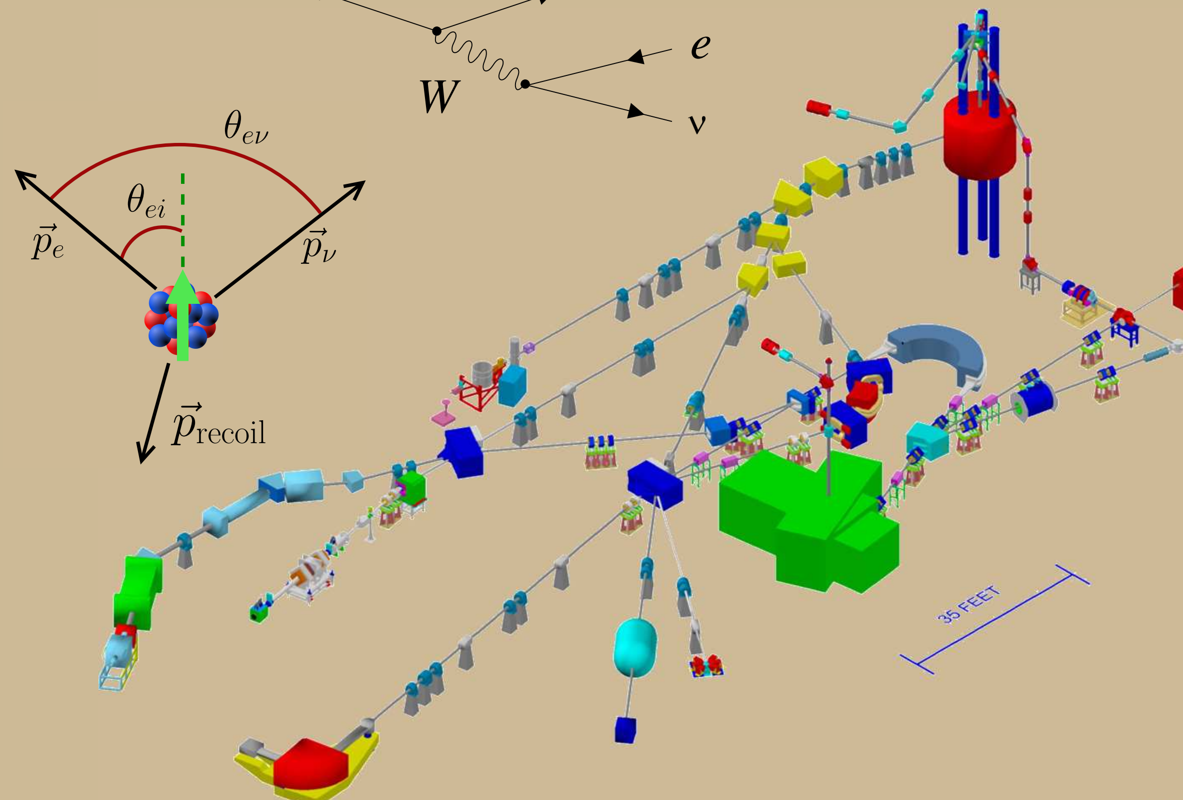
β-decay Correlations Measurements using Ion and Laser Traps







Dan Melconian

Sept 4, 2014

Overview

1. Fundamental symmetries

- brief **motivation**
- **game plan** for testing the SM

2. TAMU Penning Trap (being built)

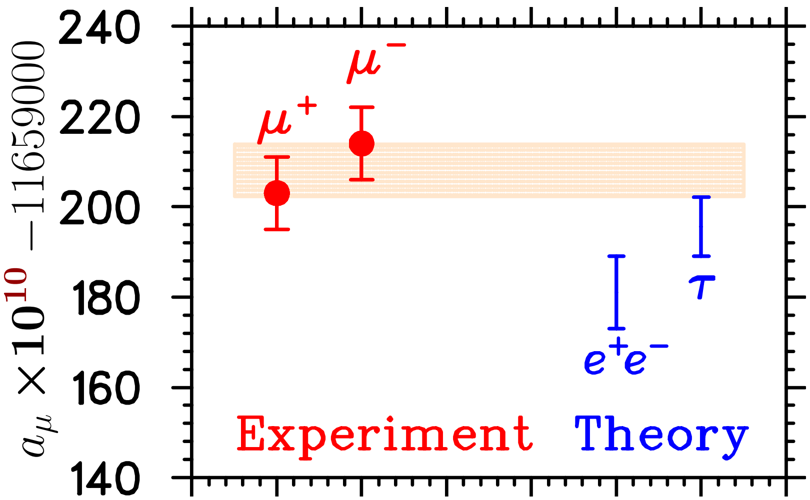
- **physics** of superallowed β decay
- **ion trapping** of proton-rich nuclei at T-REX

3. TRIUMF Neutral Atom Trap

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

We all know the SM works stubbornly well

- ✔ 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



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

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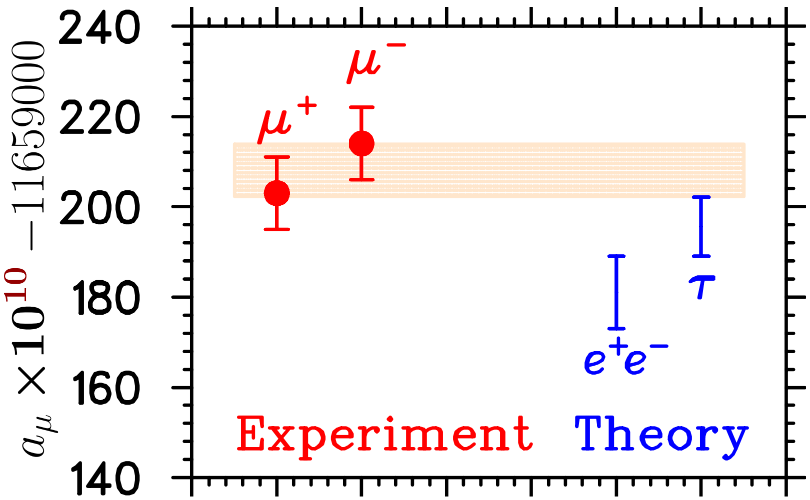

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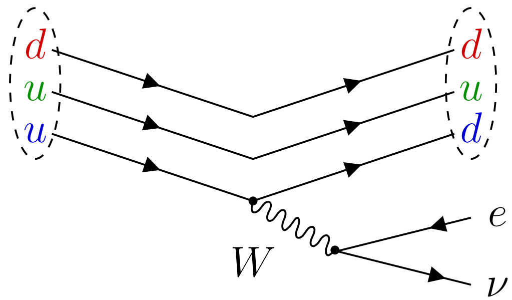
this is

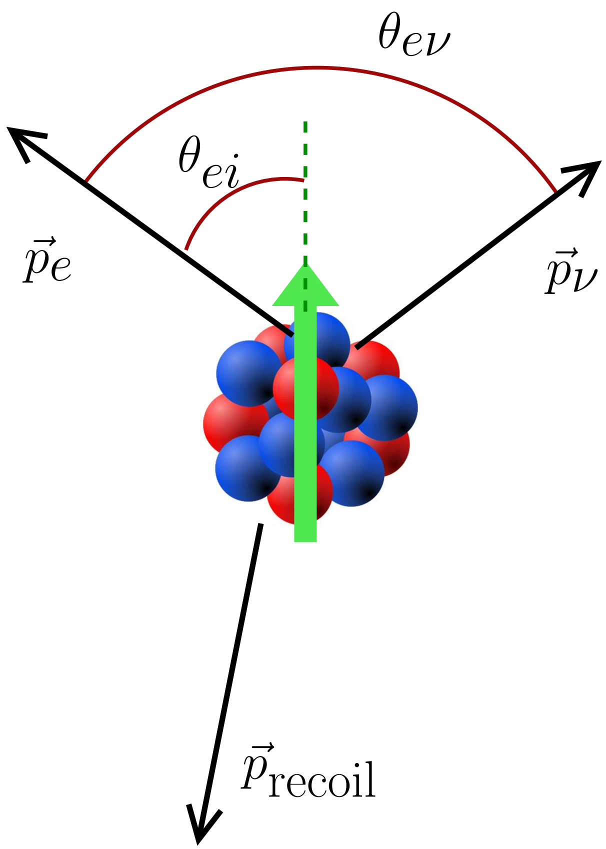
the most precisely tested theory ever conceived!

But we also know there's more to discover

- **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 do many of us plan to test the SM?



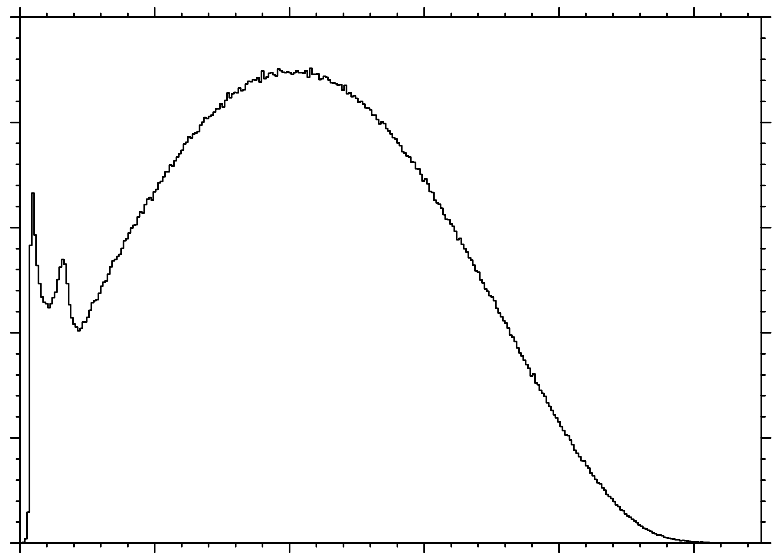


- perform a β decay experiment on **short-lived** isotopes
- make a **precision measurement** of the angular correlation parameters
- **compare** the SM predictions to observations
- look for **deviations** as an indication of **new physics**

A little more specifically...

Test SM via the **angular distribution** of β decay: the often-quoted Jackson, Treiman and Wyld (Phys Rev **106** and Nucl Phys **4**, 1957)

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



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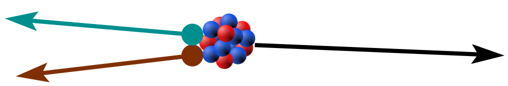
vector



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

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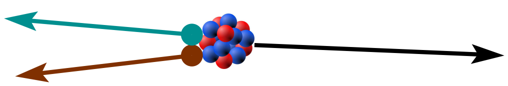
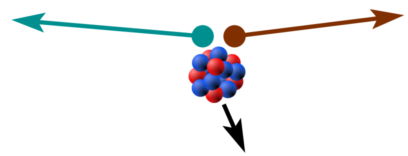


scalar



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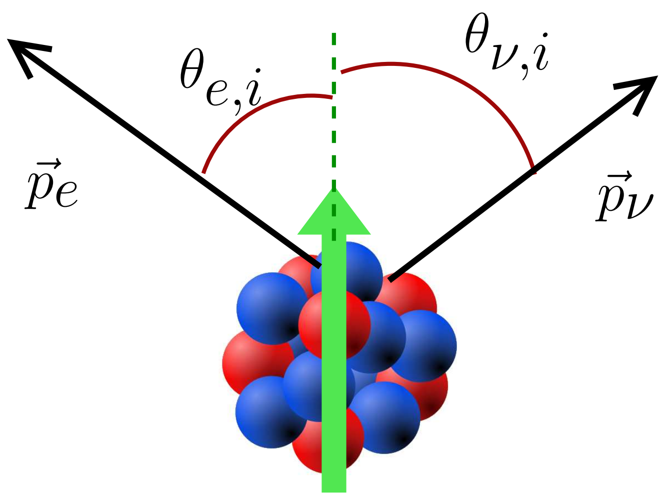

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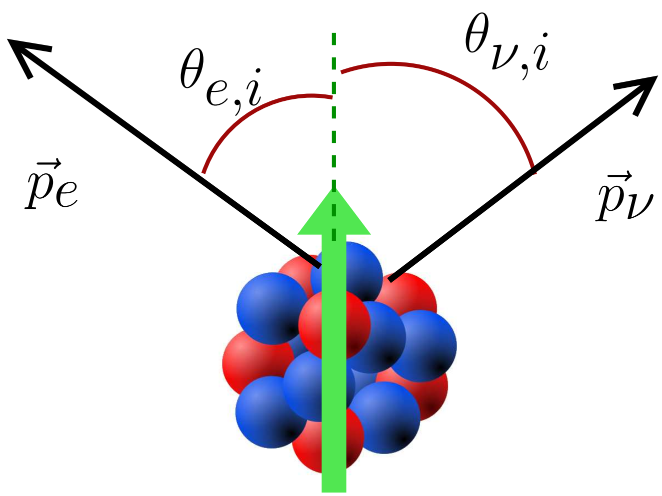

$$A_\beta = \frac{-2\rho}{1+\rho^2} \left[(1-xy) \sqrt{\frac{3(1+x^2)}{5(1+y^2)}} - \frac{\rho(1-y^2)}{5(1+y^2)} \right]$$

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

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

are right-handed current parameters that are zero in the SM

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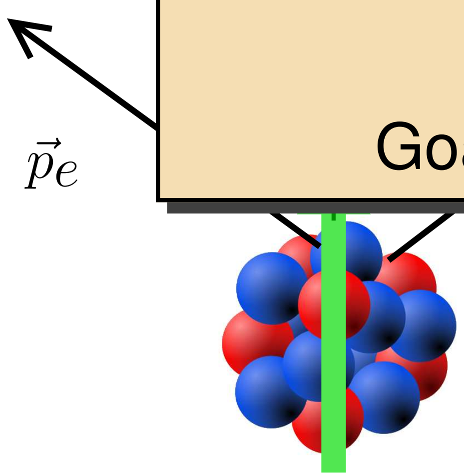
$$\left. \langle \vec{I} \rangle \left[A \frac{\vec{p}_e}{\ldots} + B \frac{\vec{p}_\nu}{\ldots} + D \frac{\vec{p}_e \times \vec{p}_\nu}{\ldots} \right] \right) + \ldots$$

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

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

Goal must be 0.1% to complement LHC



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

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Overview

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- **physics** of superallowed β decay
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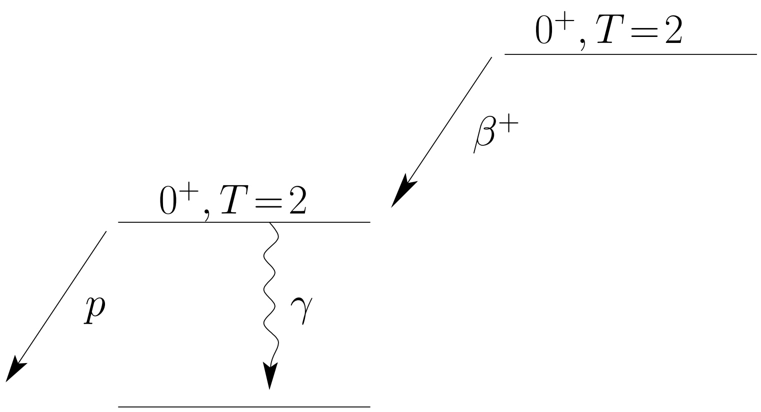
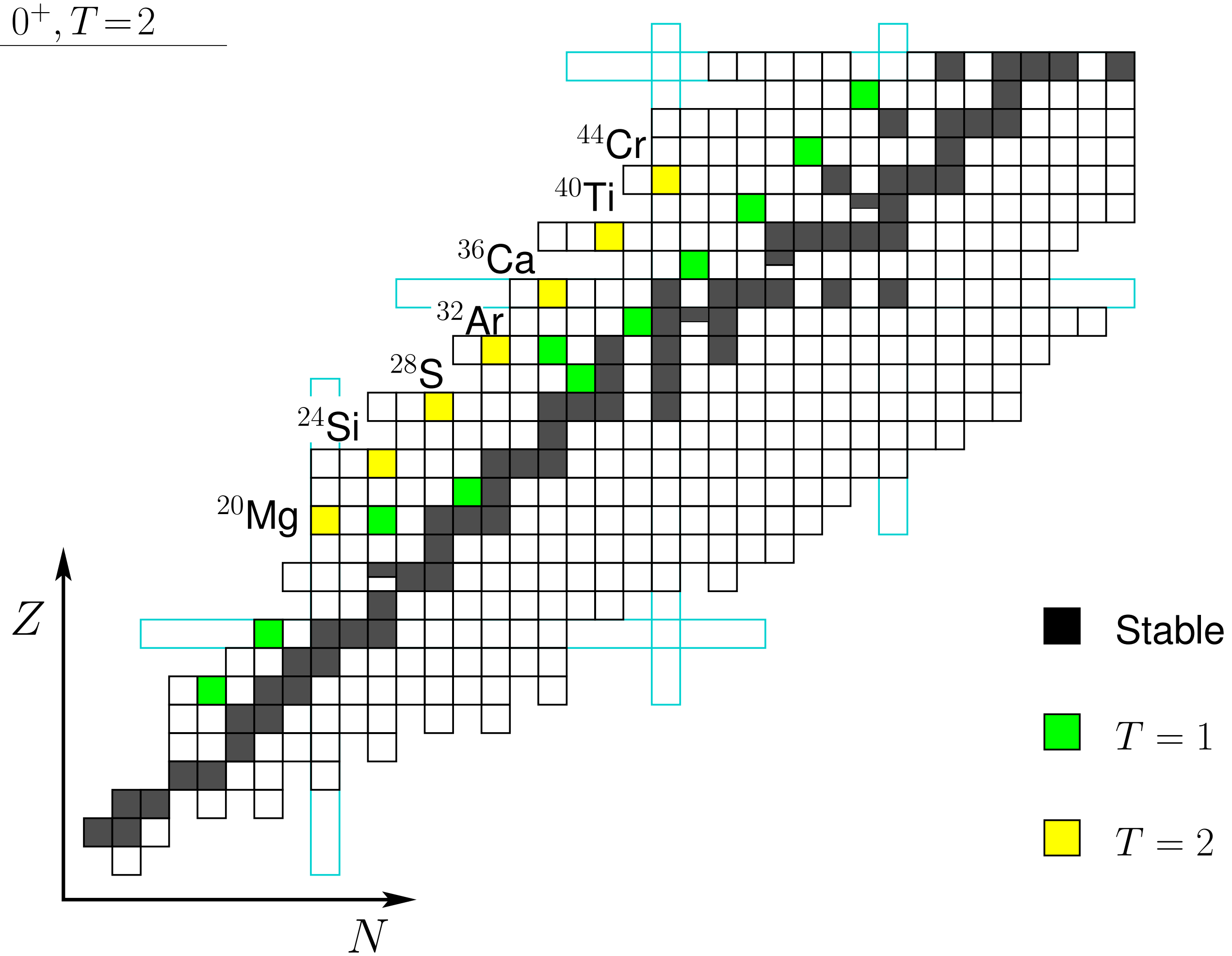
3. Community needs

- clean measurement of low-energy βs
- theory support as we approach 0.1%

$T = 2$ superallowed decays





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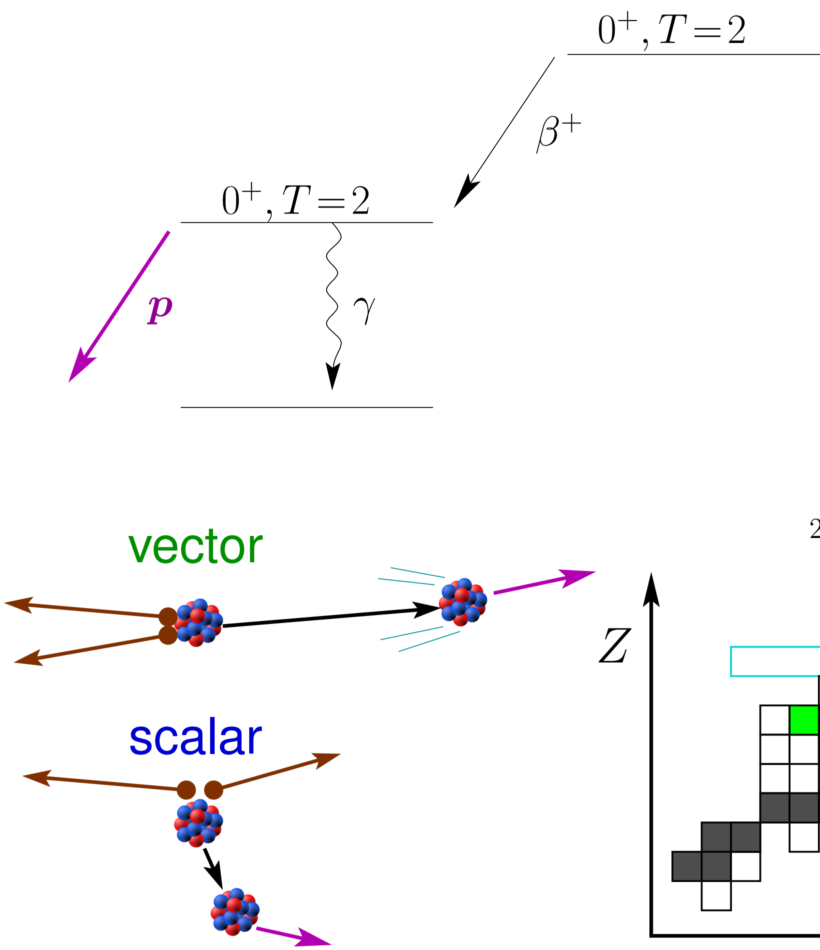

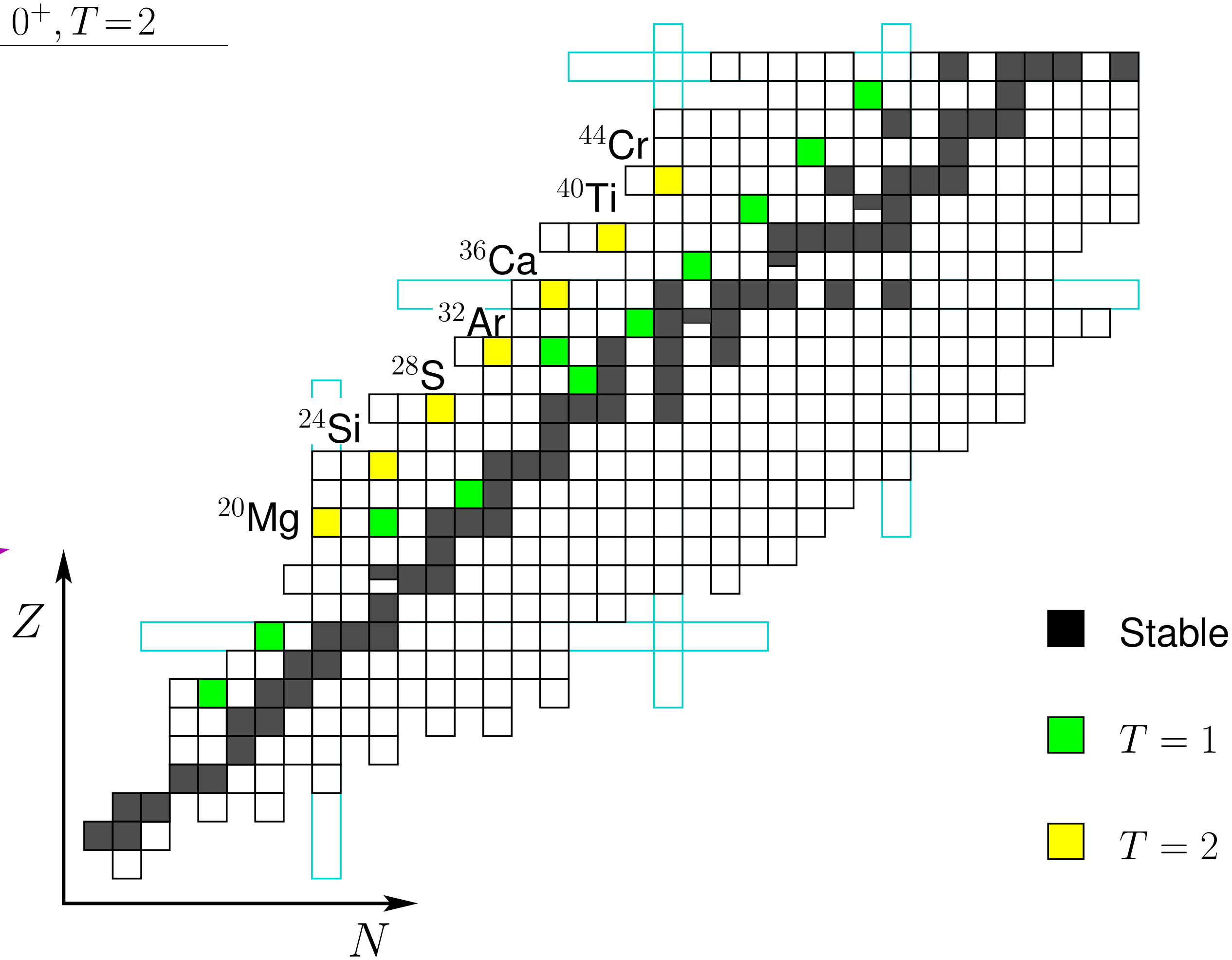

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- ft values: test δ_C; V_{ud} (?)
- spectroscopy of proton-rich nuclei

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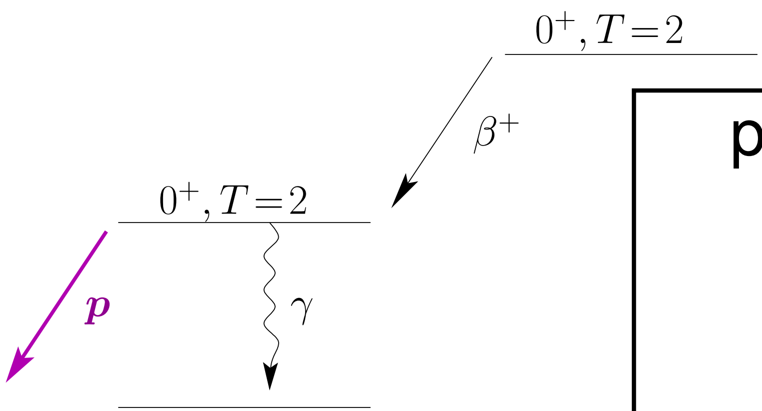

pure Fermi decay ⇔ minimal structure effects; decay rate simply given by:

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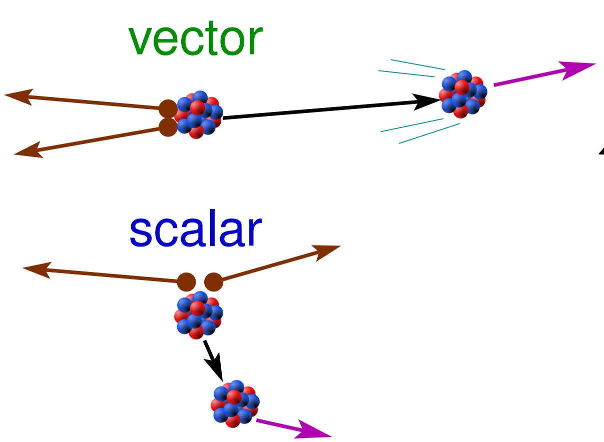

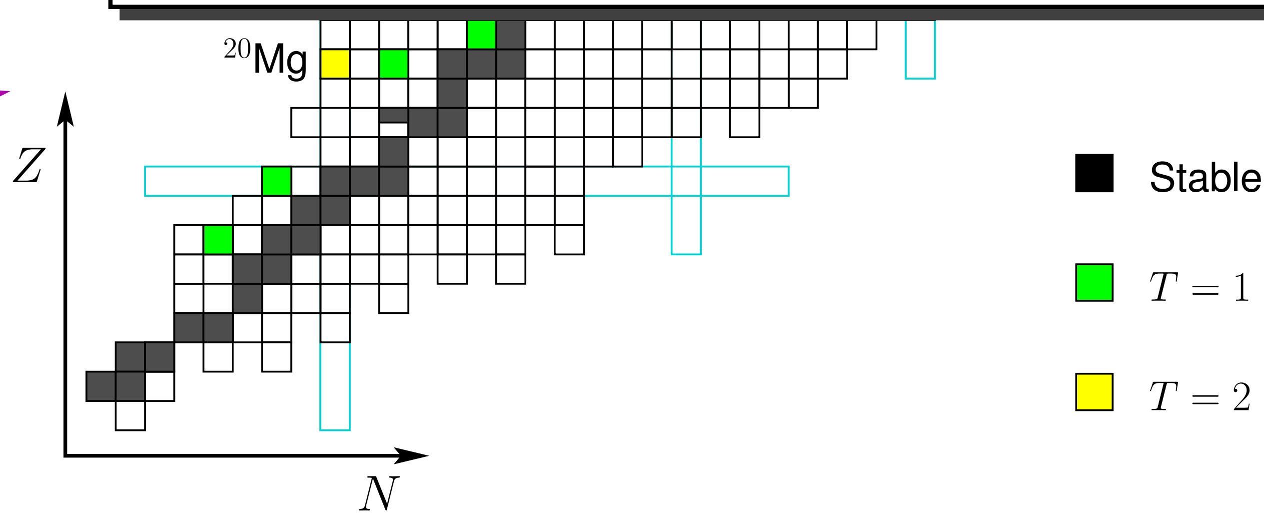

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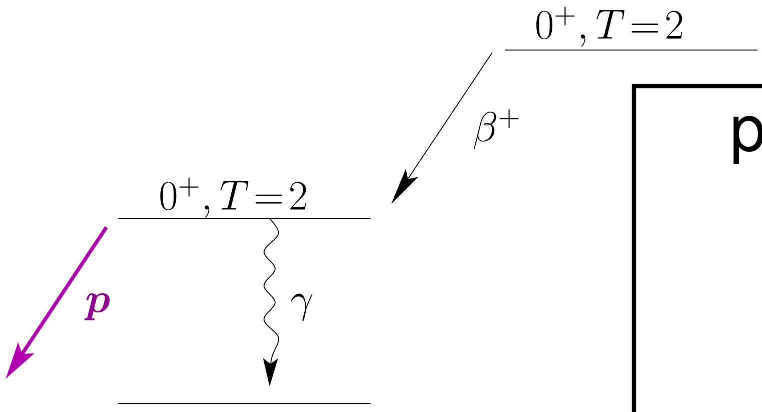

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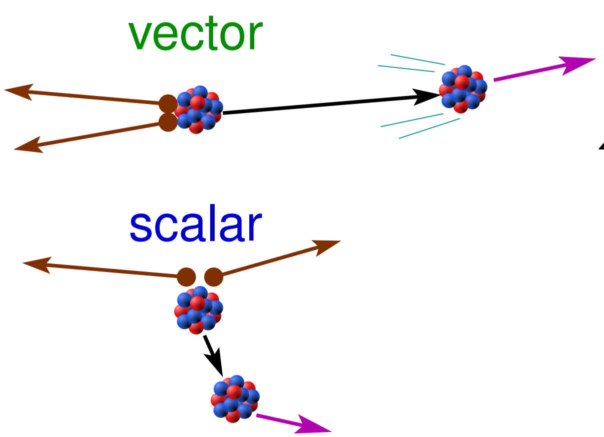

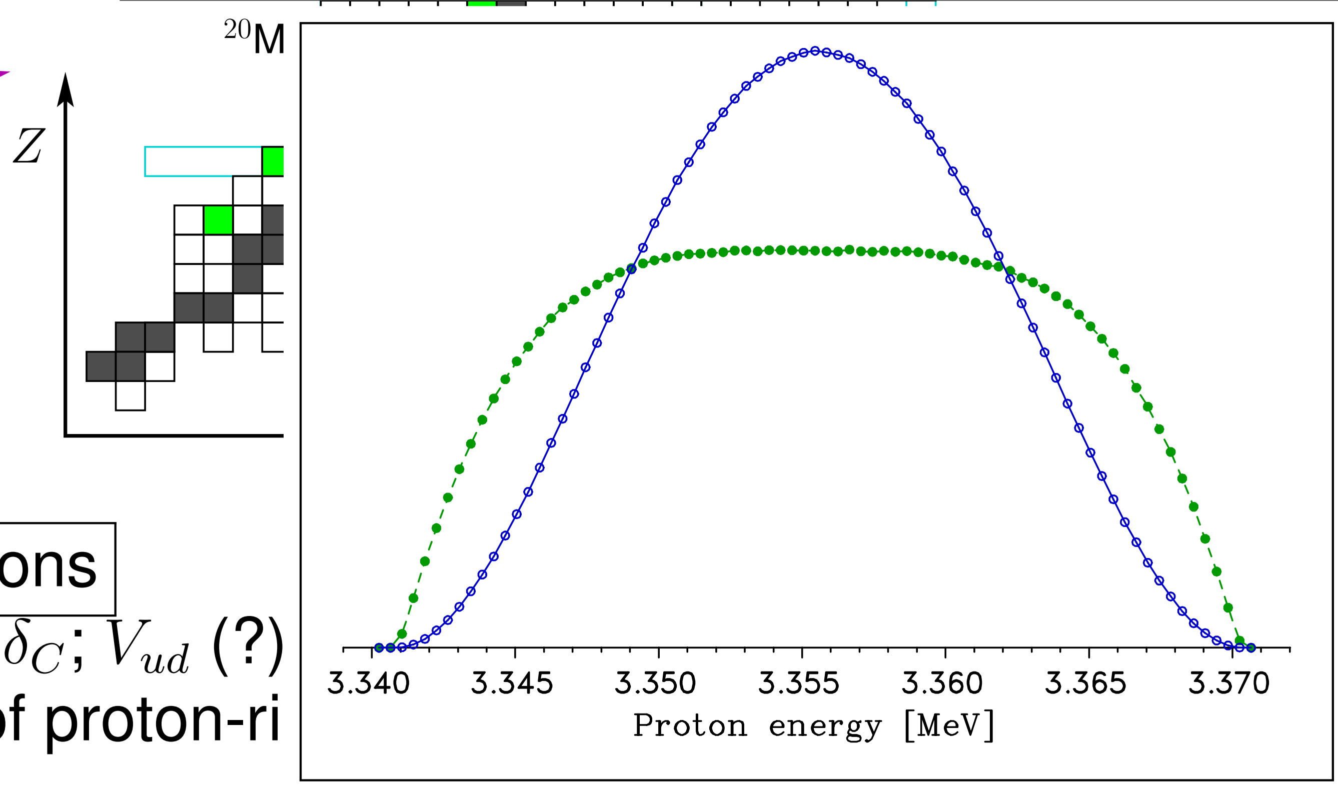

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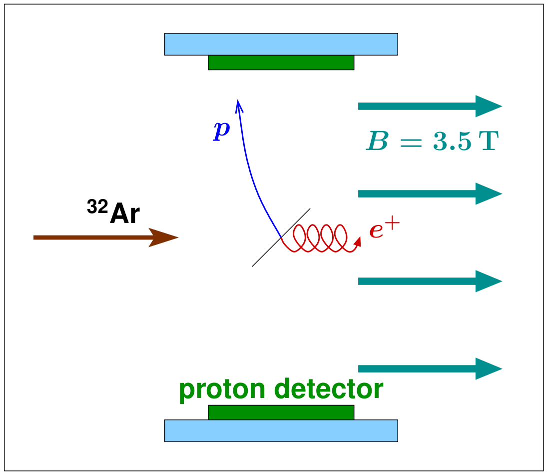

VOLUME 83, NUMBER 7 PHYSICAL REVIEW LETTERS 16 AUGUST 1999

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

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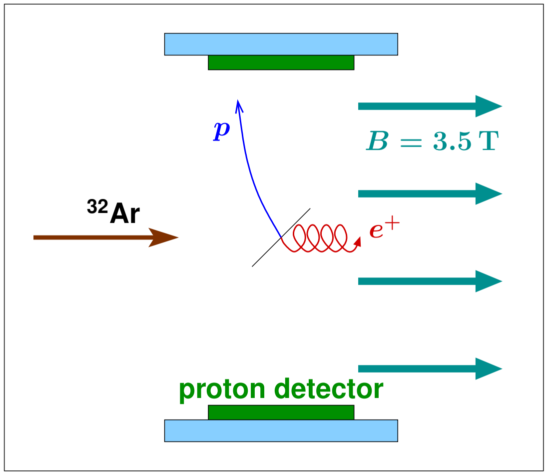
[2]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556*
[3]*Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain*
[4]*EP Division, CERN, Geneva, Switzerland CH-1211*

(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.

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



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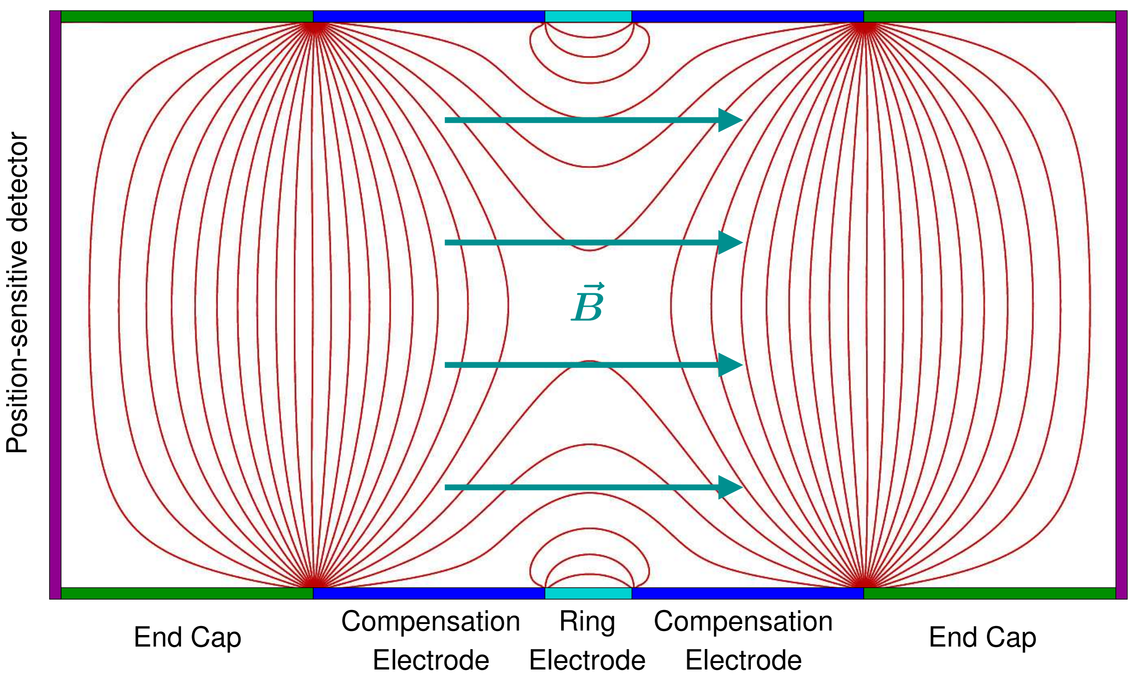
Mehlman *et al.*, NIM **A712**, 9 (2013)



But why throw away useful information?

$\rightsquigarrow$ increase sensitivity and solid angle using a Penning trap to observe $e - p$ coincidences!

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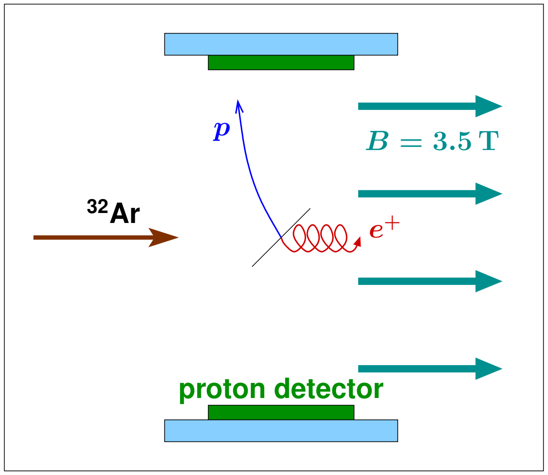

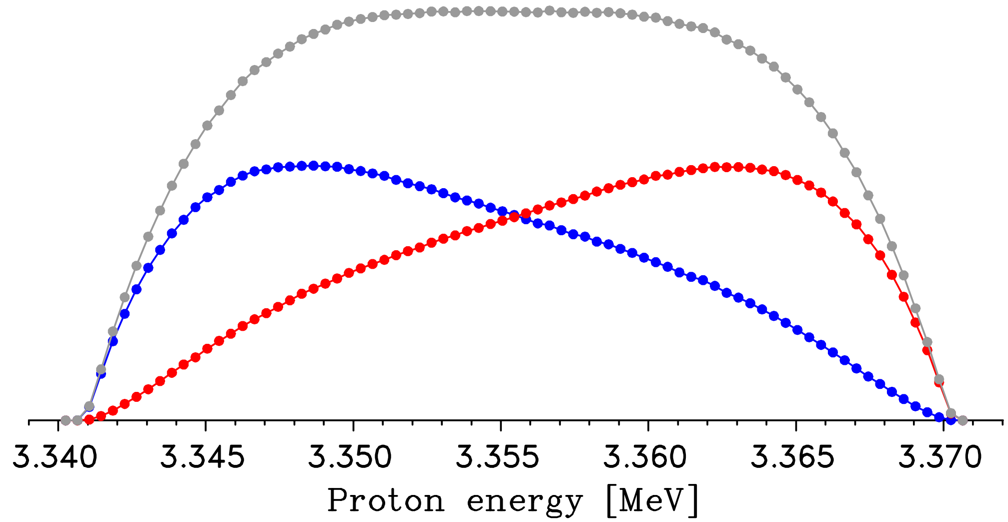

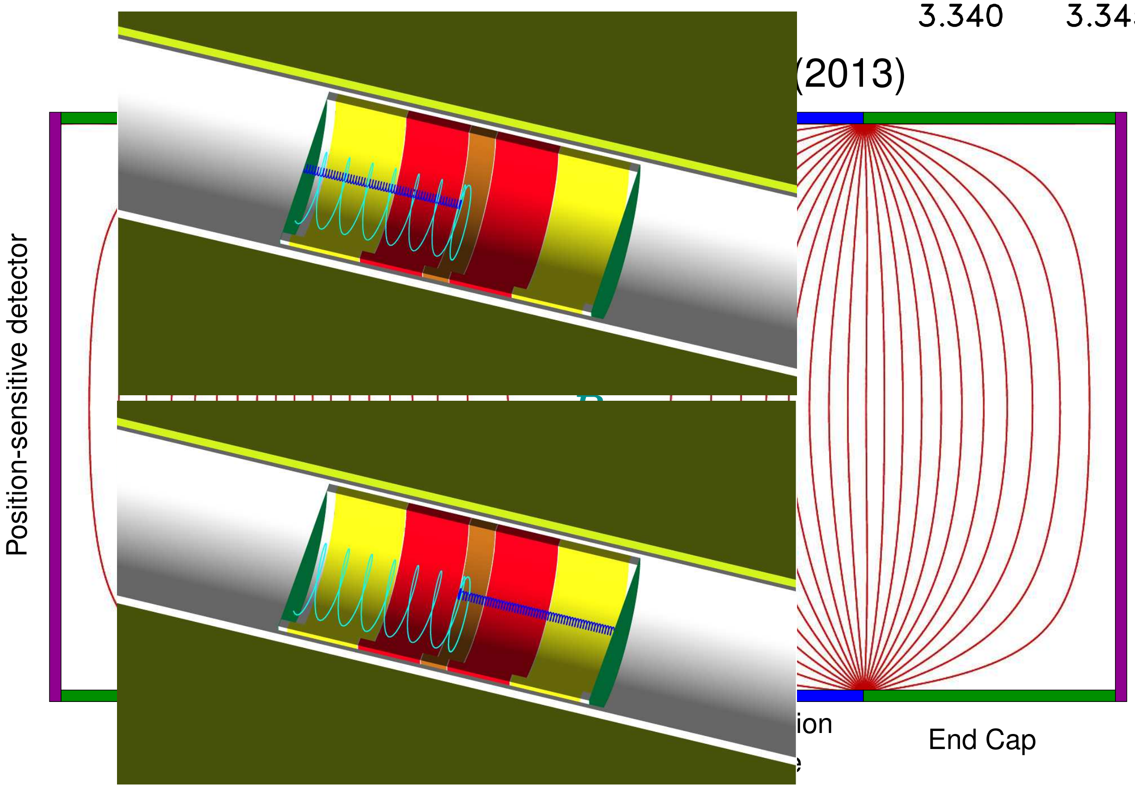

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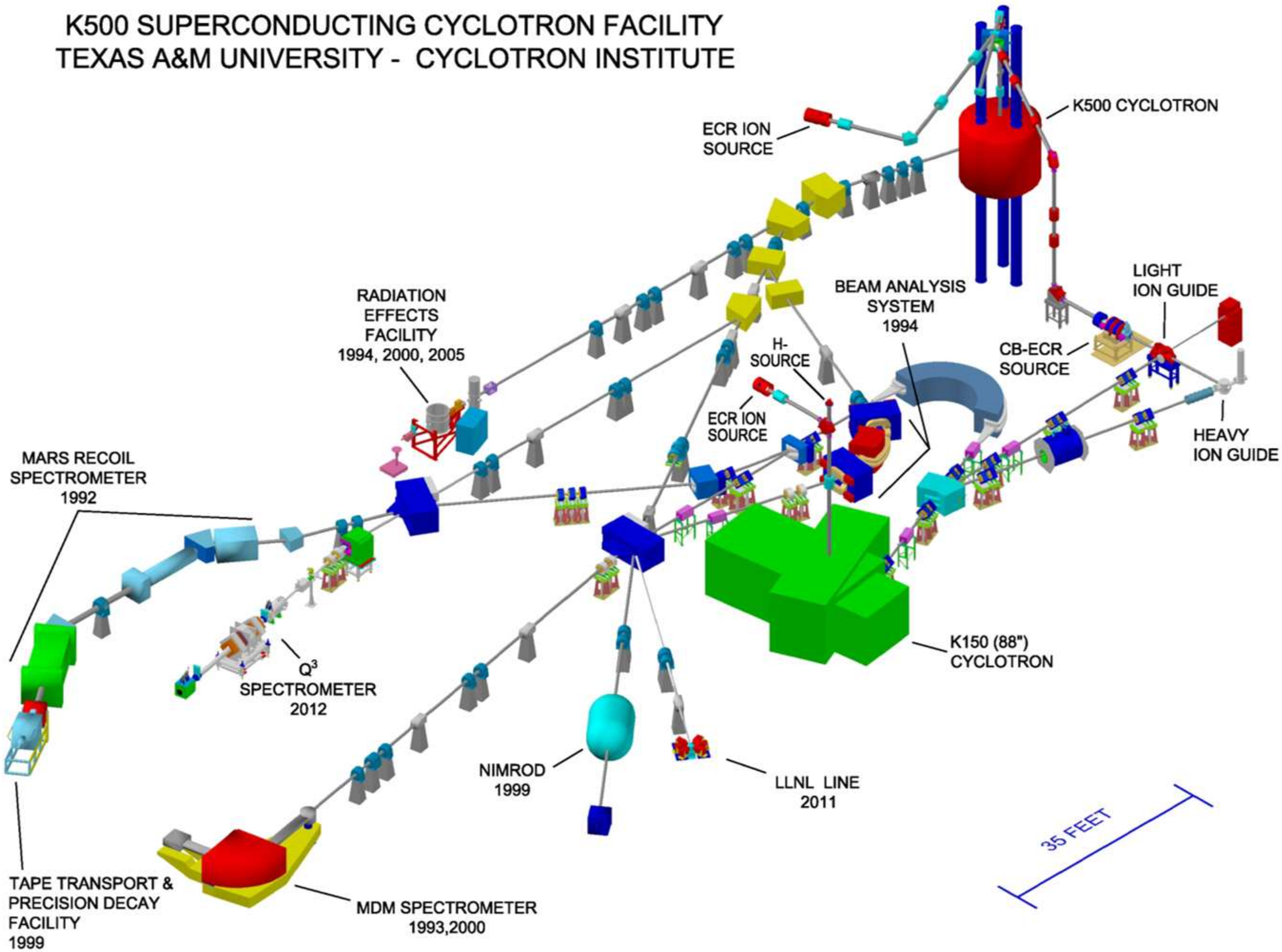
A Penning trap at T-REX CI/TAMU



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:

  β-ν correlations, ft values/V_{ud}
- also amendable to mass measurements, EC studies, laser spectroscopy, . . . ⟨insert your idea here⟩

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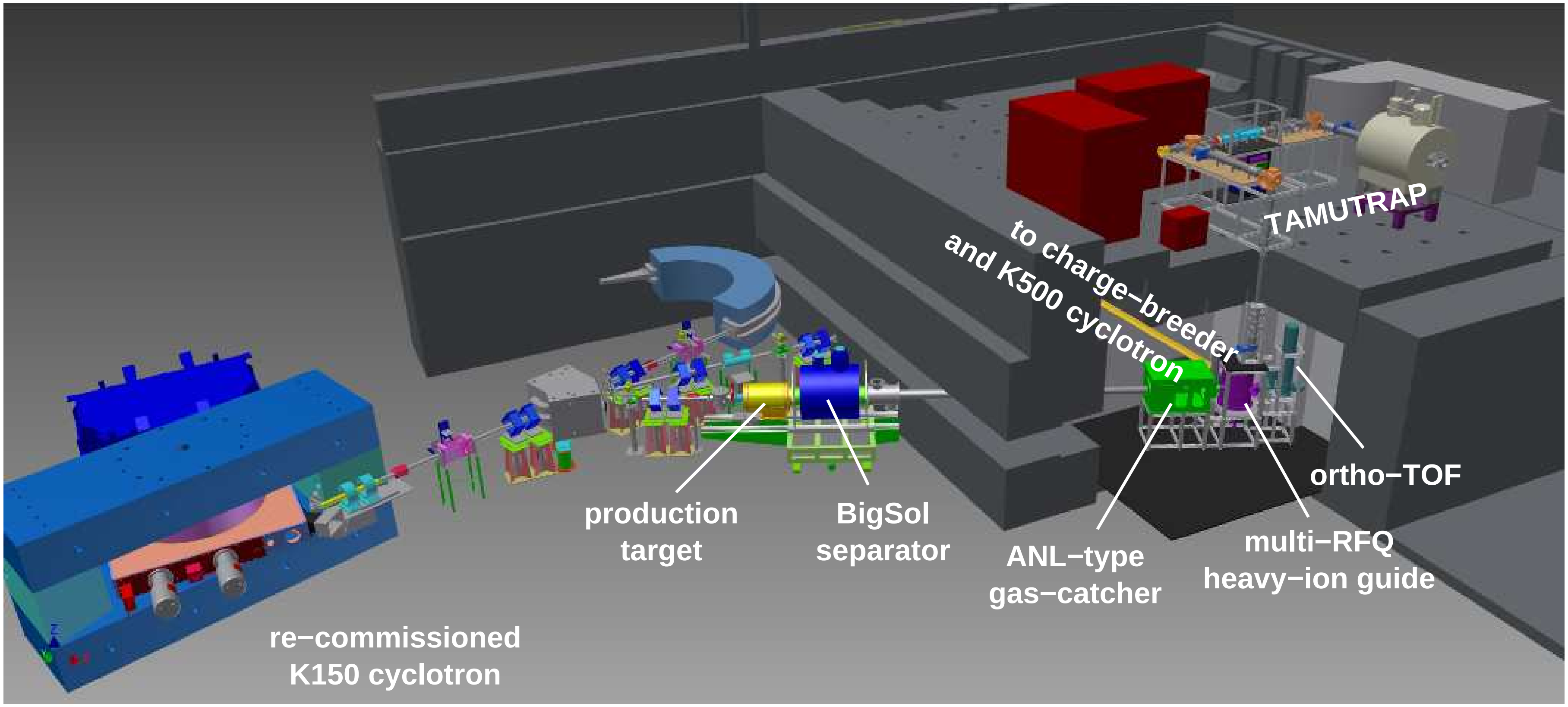

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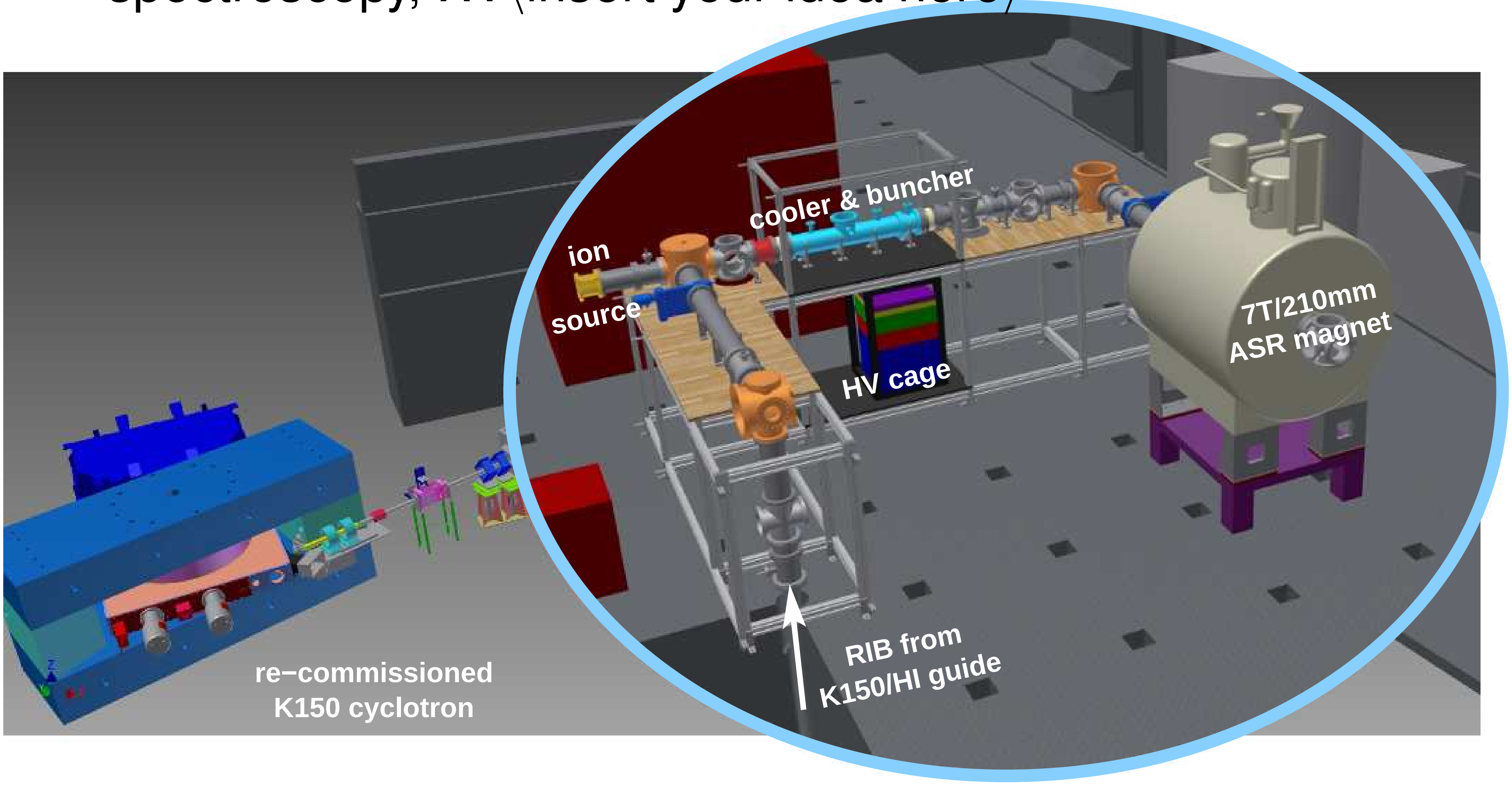

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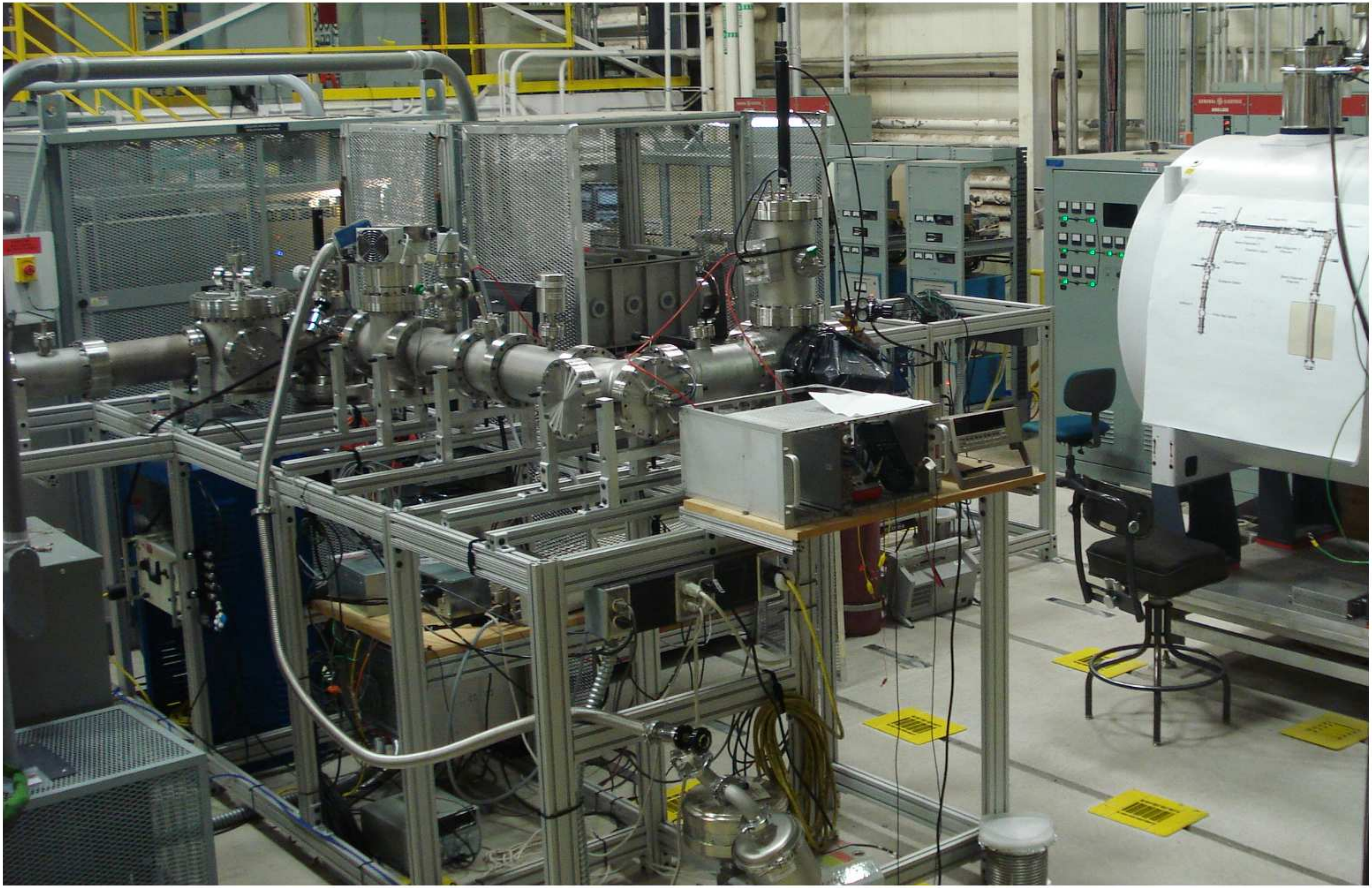

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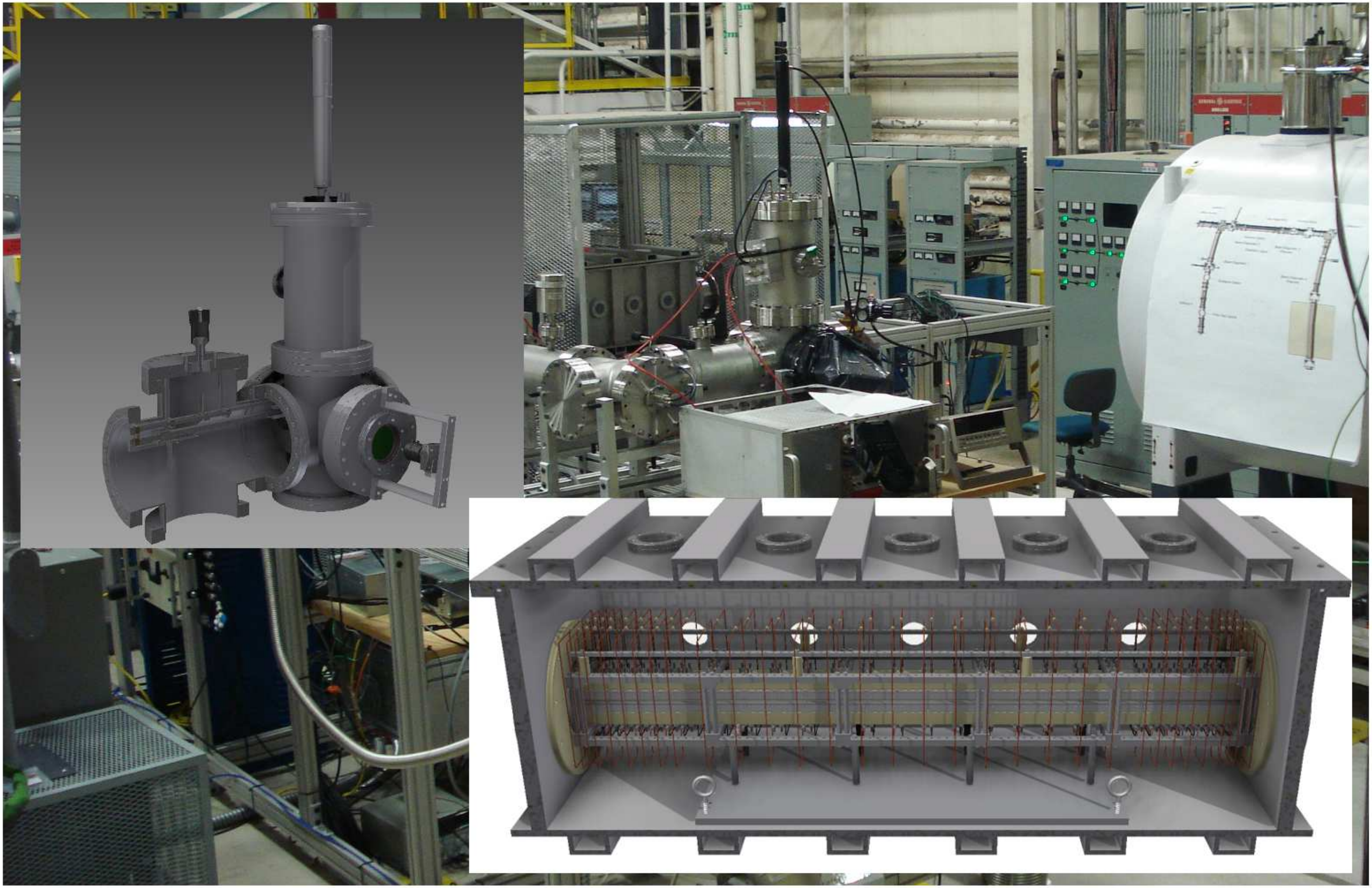

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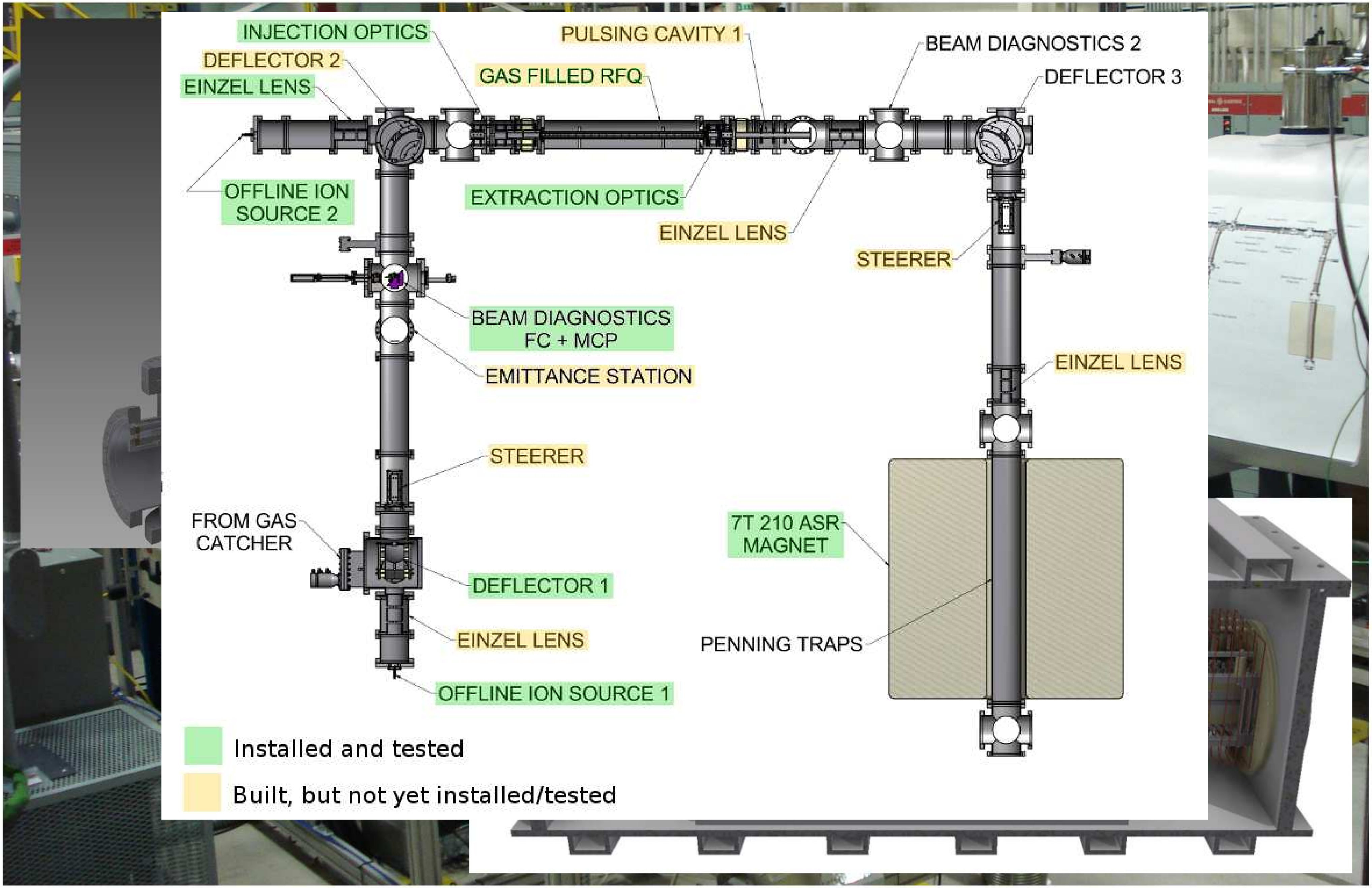

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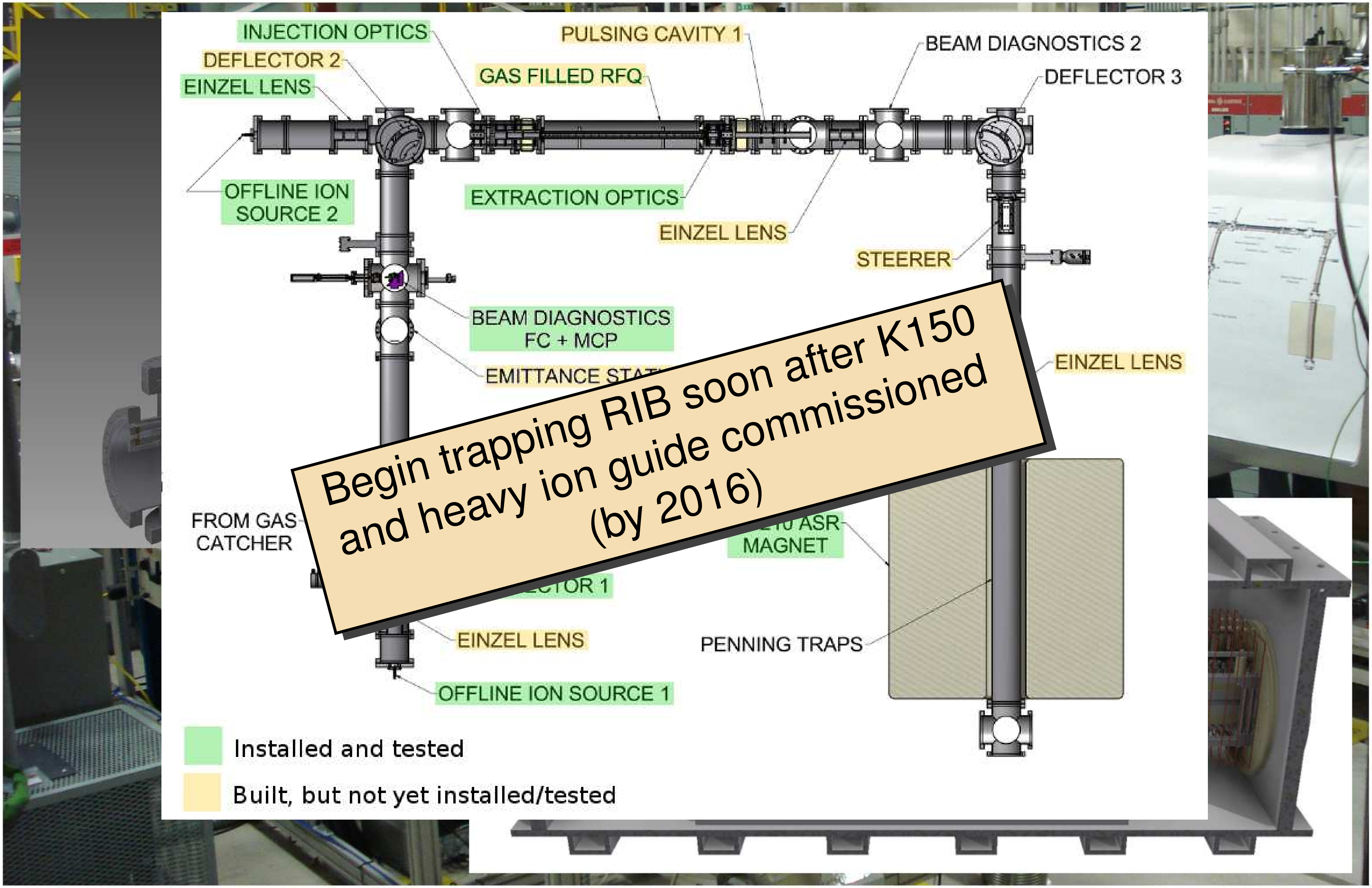

Begin trapping RIB soon after K150 and heavy ion guide commissioned (by 2016)

Overview

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   - **physics** of superallowed β decay
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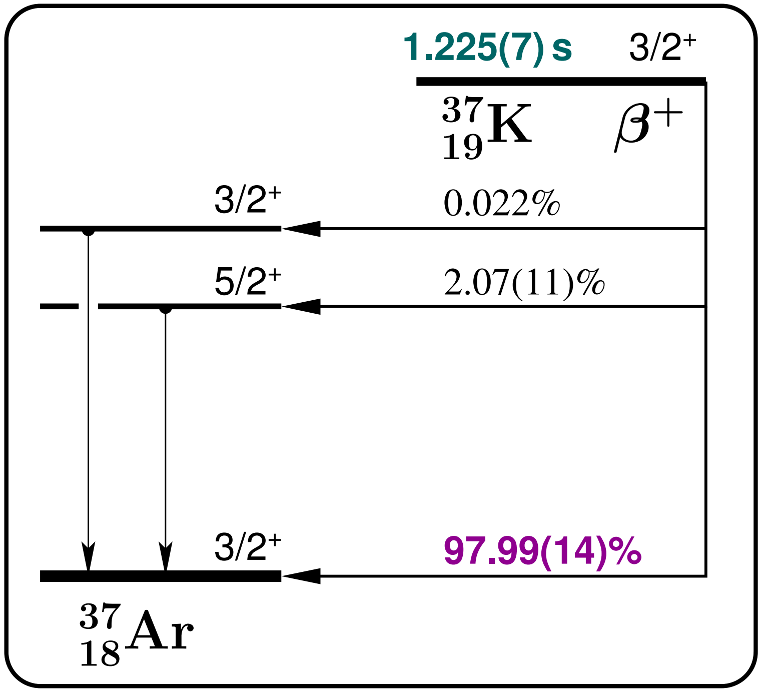

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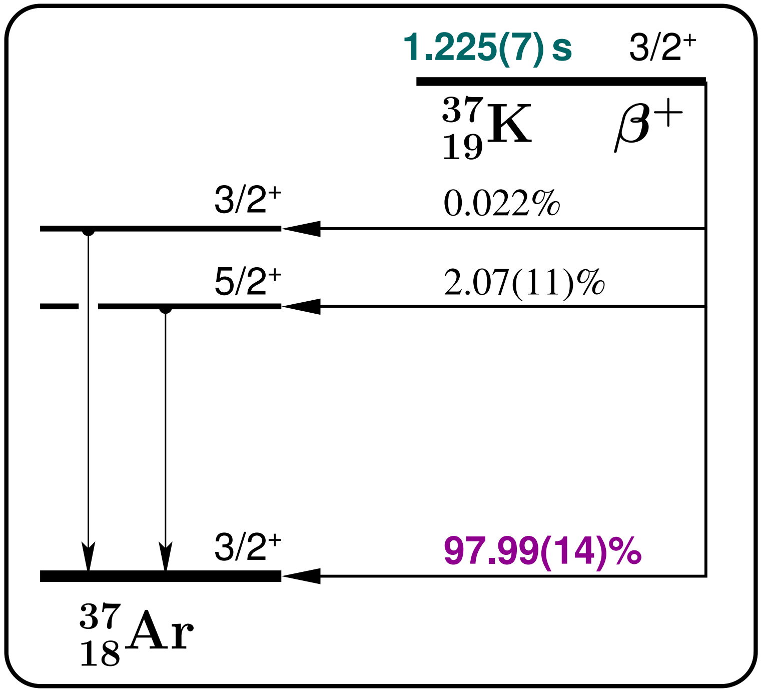

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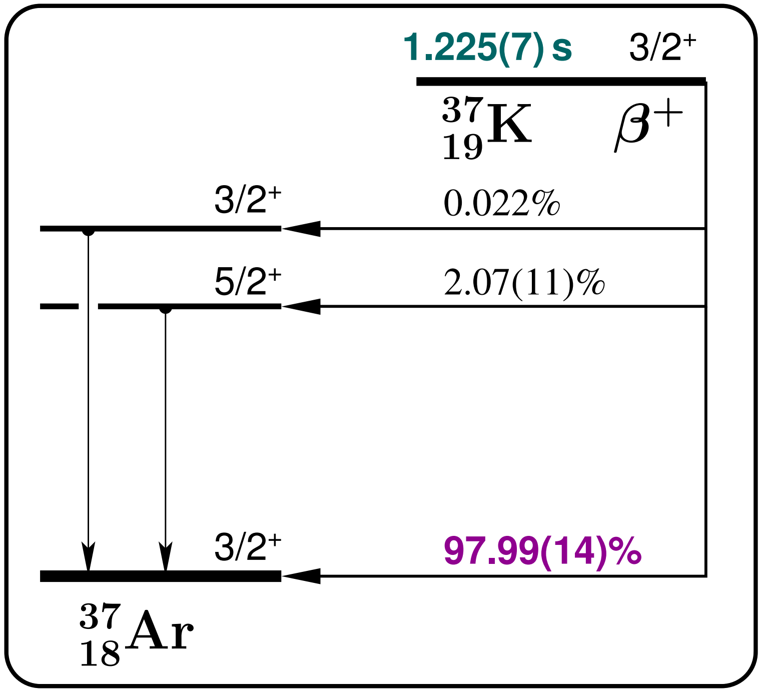

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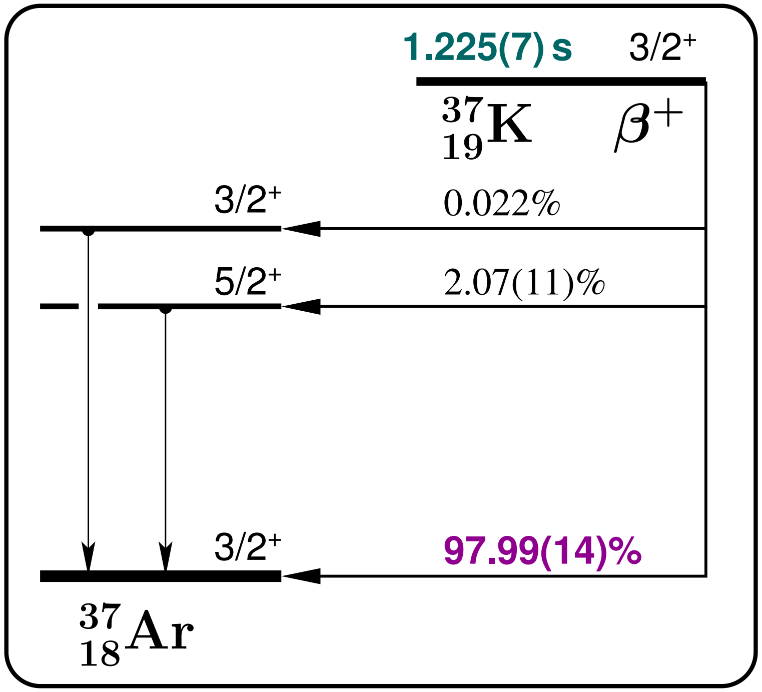

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$$\left.\begin{array}{l} Q_{EC}\text{: } \pm 0.003\% \\ BR\text{: } \pm 0.14\% \\ t_{1/2}\text{: } \pm \mathbf{0.57\%} \end{array}\right\} \mathcal{F}t = 4562(28) \quad \Rightarrow \quad \rho = 0.5874(\mathbf{71})$$

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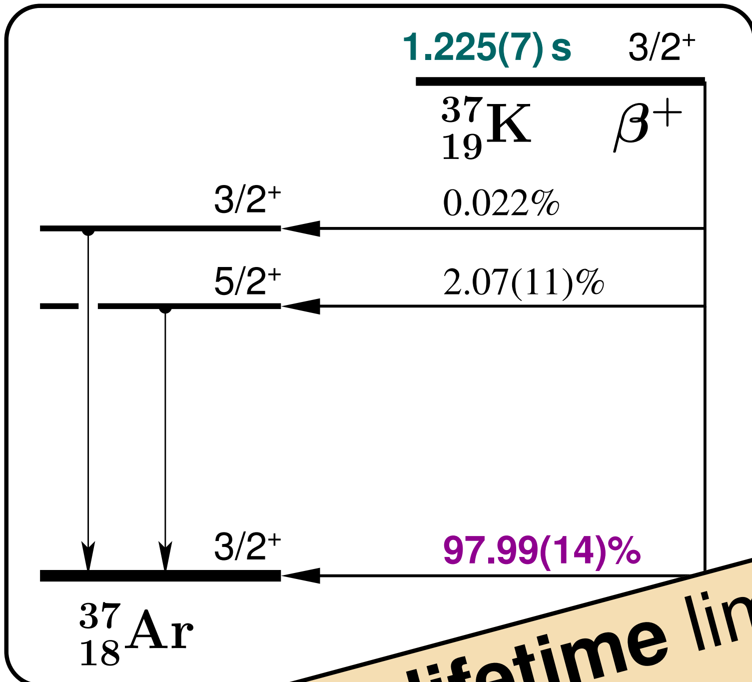

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$\Rightarrow$ nee... $M_{GT}/G_V M_F$

... for correla-

get ρ

$$\ldots - 1 \quad \mathcal{F}t$$

Q_{EC}:

BR: ...%

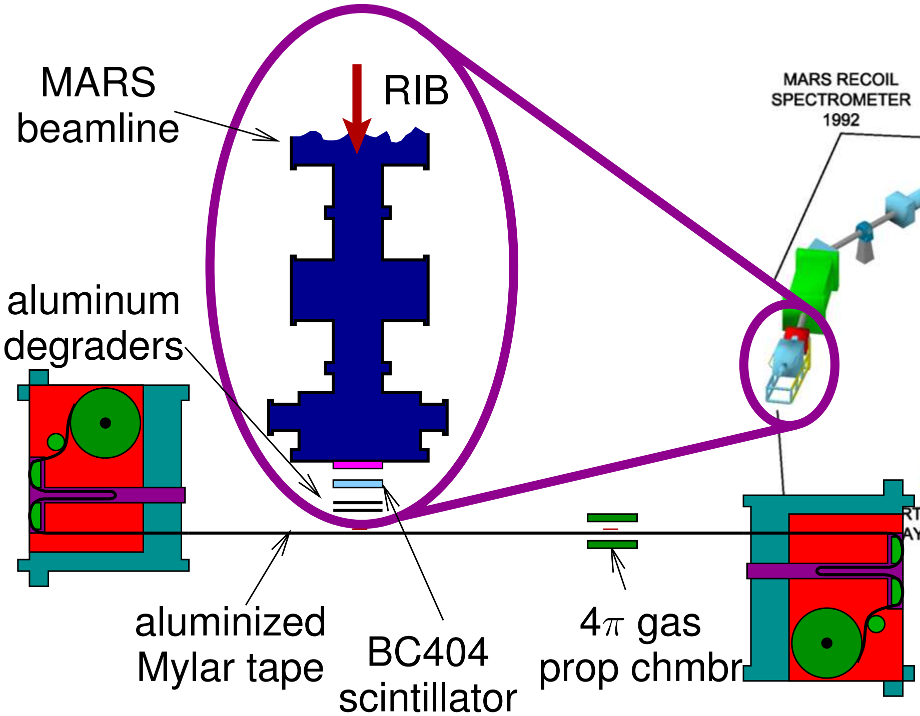
$t_{1/2}$: $\pm$**0.57%**

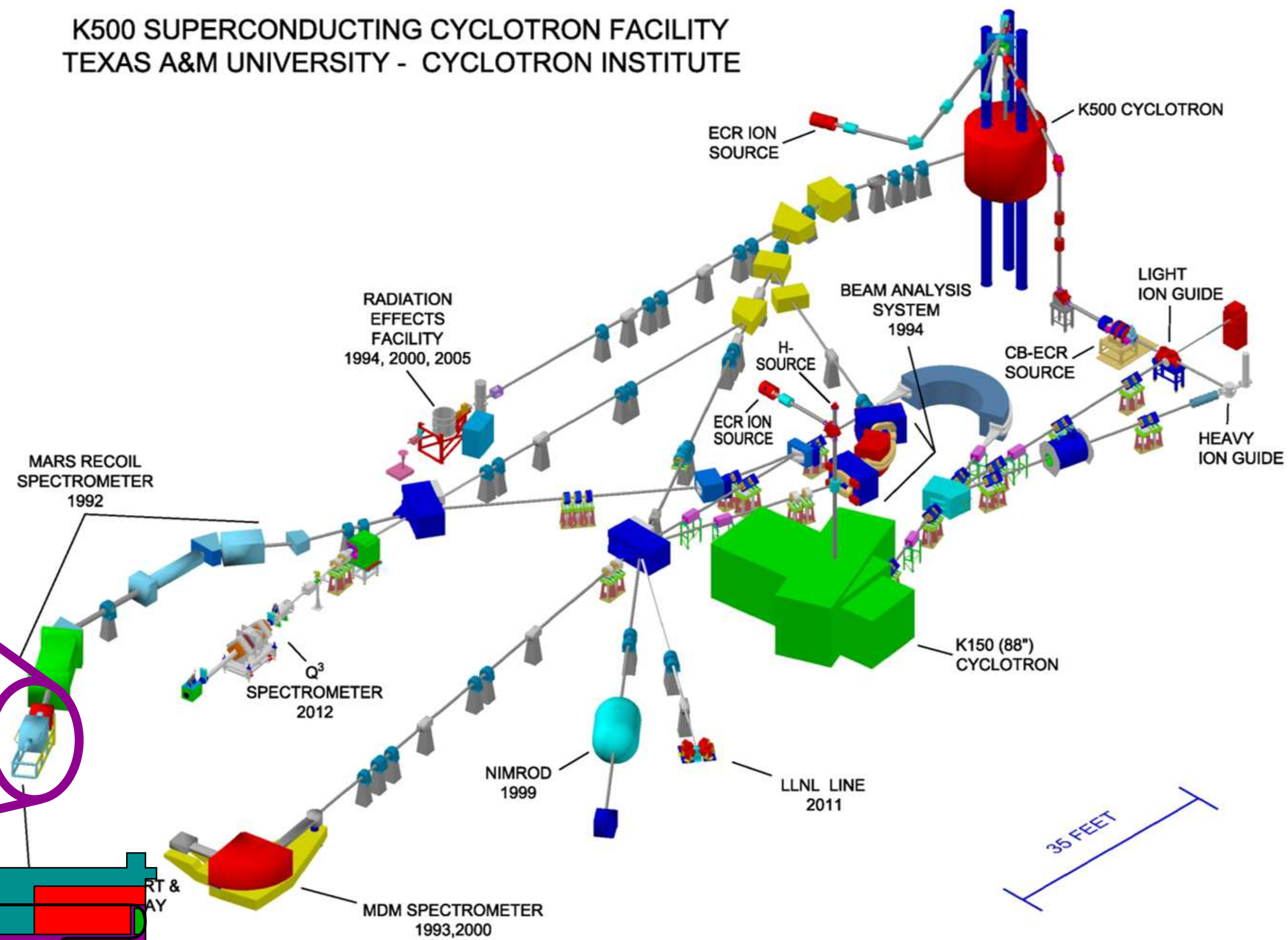
$\mathcal{F}t = 4562(28) \Rightarrow \rho = 0.5874(\mathbf{71})$

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

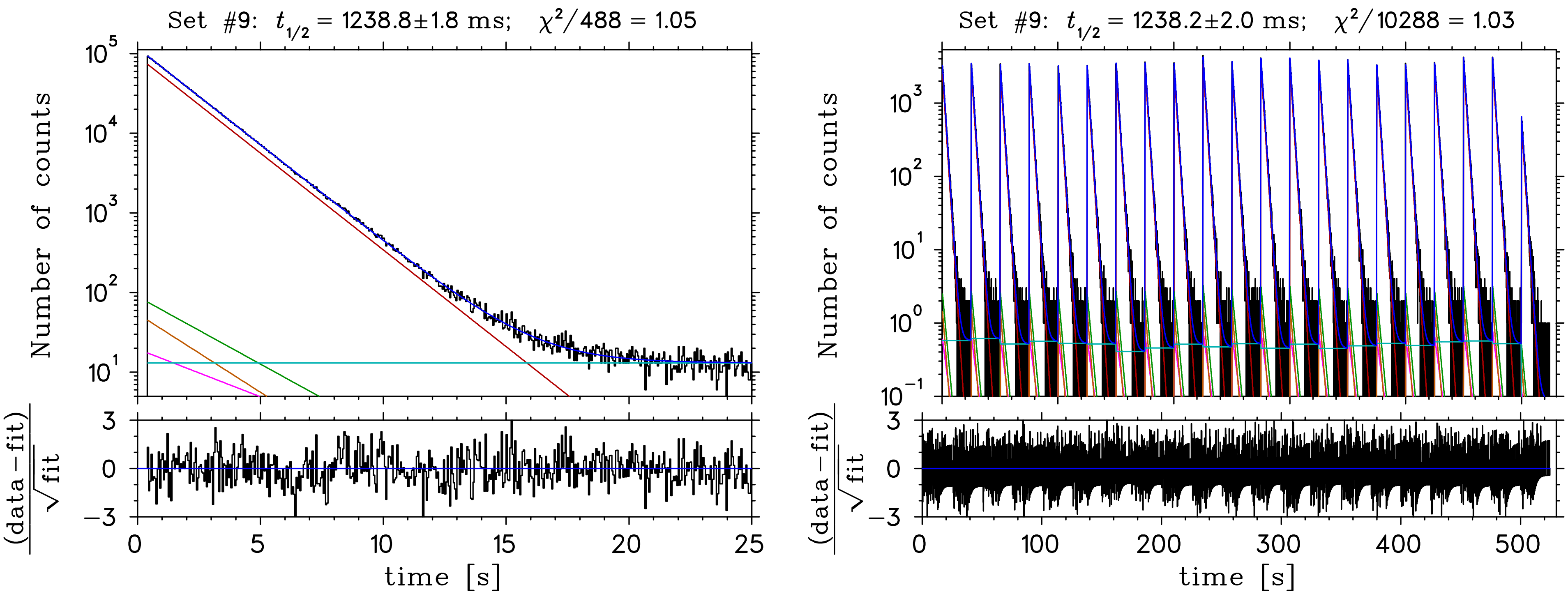
Measuring the lifetime at the CI

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





Improving the lifetime



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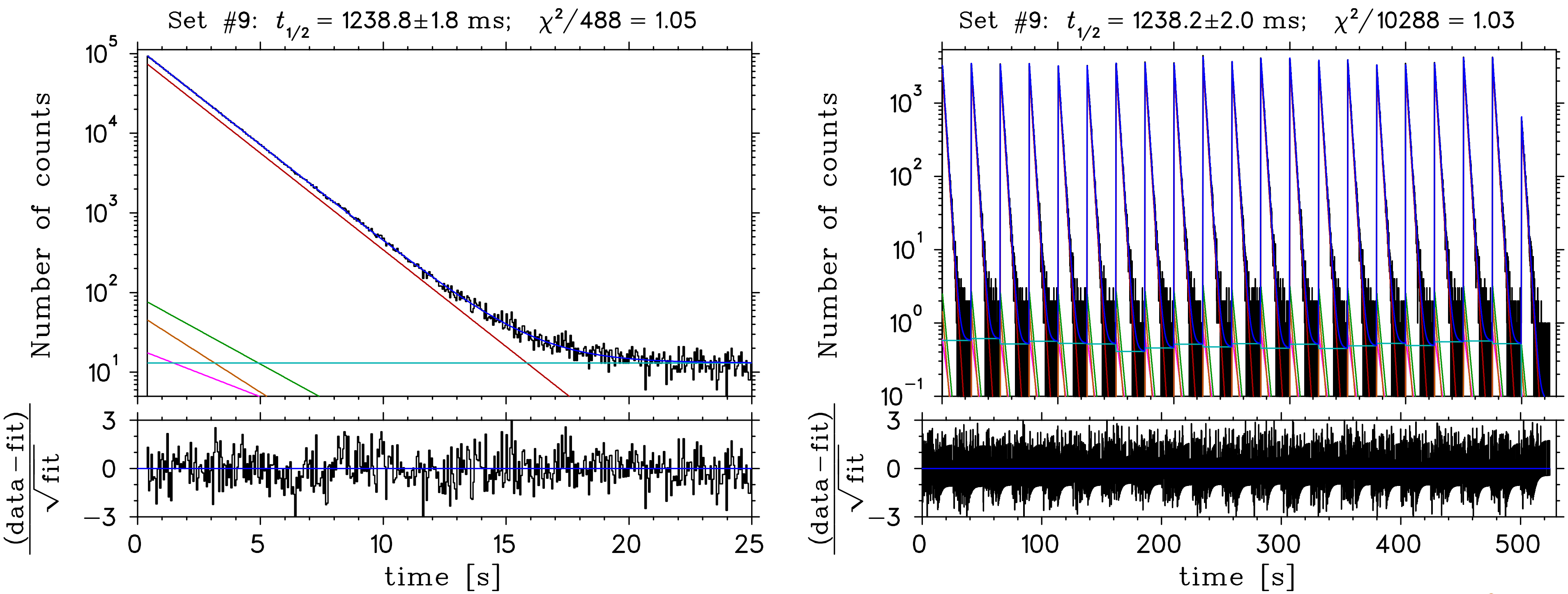

nearly a $10\times$ improvement: $t_{1/2} = 1236.51 \pm 0.47 \pm 0.83$ ms

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

and $\Delta\rho = 1.2\% \longrightarrow$ **0.4%**

P. Shidling *et al.*, Phys Rev C (R), in press

arXiv:1407.1742

Branching ratio — analysis just starting

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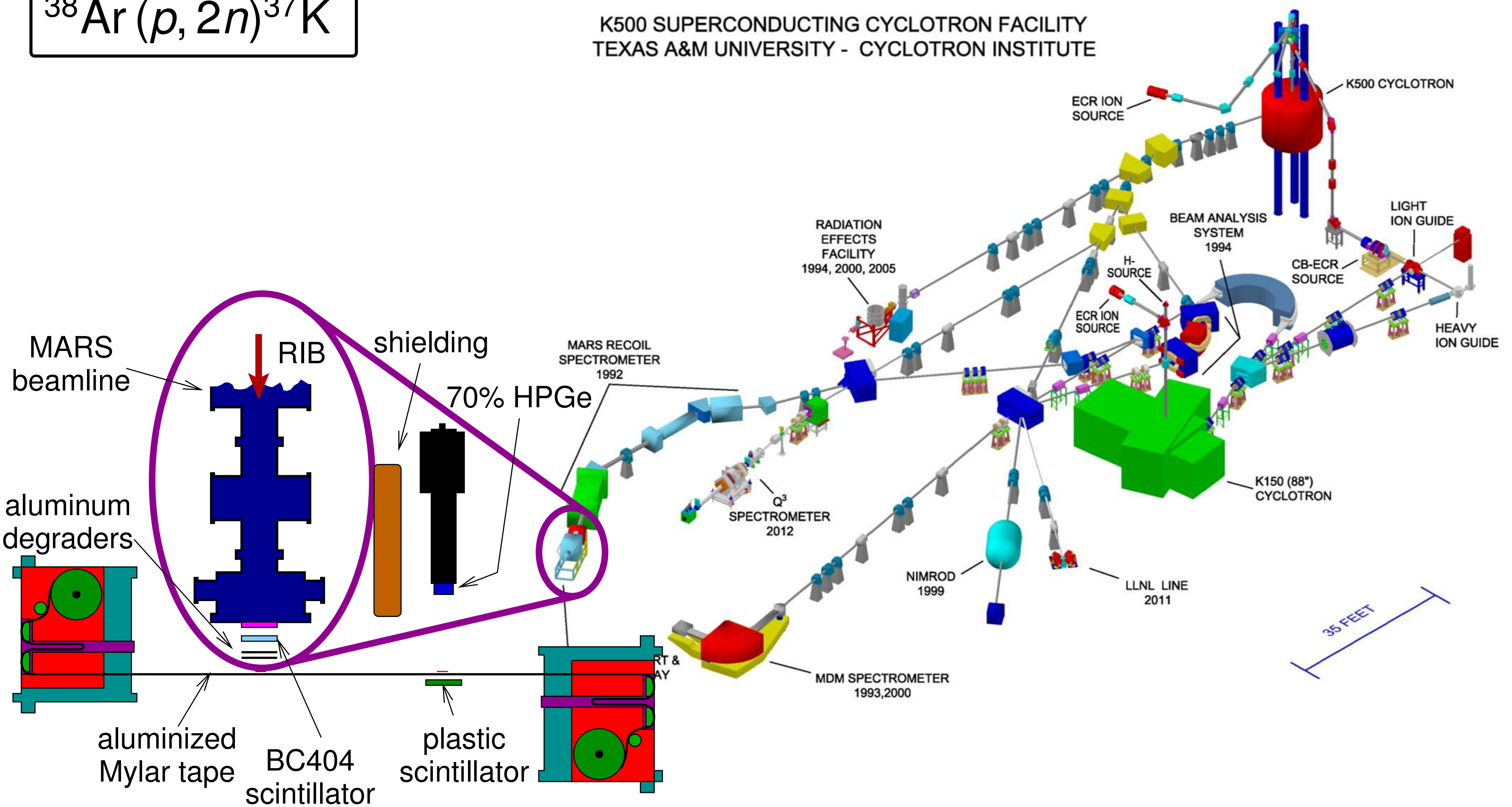

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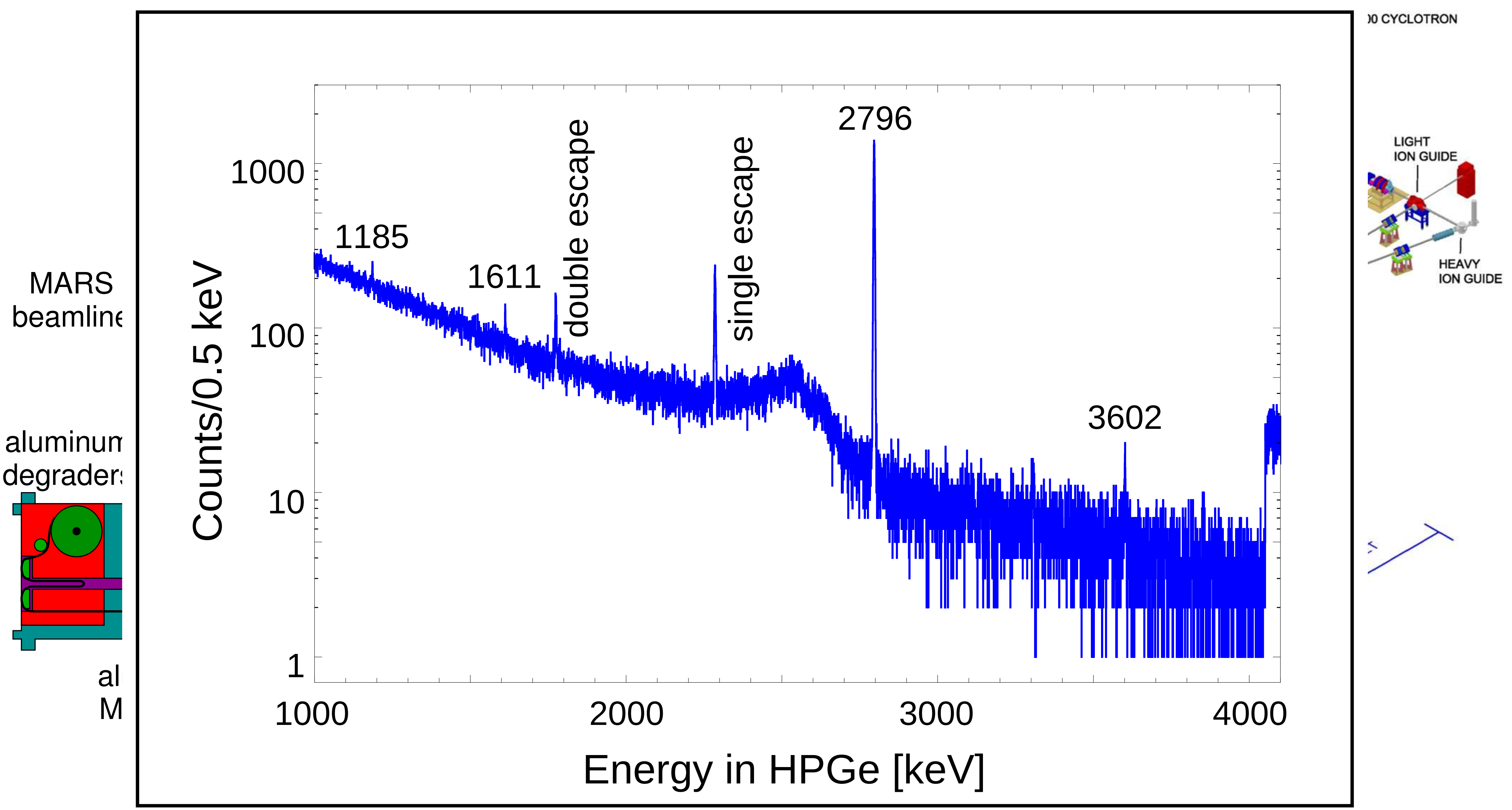
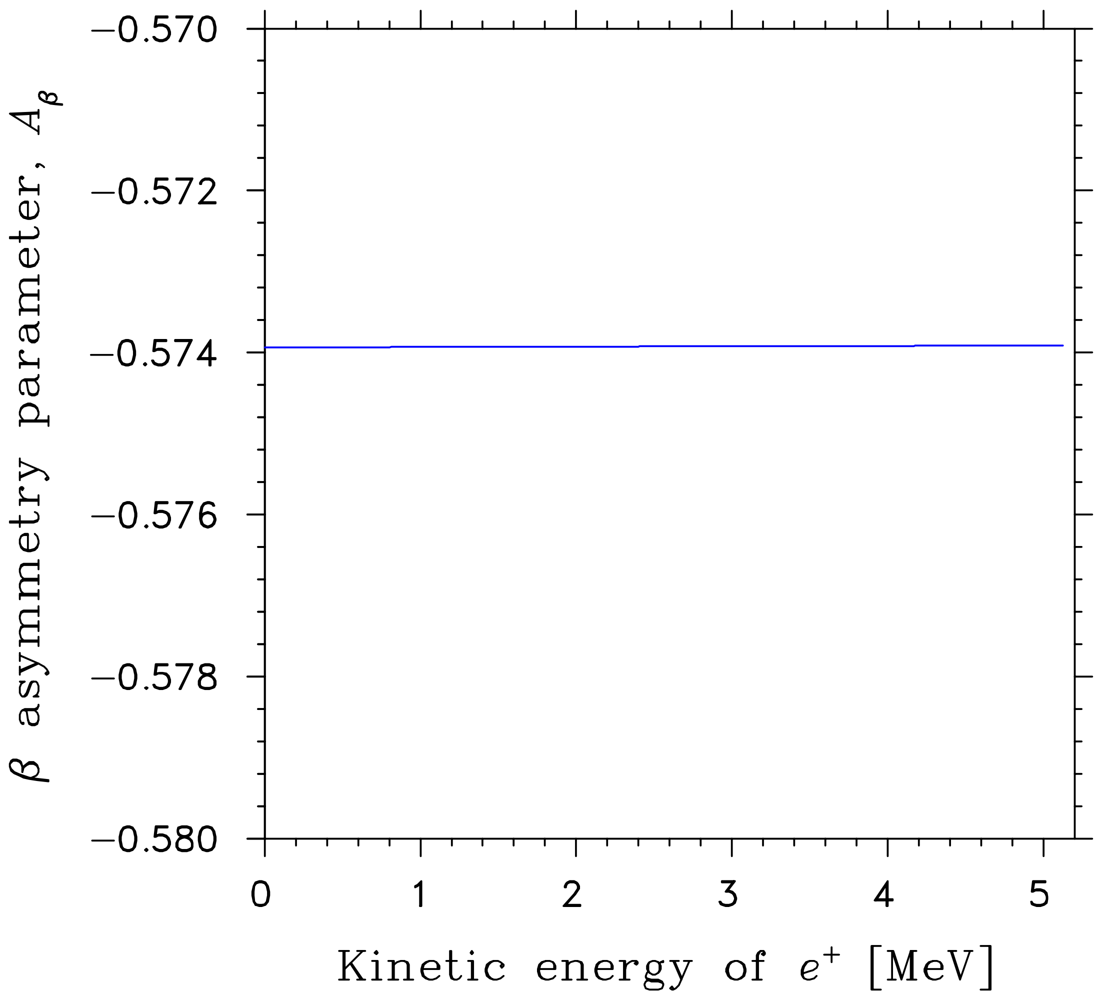
K500 SUPERCONDUCTING CYCLOTRON FACILITY
TEXAS A&M UNIVERSITY - CYCLOTRON INSTITUTE



What can we learn, e.g. from A_β?

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



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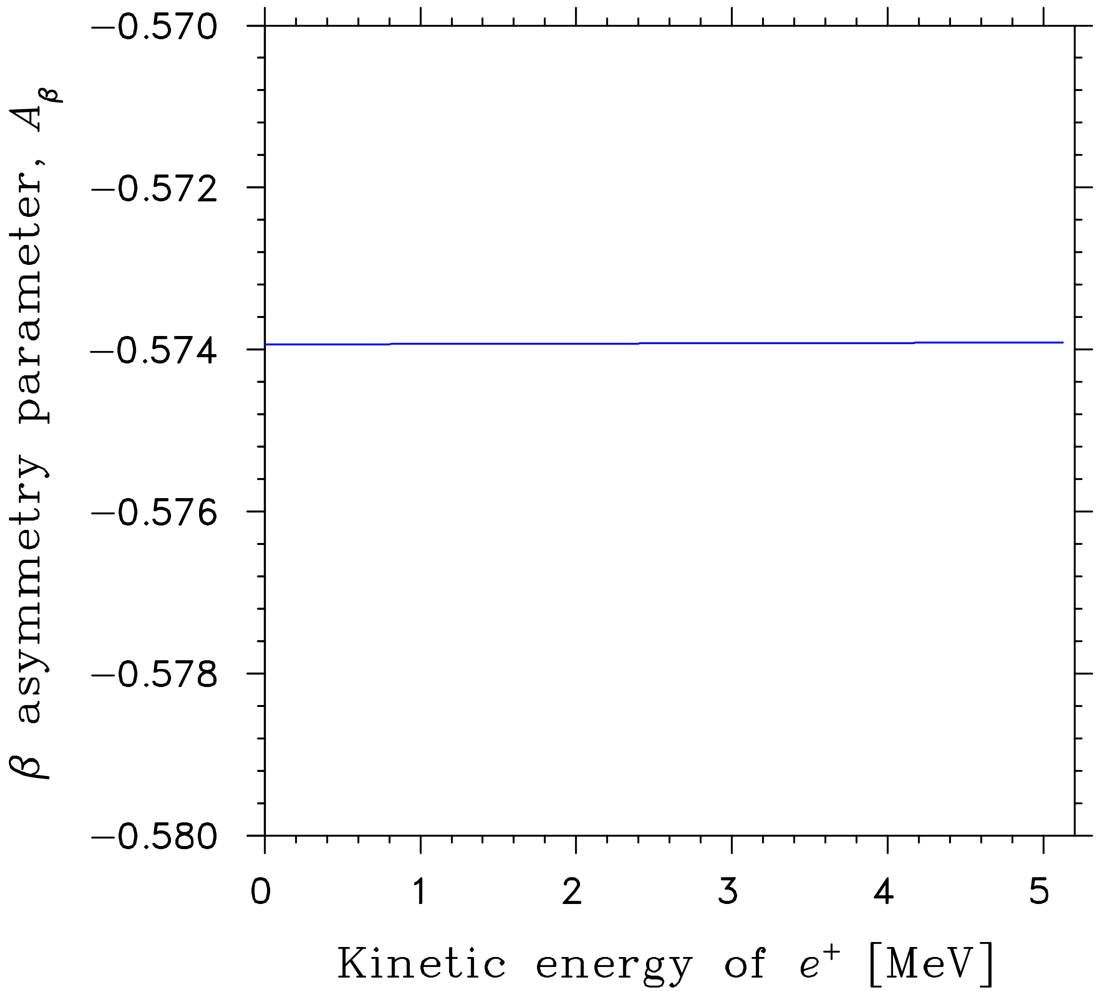

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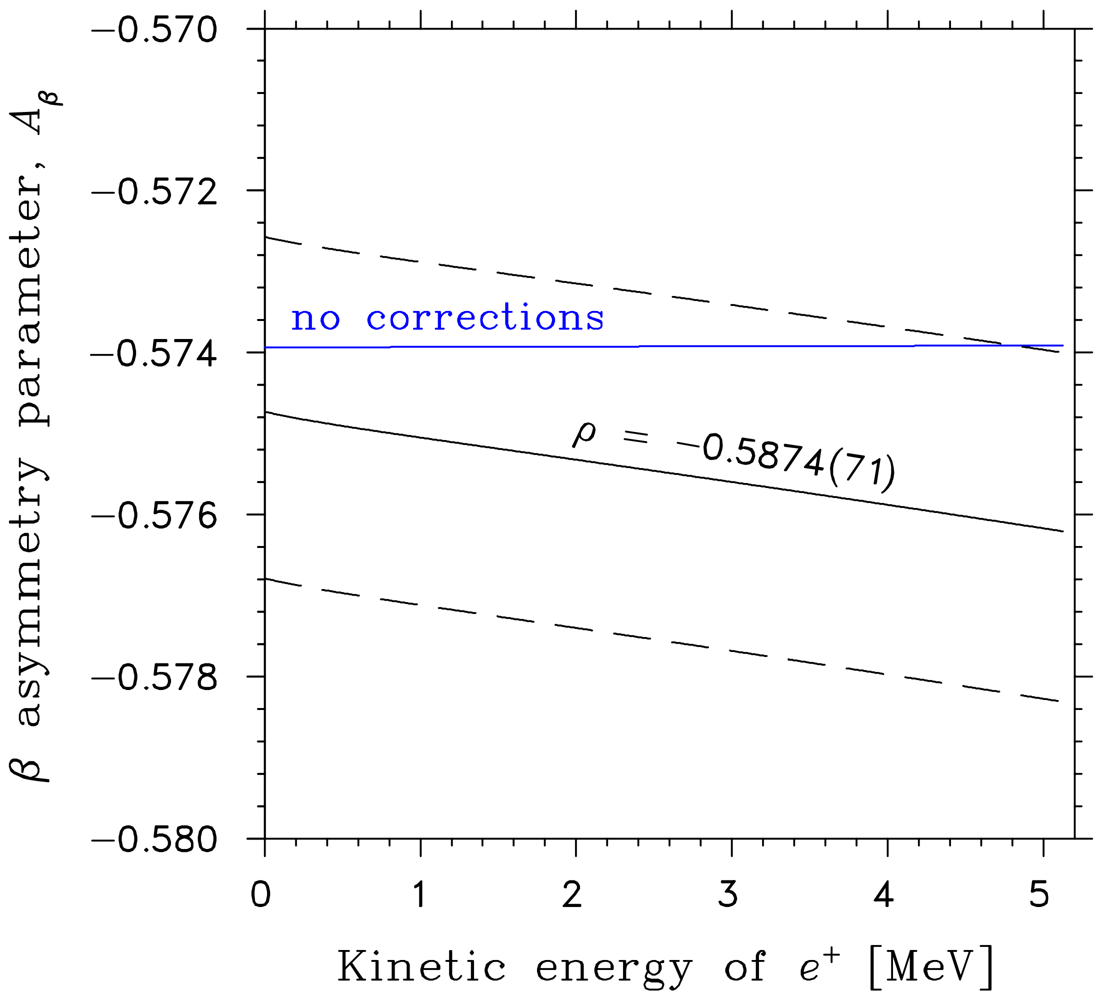

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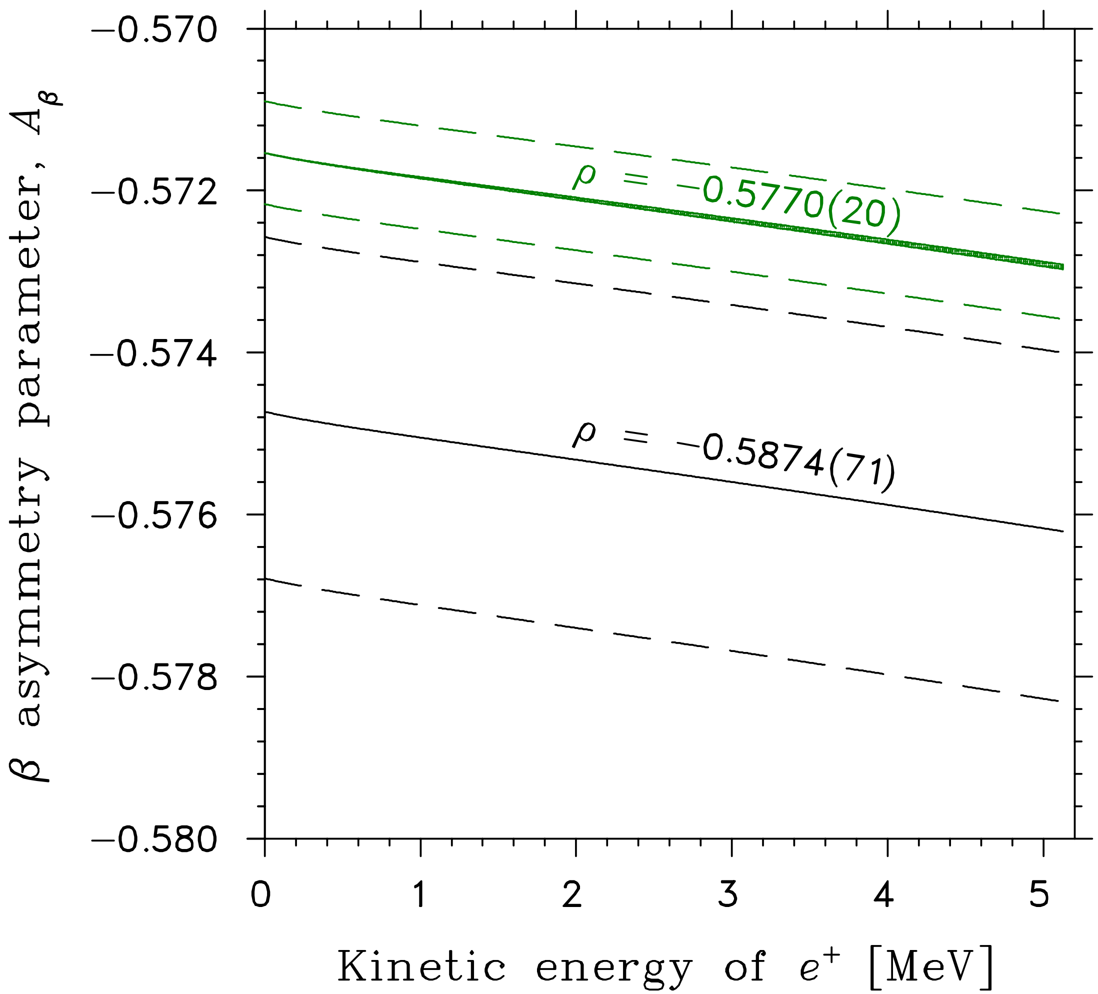

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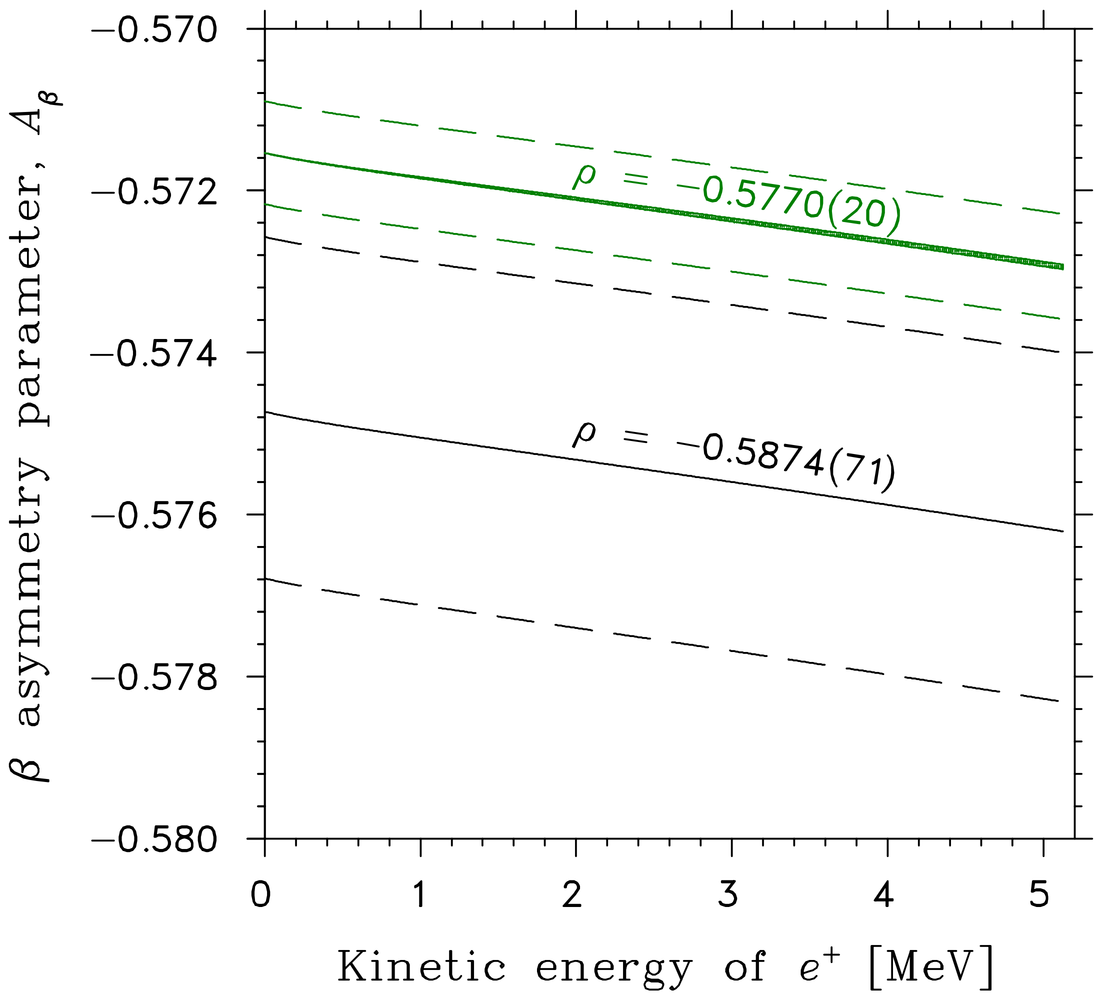

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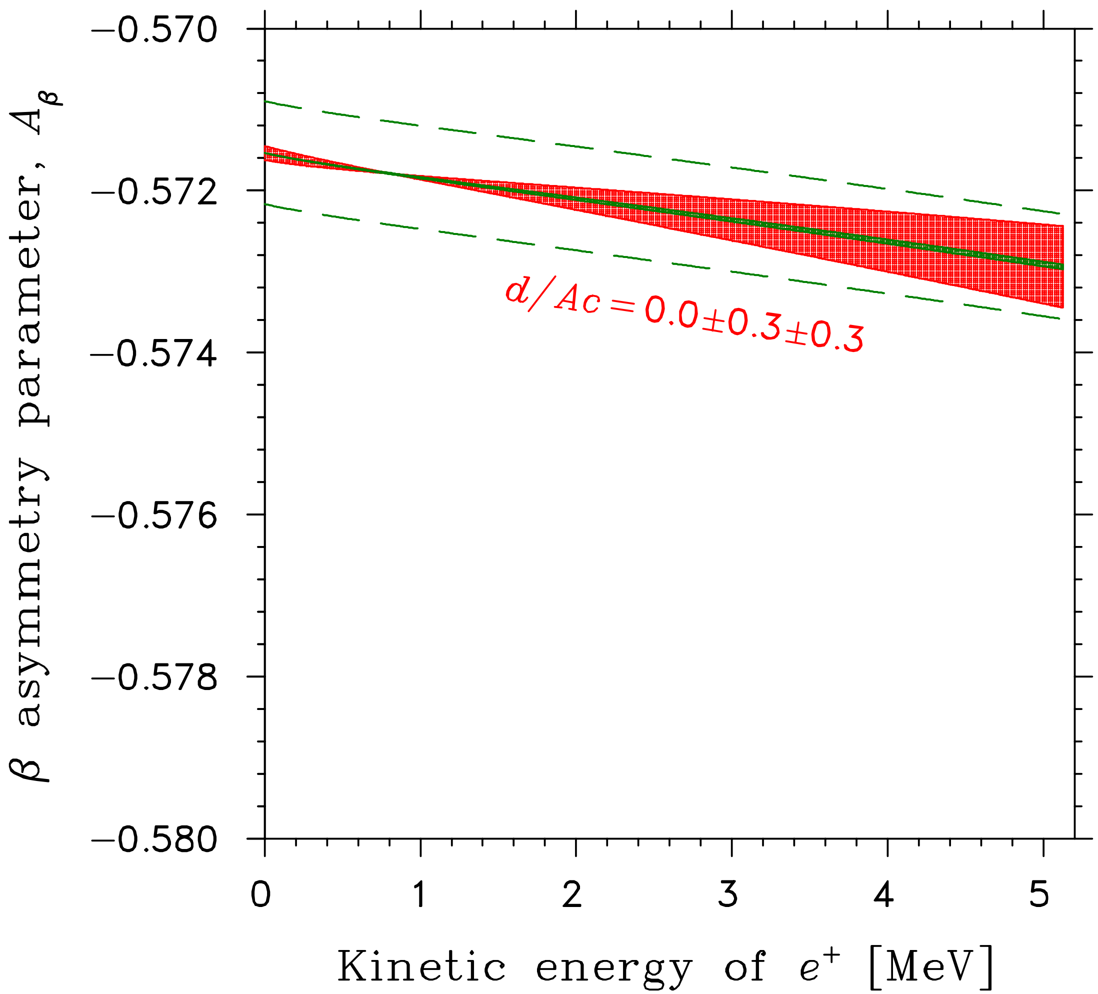

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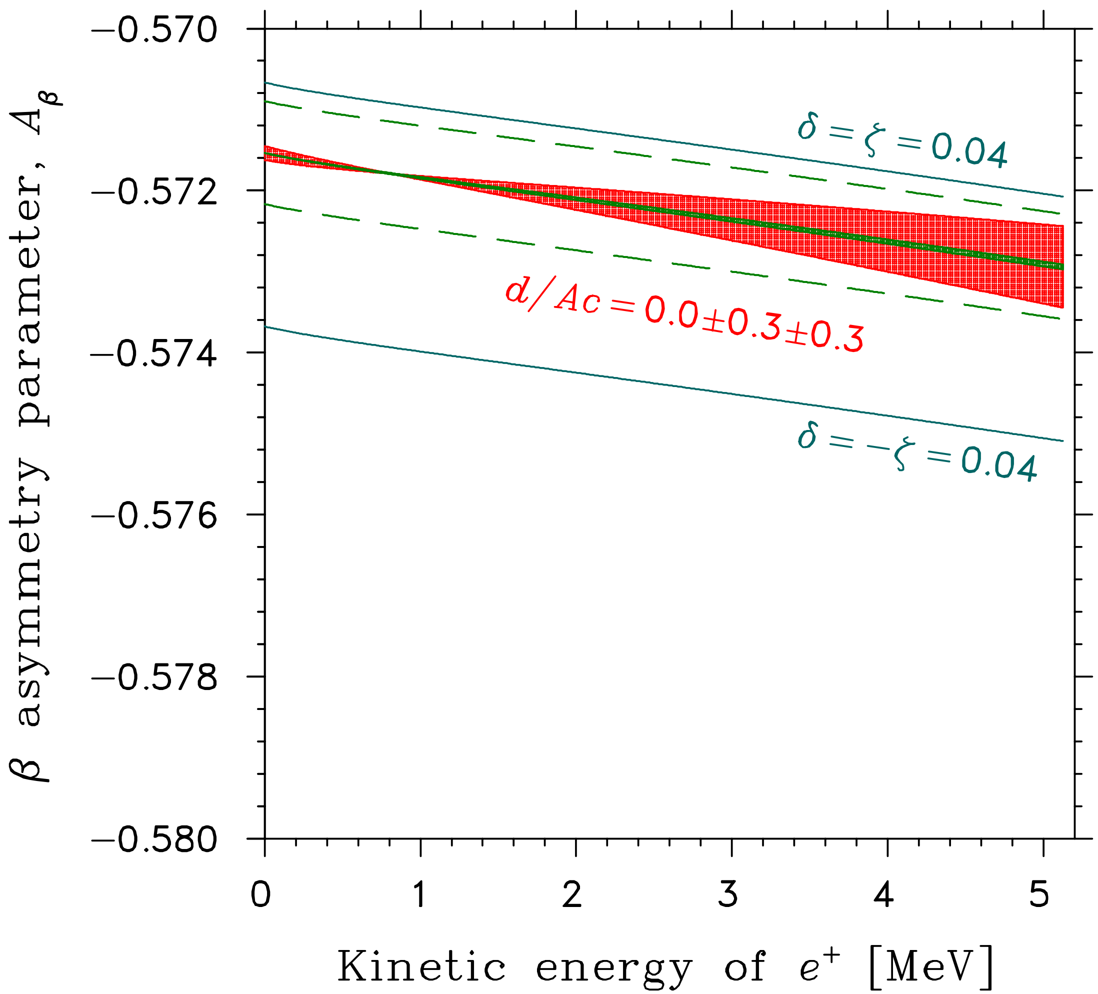

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- laser-cooling and trapping (magneto-optical traps)
- sub-level state manipulation (optical pumping)
- characterization/diagnostics (photoionization)

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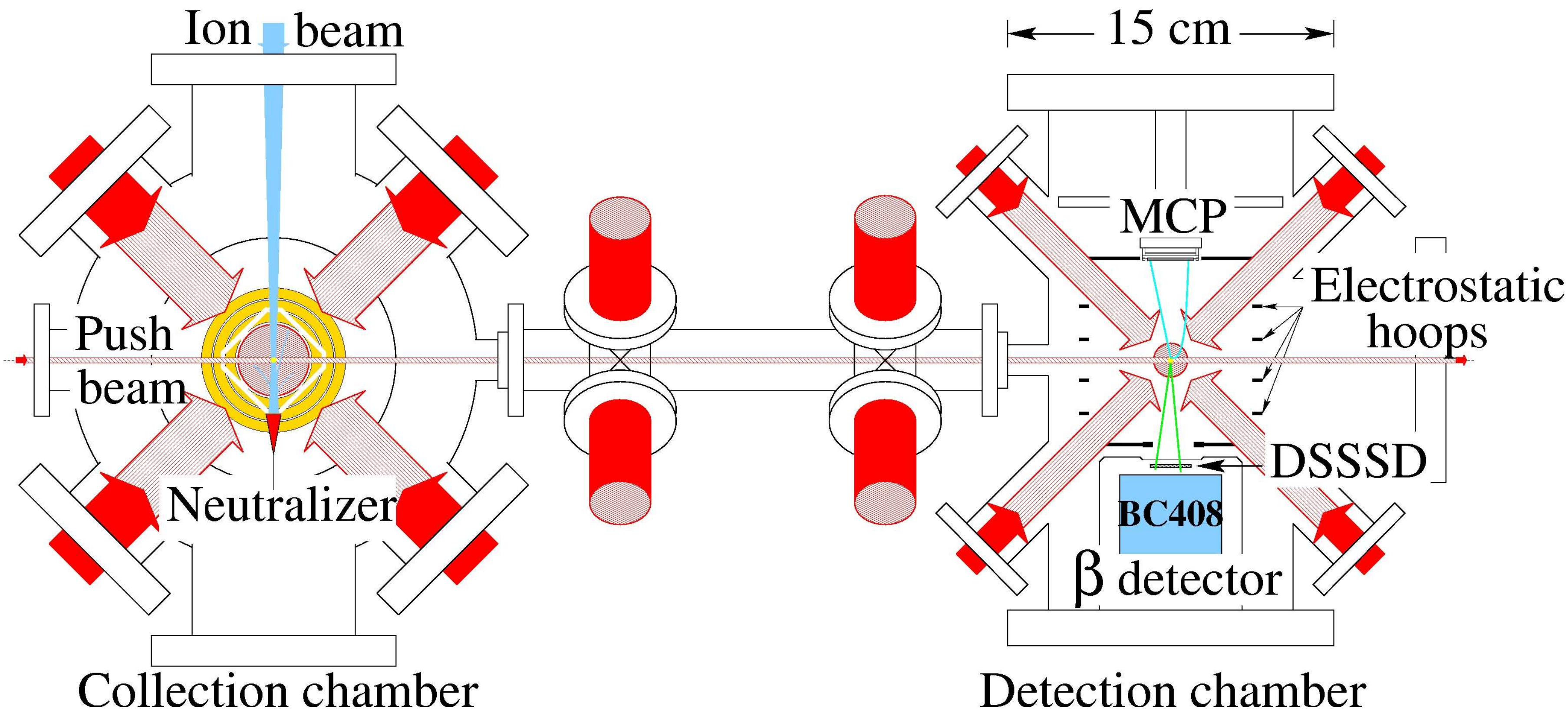

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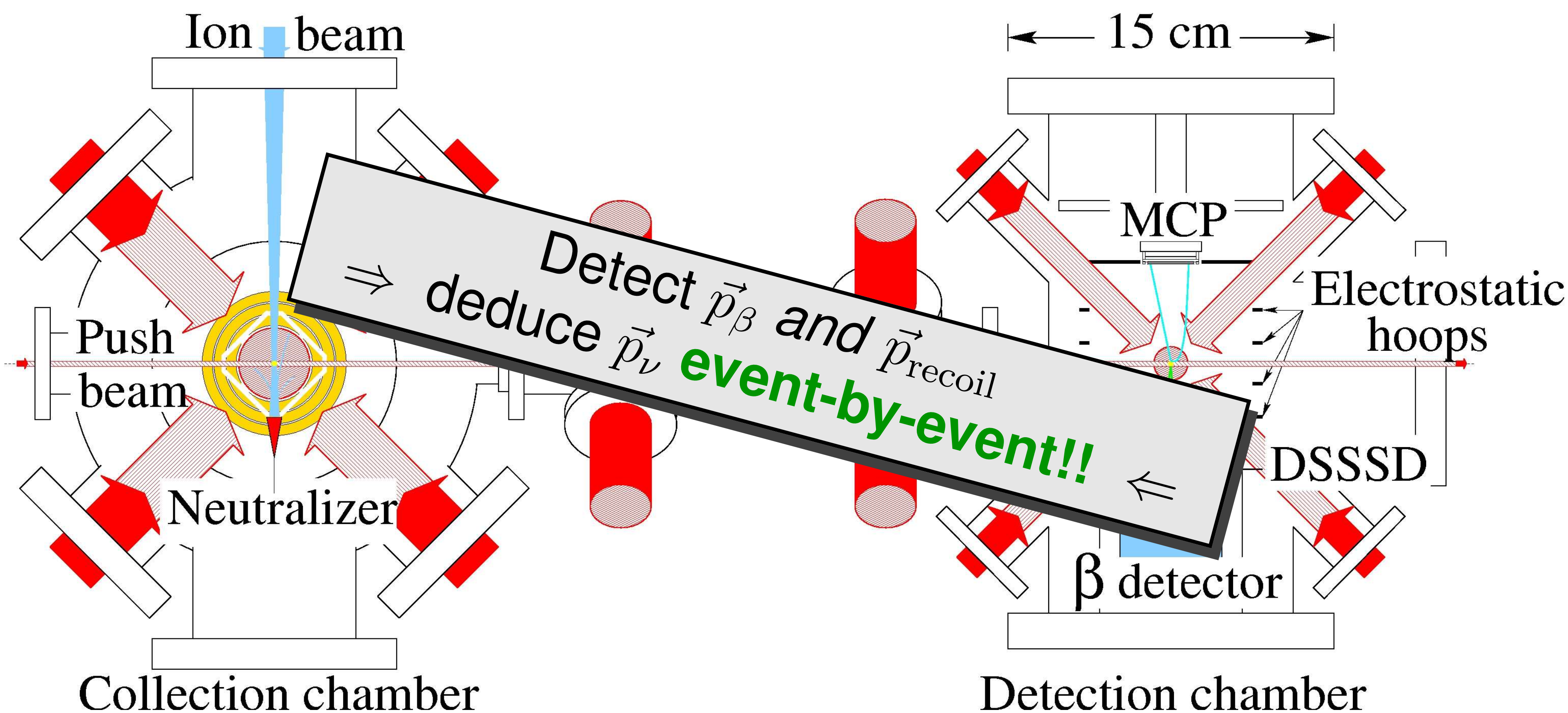

Detect $\vec{p}_\beta$ and $\vec{p}_{recoil}$ $\Rightarrow$ deduce $\vec{p}_\nu$ event-by-event!! $\Leftarrow$

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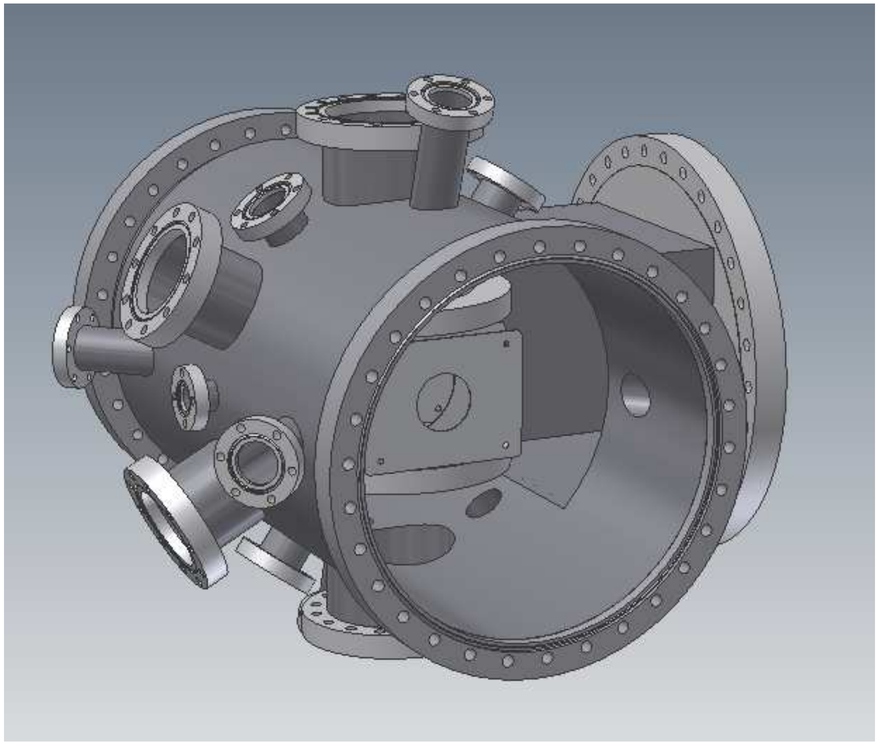
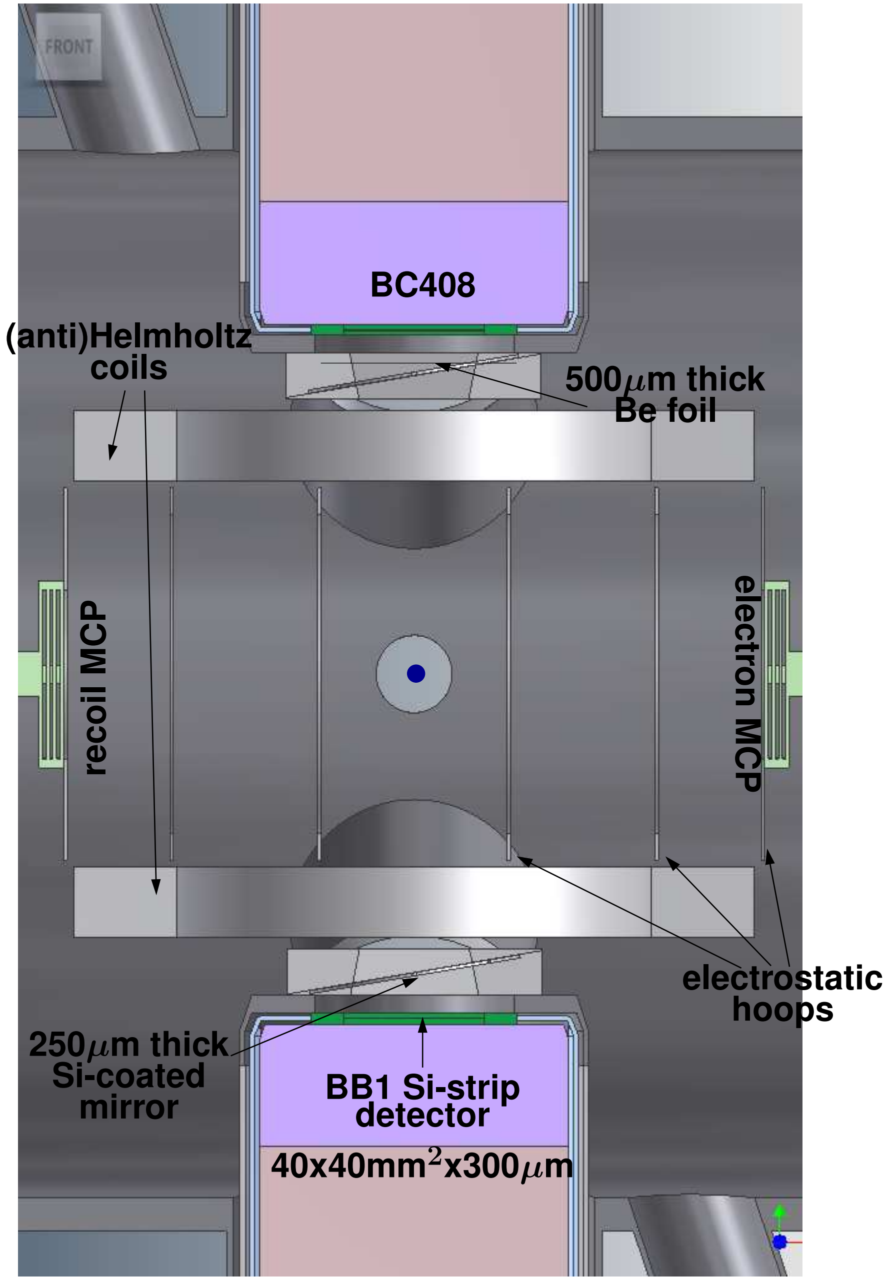
Highlights of the measurement trap



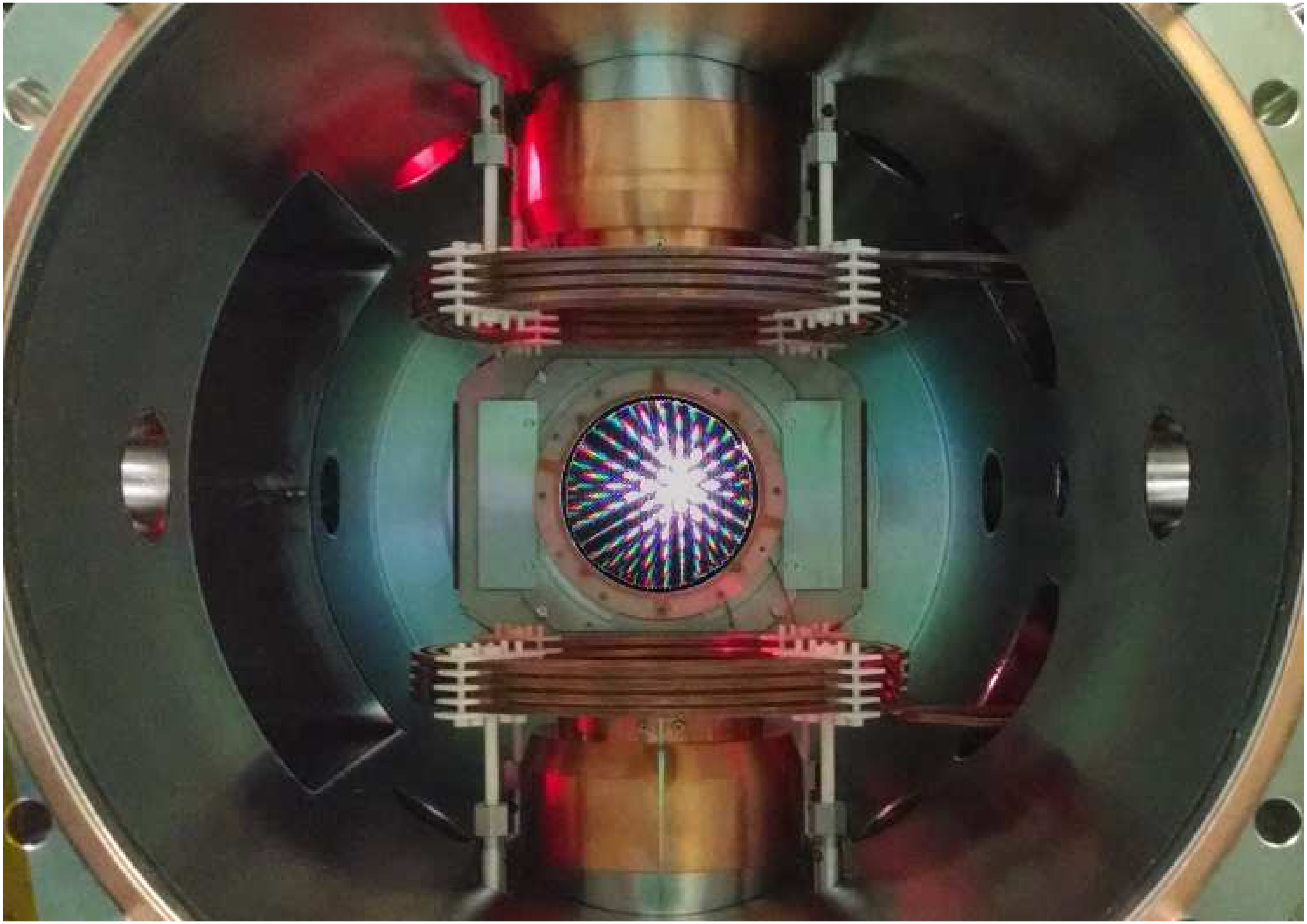


- $B_{\text{quad}} \rightarrow B_{\text{OP}}$ quickly: AC-MOT (Harvery & Murray, PRL **101** (2008))

- Better control of laser beams
- Shake-off e^- detection
- Increased β/recoil solid angles

⋮

Outline of polarized experiment



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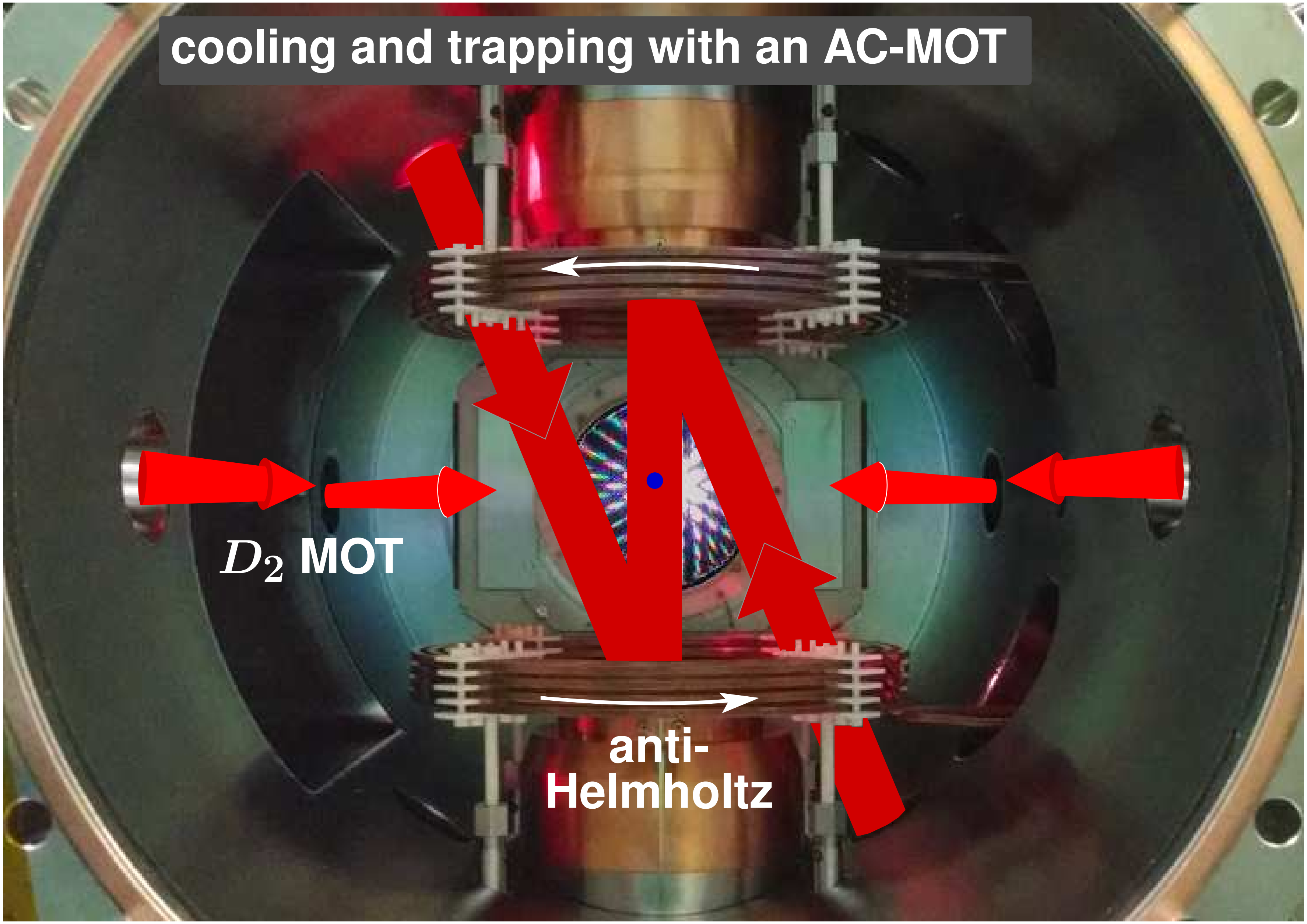

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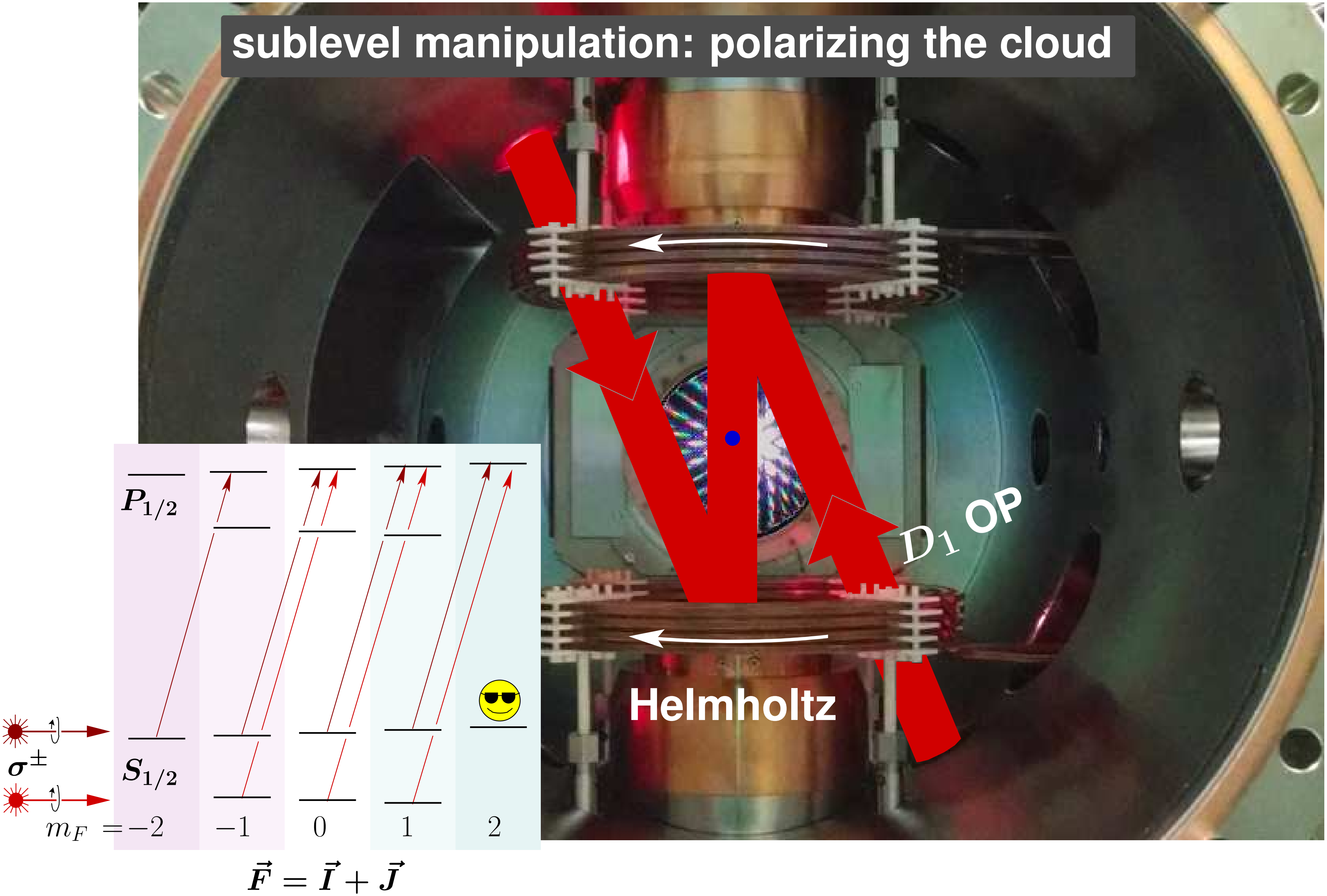

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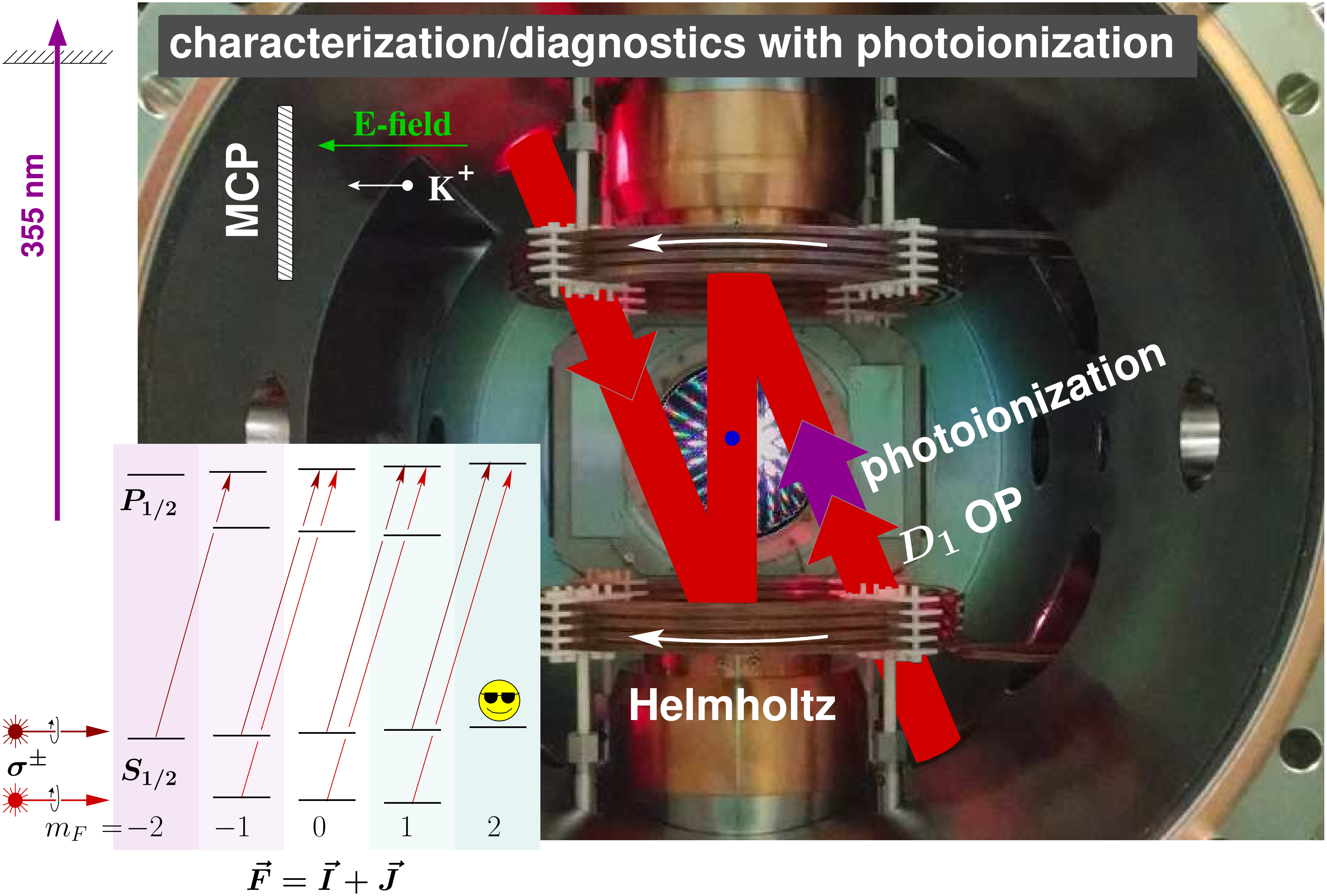
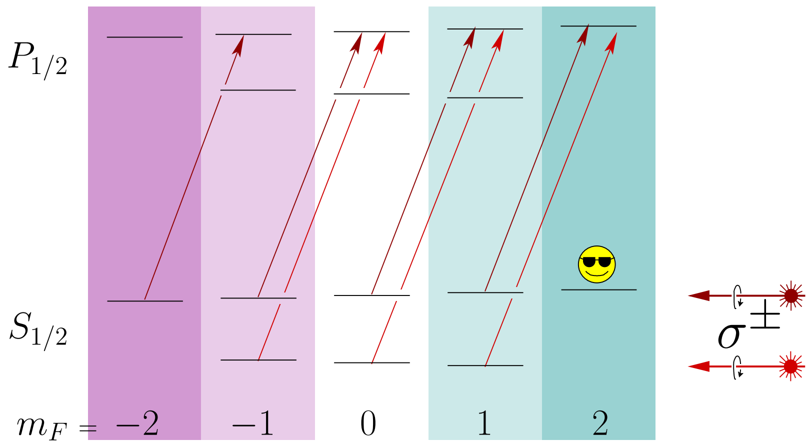
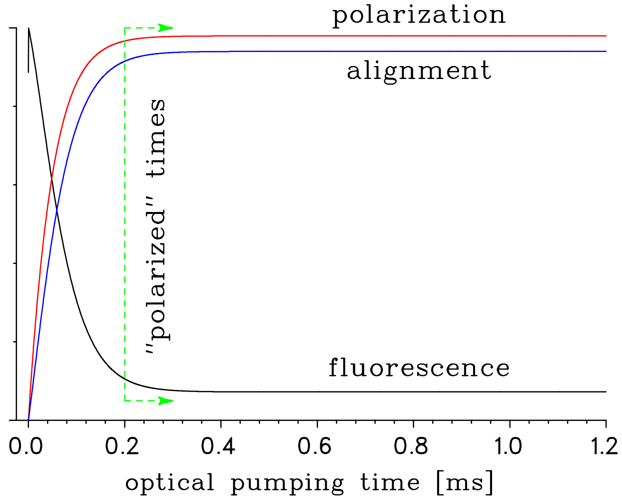


Atomic measurement of P

Deduce P based on model of excited state populations:





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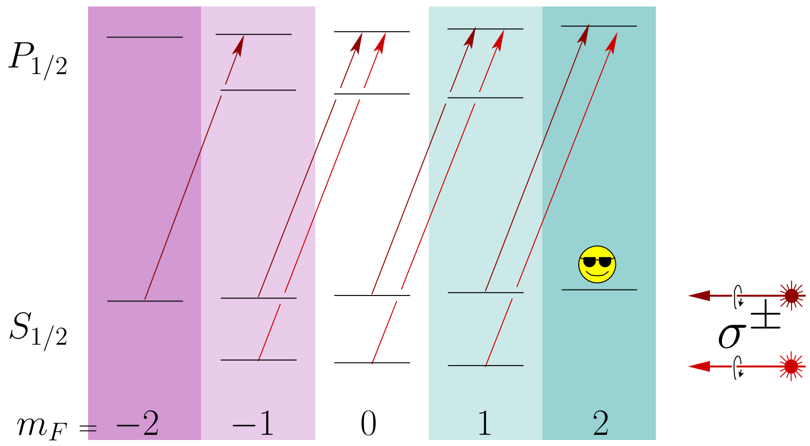
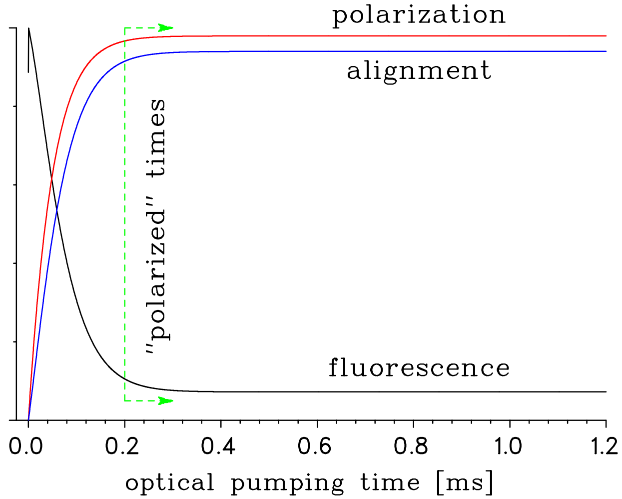
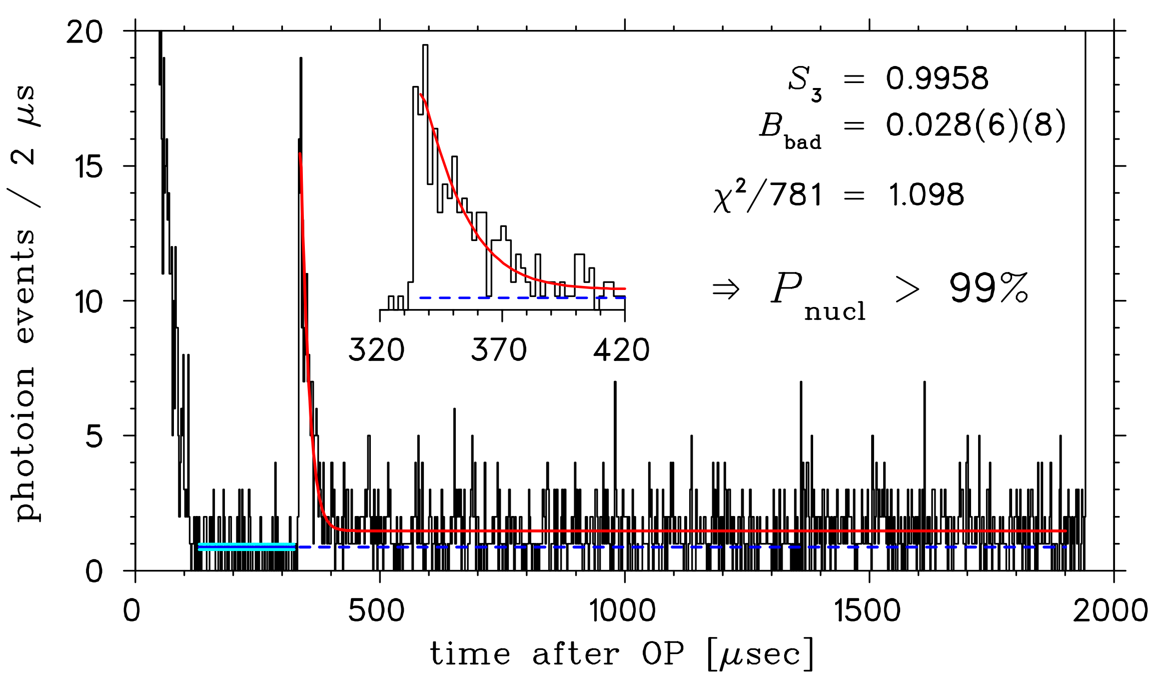
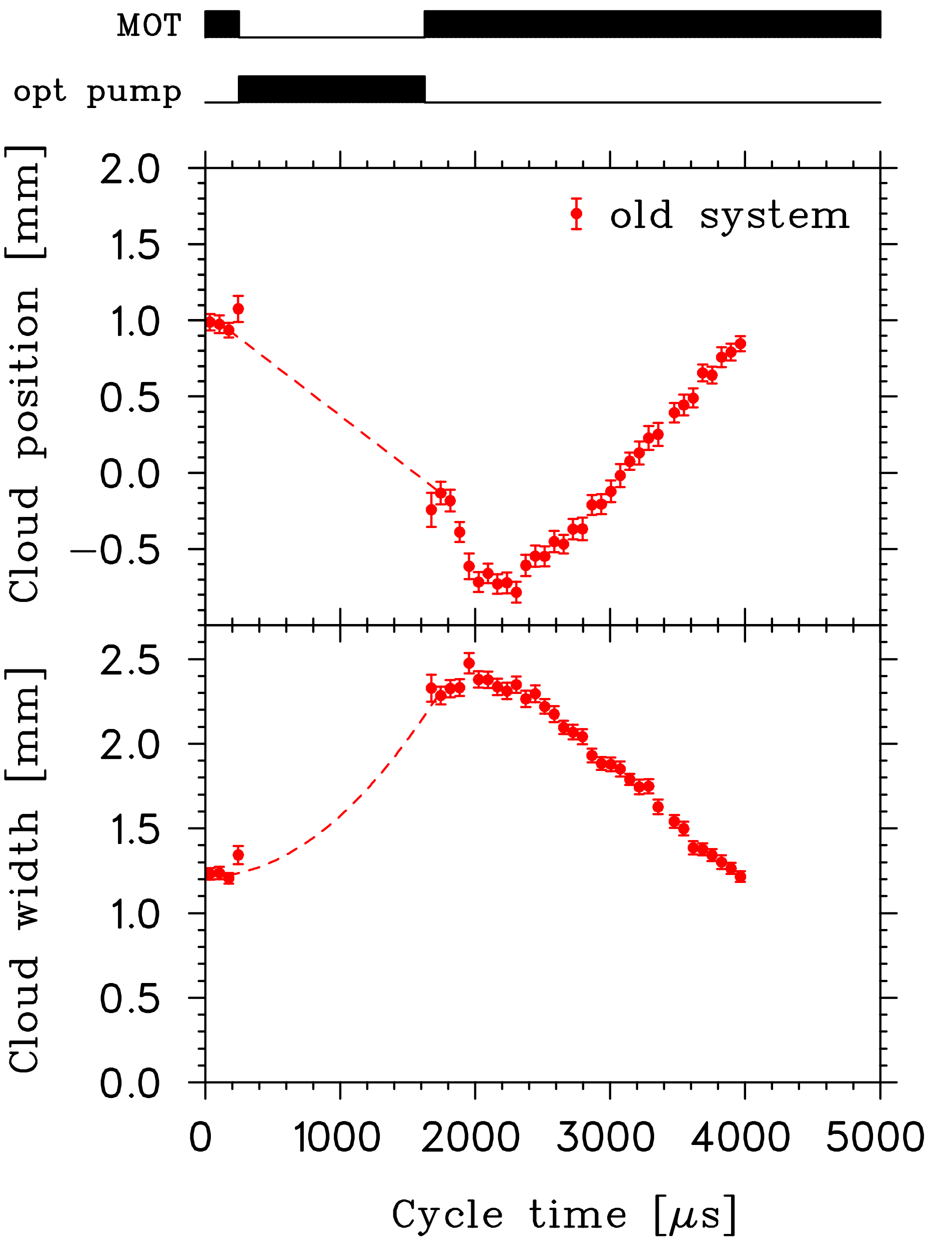






1st improvements for polarized program



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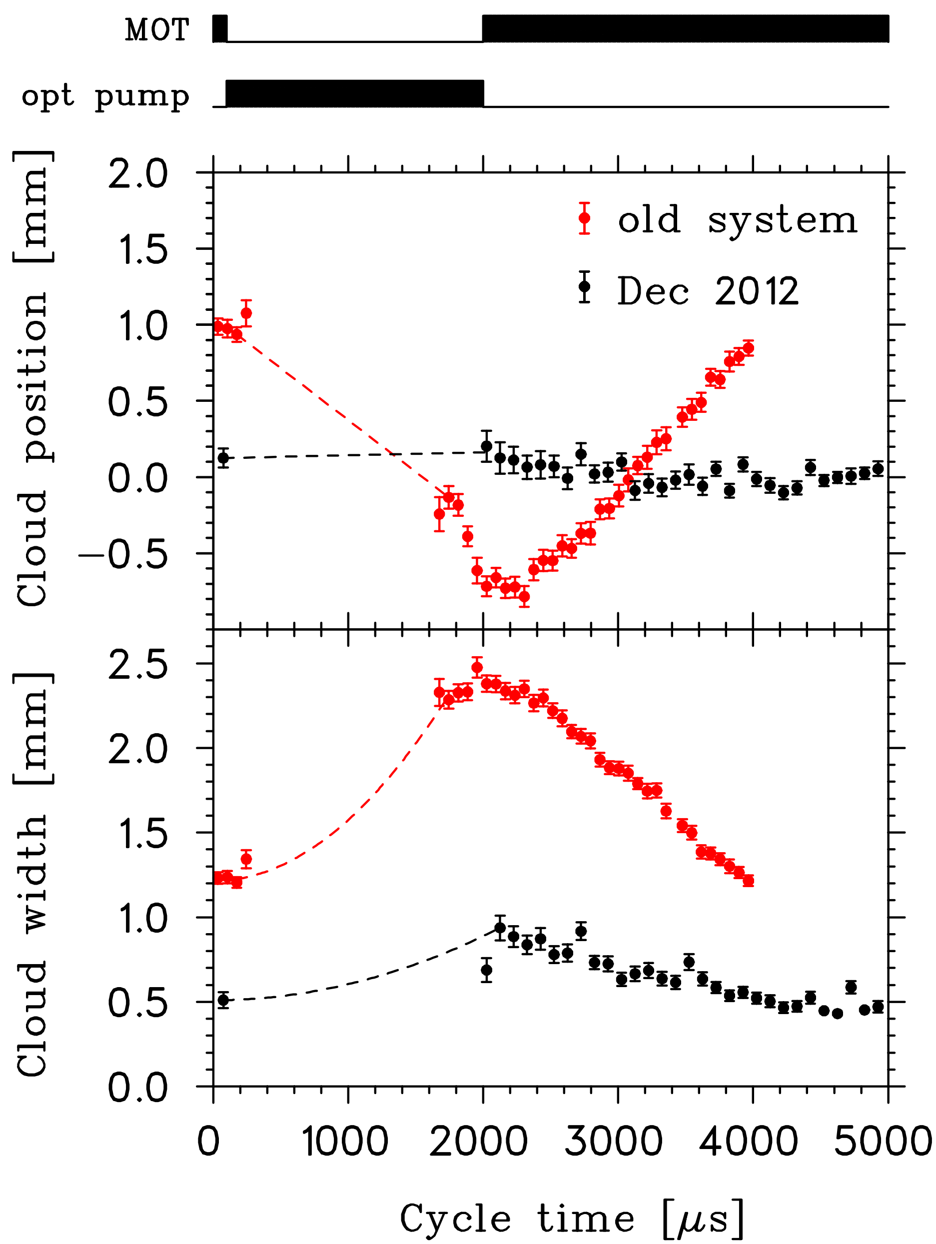

- old system:
  - retroreflected beams
  - "Helmholtz" coils not really Helmholtz
  - eddy currents
- Dec 2012:
  - beams balanced
  - (anti-)Helmholtz very well-defined
  - ac-MOT $\Rightarrow$ fast switching and low eddy currents

much more stable!
lower cloud temperature!

June 2014 run

Debugging the new system: some key improvements in a very recent 2nd run:

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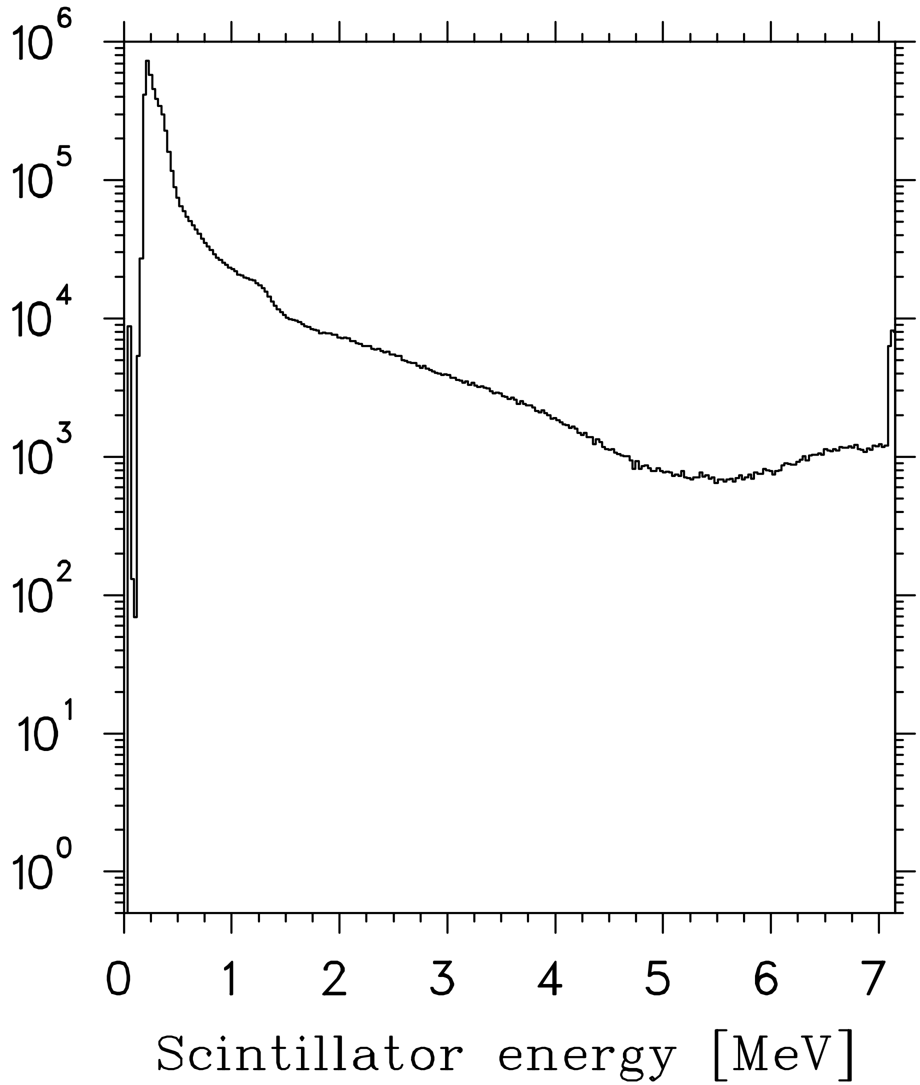
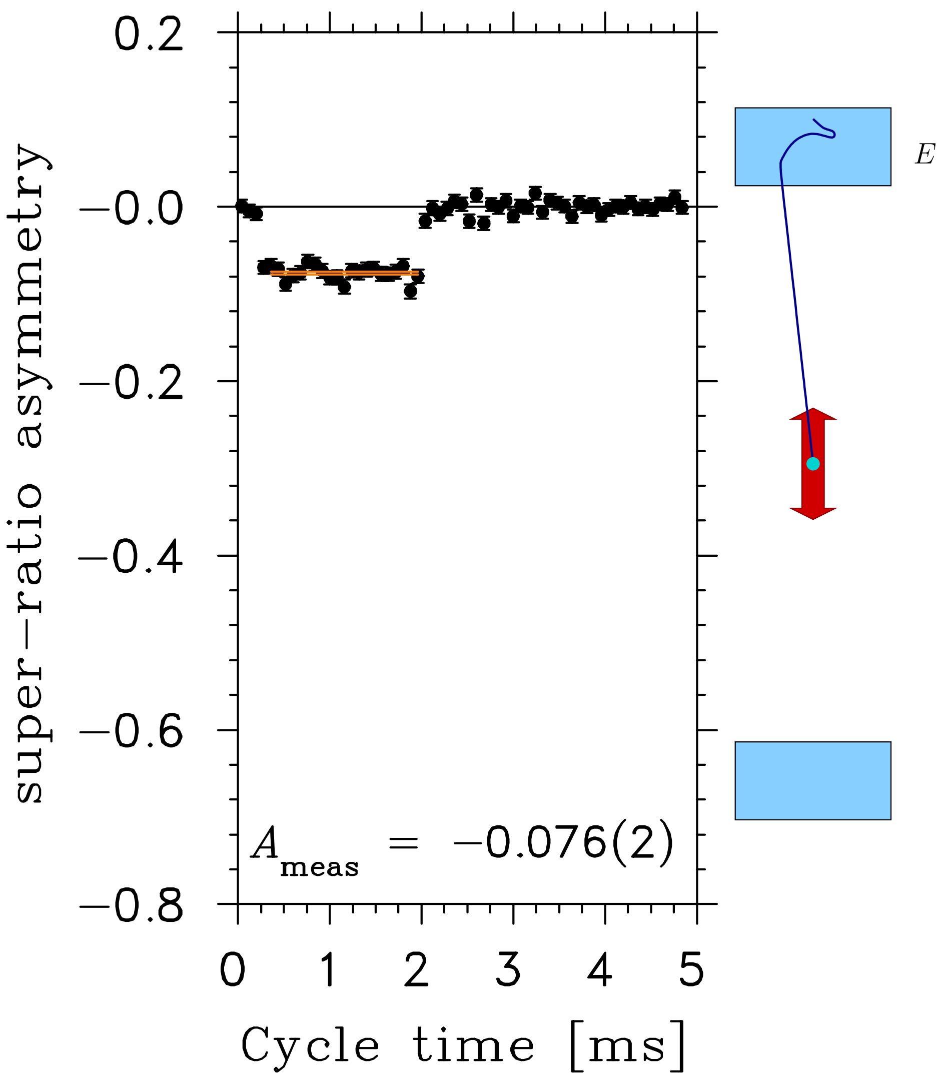
- $\approx 20\times$ more β-decay events!
  - 2×10^6 enough stats for $\leq 0.5\%$ measurement of A_β
  - also $a_{\beta\nu}$ and $\beta-$recoil correlation

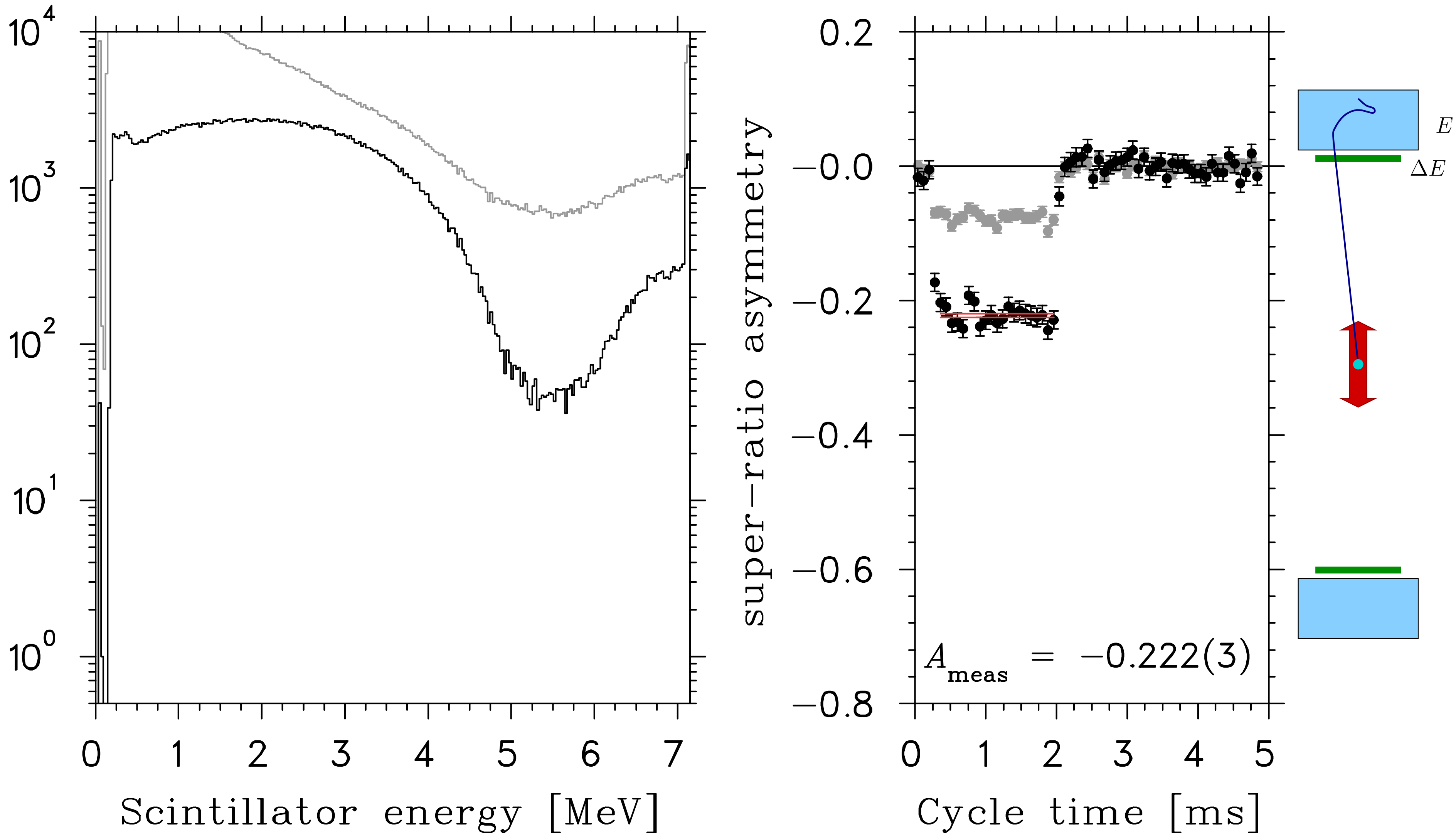
Scintillator spectra — Fall 2012

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

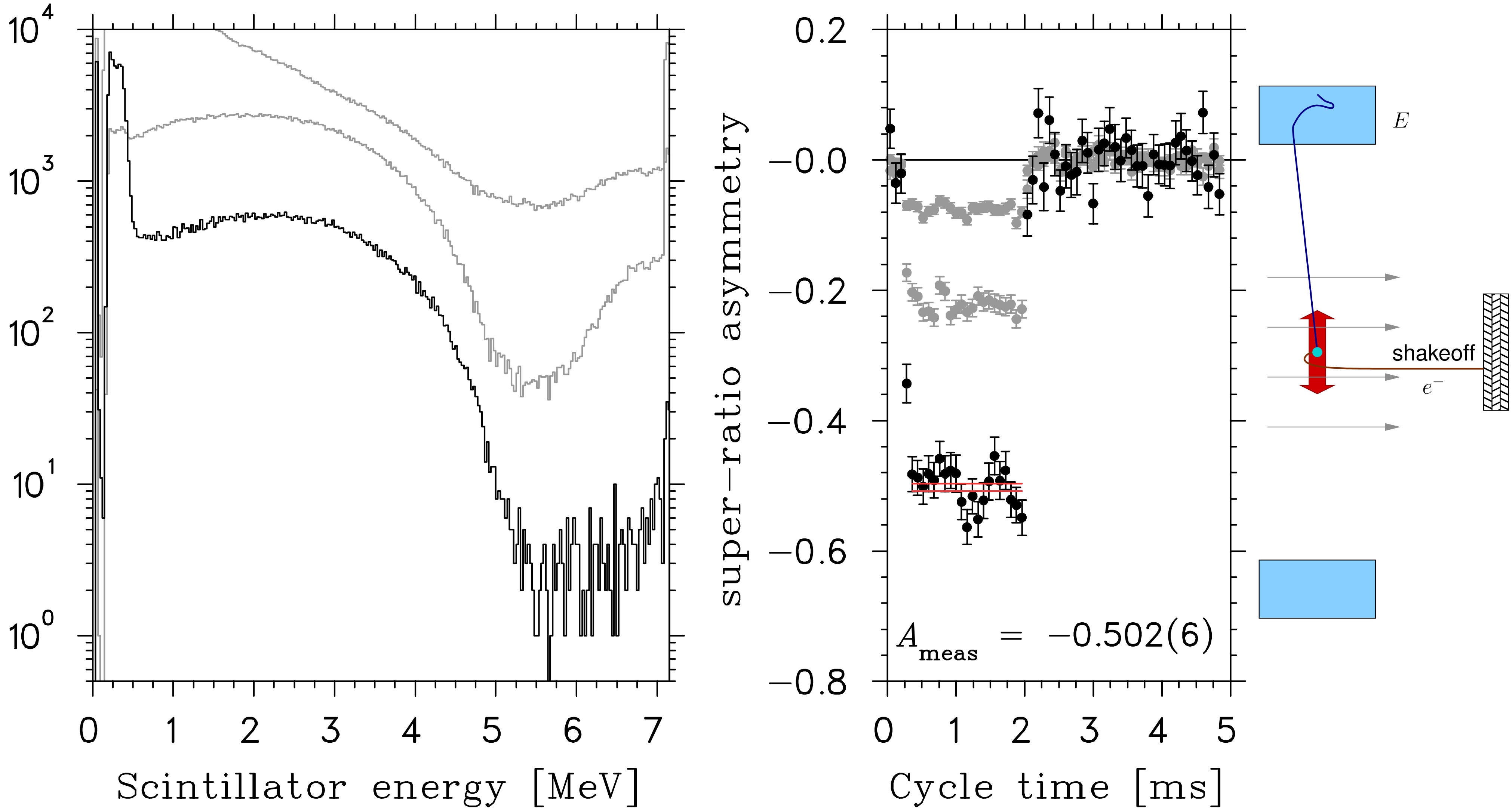




Requiring a ΔE coincidence $\Rightarrow$ remove γs

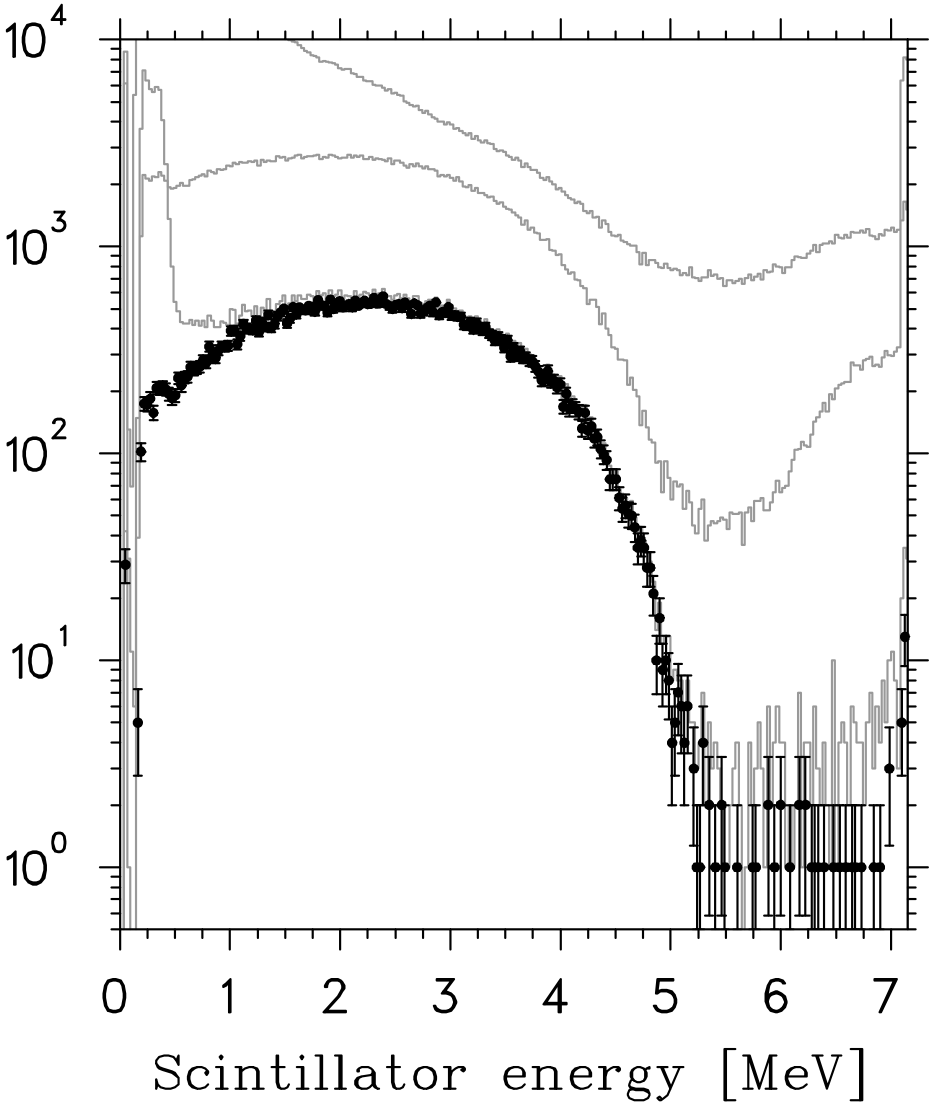


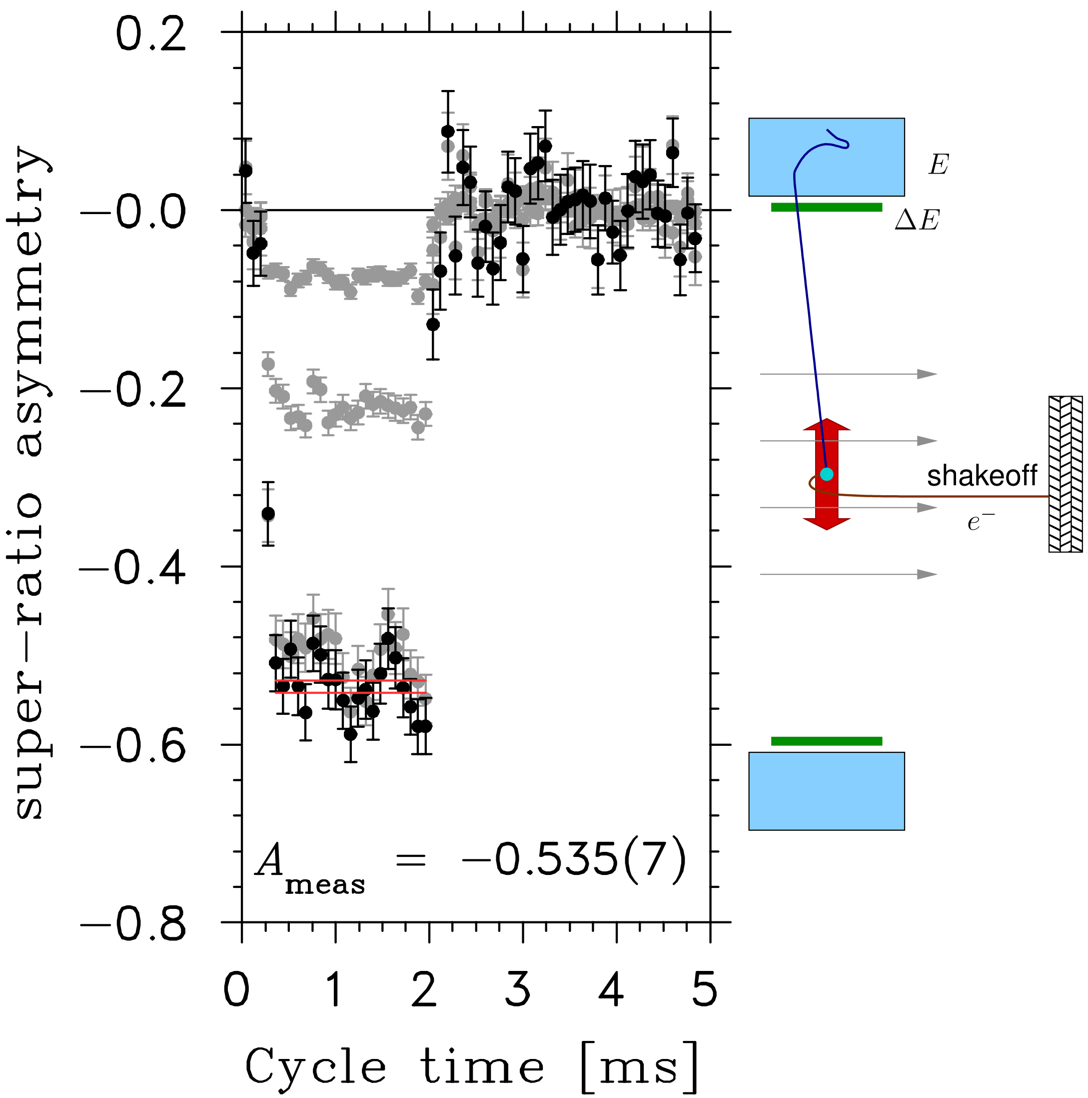
Requiring a shake-off e^- $\Rightarrow$ decay occured from trap!



Scintillator spectra — Fall 2012

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





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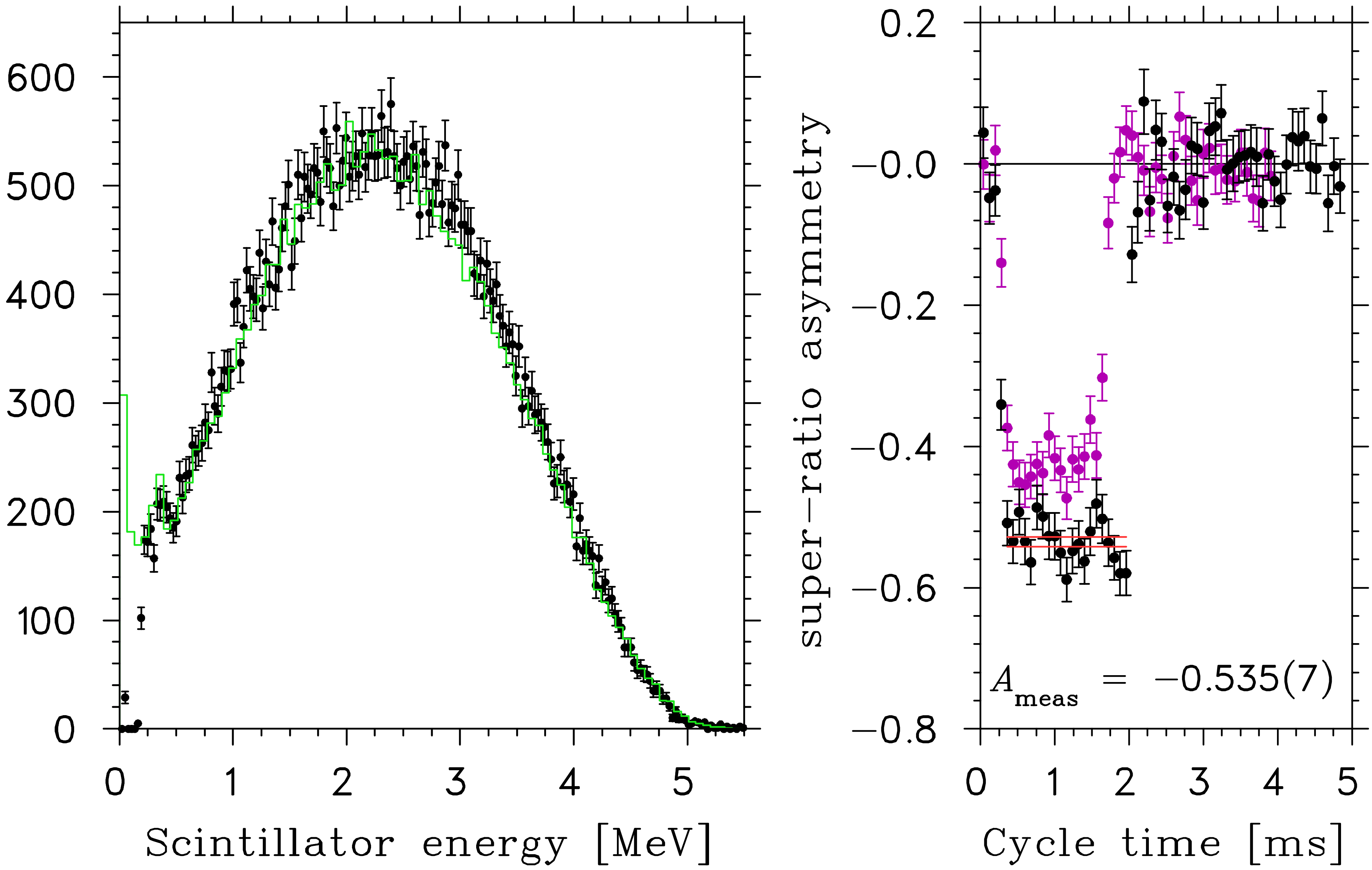

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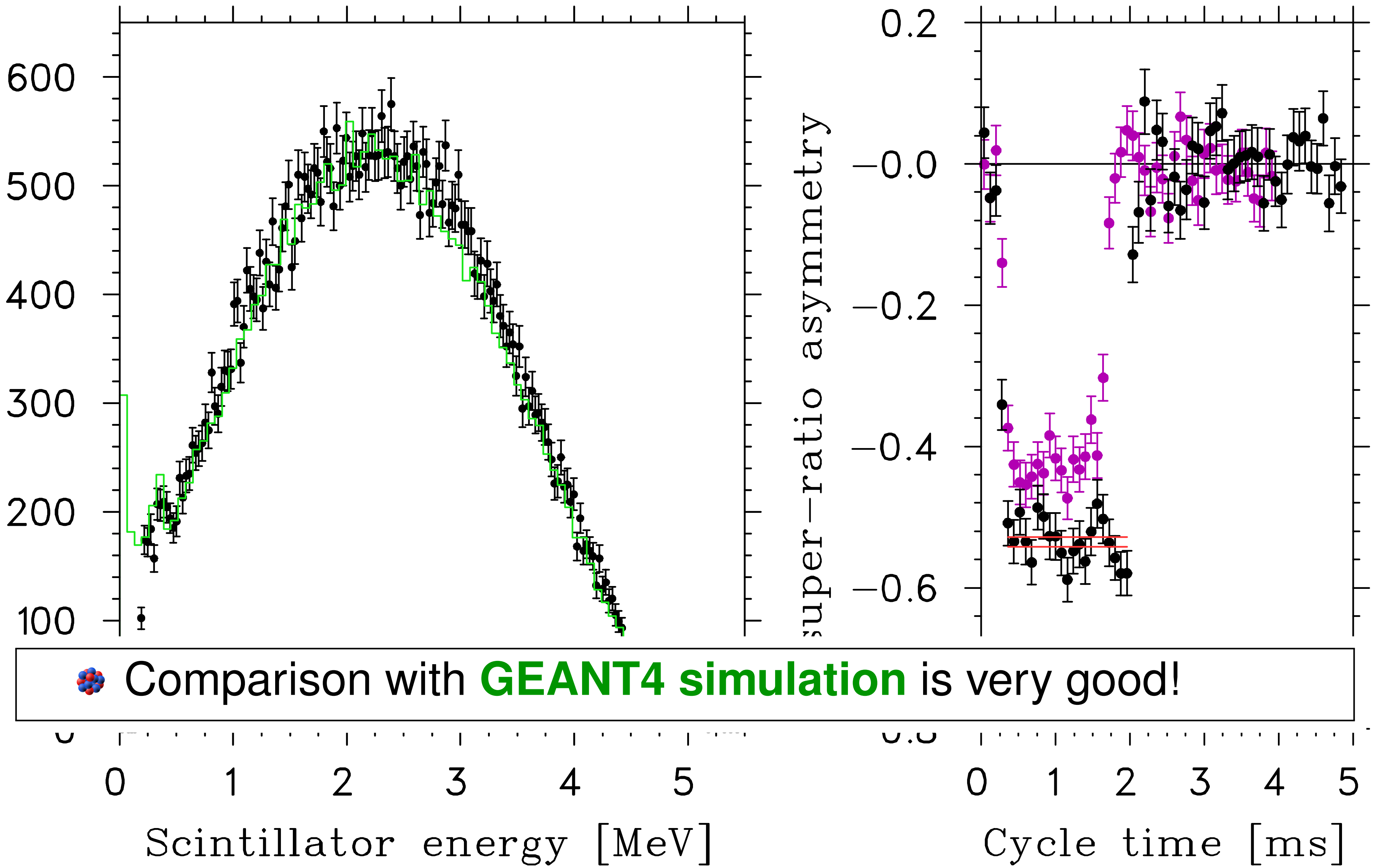

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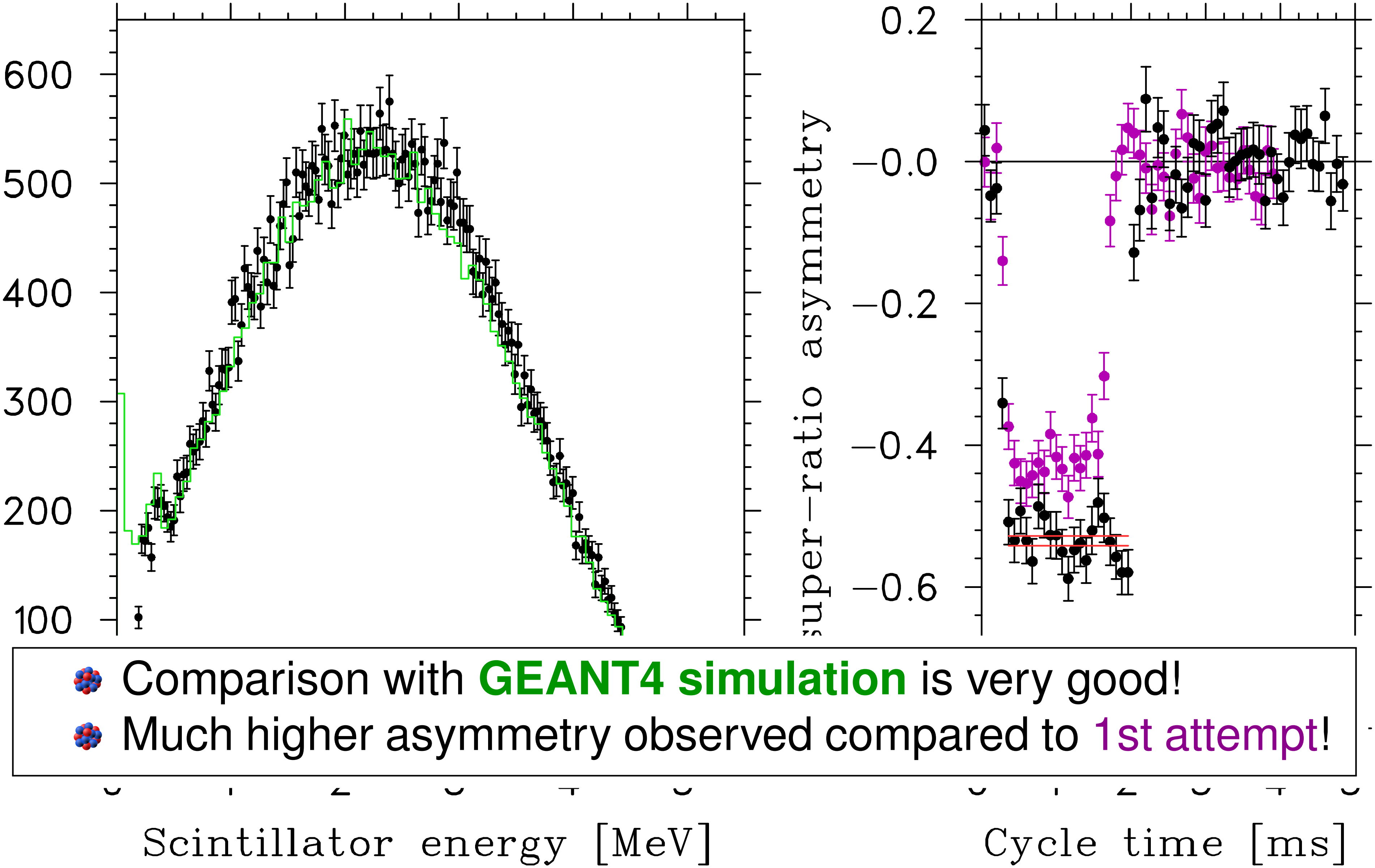
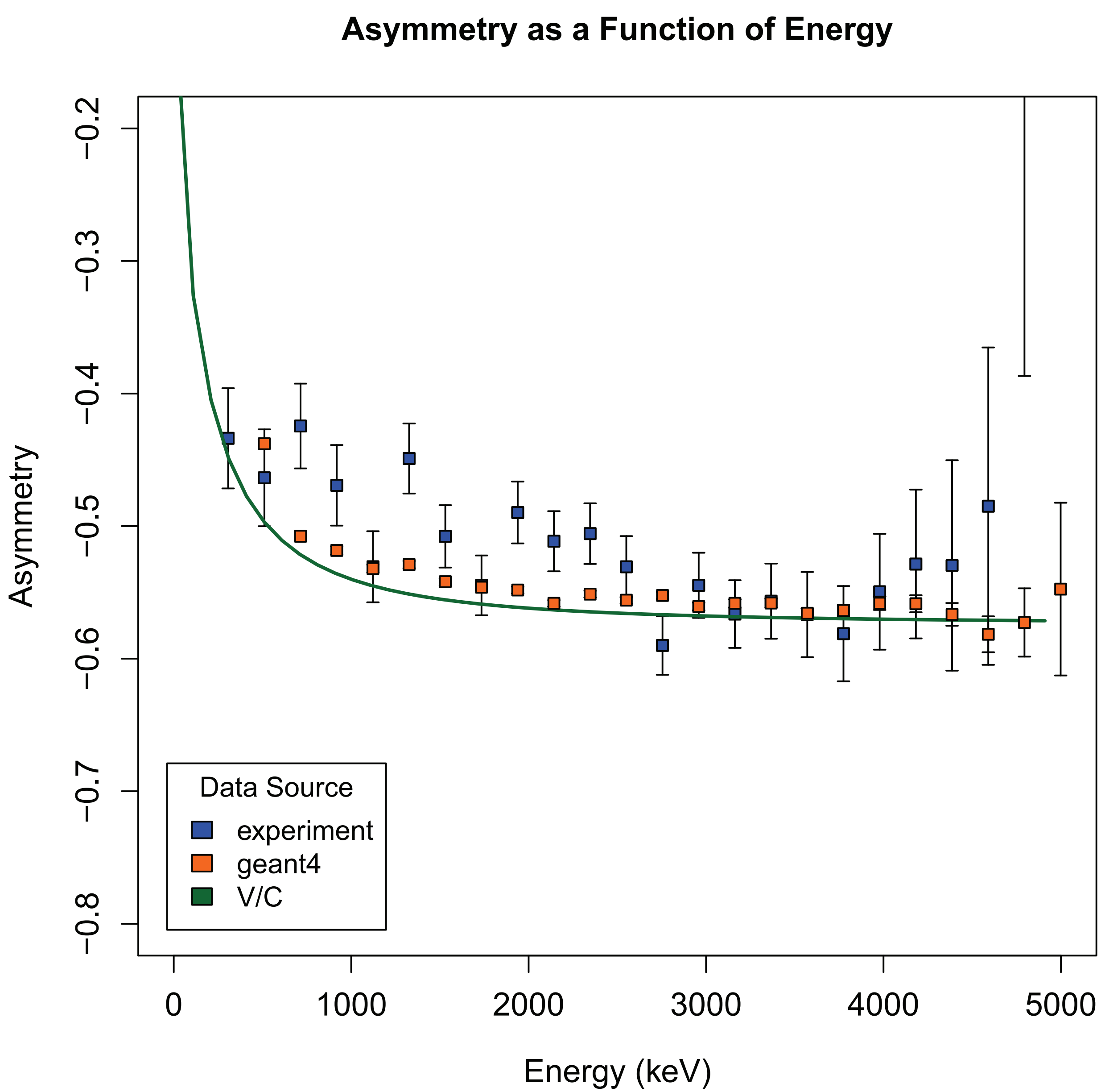
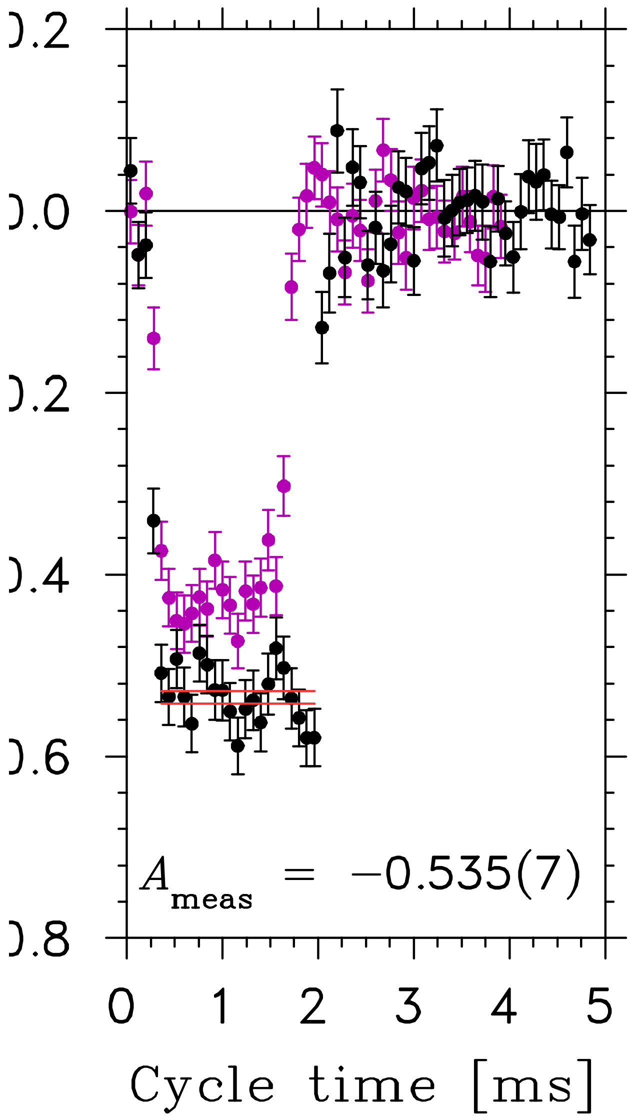


- Comparison with **GEANT4 simulation** is very good!
- Much higher asymmetry observed compared to 1st attempt!

But we have some problems still. . .





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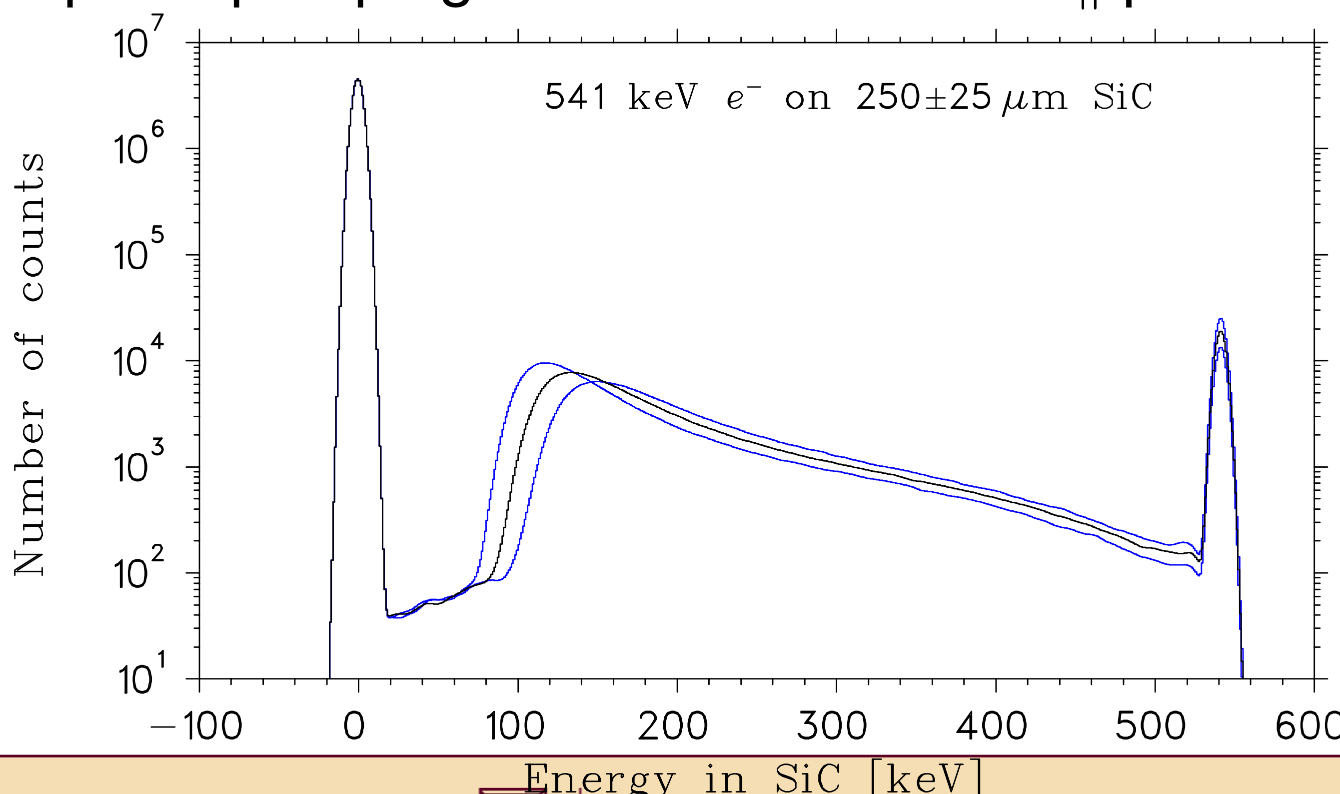
  - Si detectors fail at the lowest β energies. . . *any* material is a killer
  - Optical pumping: mirror vs. detection $\parallel$ polarization axis



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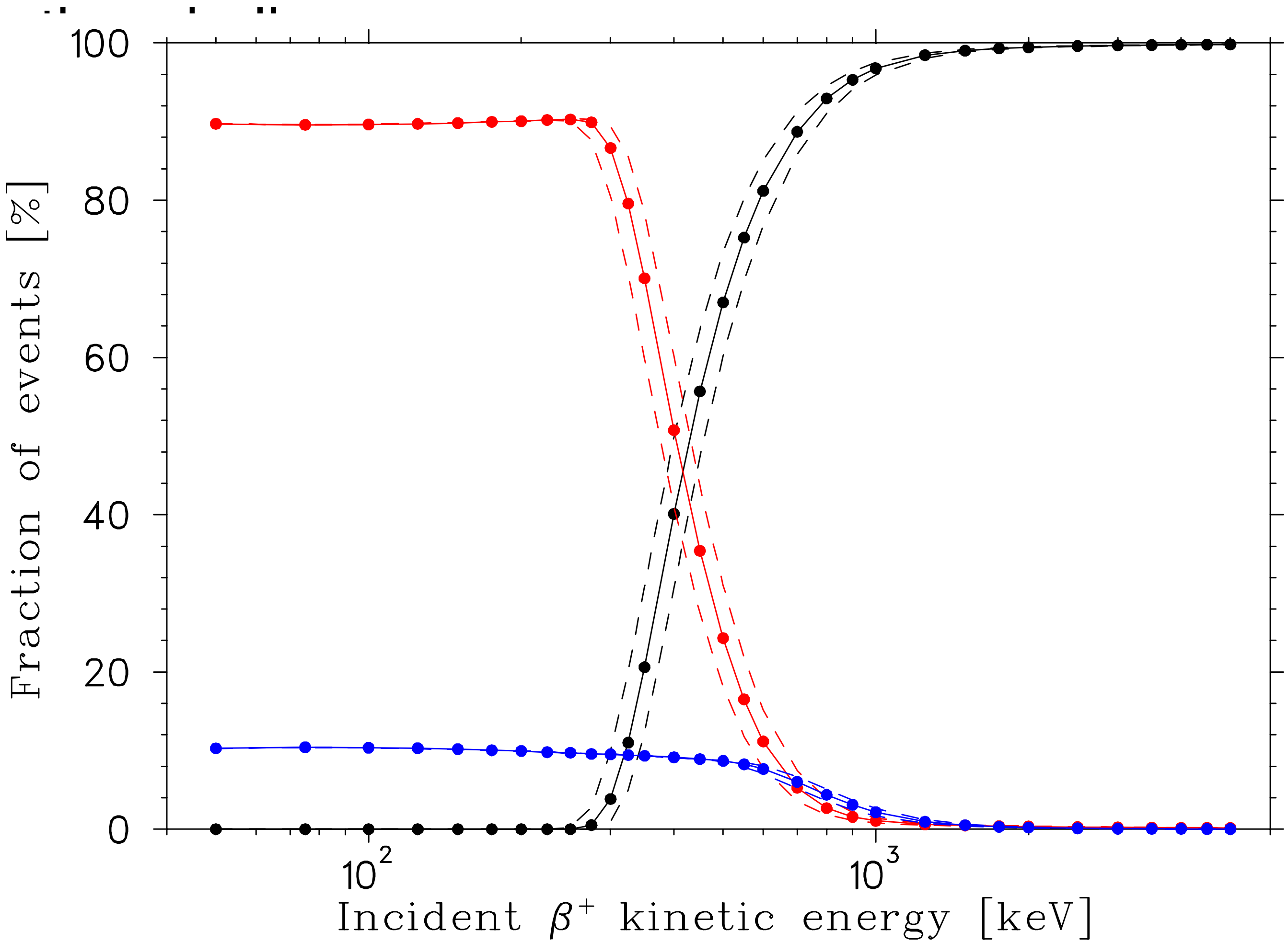
- Traps are **great** at providing an ideal source of short-lived atoms/ions
- Almost all sensitivity to interesting physics is at **low β energies**
- Dete…
  - …naterial is
  - …on axis



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$\frac{M_1+M_2}{2}$ = 36.97007611(12) amu	$E_\circ$ = 5.63646(23) MeV	$\langle E \rangle$ = 3.35 MeV
f_V = 3623.9(7)	f_A/f_V = 1.00456(91)	I = 3/2
$t_{1/2}$ = 1.2365(9) s	branch = 97.99(14)%	P_{EC} = 0.080(2)%
δ_C = 0.73(6)%	$\delta_{\rm NS} = -0.06(2)$%	δ'_R = 1.431(39)%
a_1 = 1	a_2 = **2.150**	$b = A\sqrt{\frac{I+1}{I}} M_F \left(\frac{\mu-\mu'}{T_3-T'_3}\right)$
$c_1 = 0.5794(20)$ (from $\mathcal{F}t$)	$\mu(^{37}{\rm K}) = 0.20321(6)\mu_N$	$\mu(^{37}{\rm Ar}) = 1.146(1)\mu_N$
c_2 = **1.764**	$d = 0 \pm 0.4Ac$	$e = 0$ (by CVC)
$f = -3.394$ (not zero)	$g = -M_F\sqrt{\frac{(I+1)(2I+3)}{I(2I-1)}}\frac{2M^2}{3\hbar^2c^2}\left(Q - Q'\right)$	
$h = -4.10 \times 10^4$	$Q(^{37}{\rm K}) = 10.6(4)e$ fm^2	$Q(^{37}{\rm Ar}) = 7.6(9)e$ fm^2
$j_1 = -1.97 \times 10^5$	$j_2 = 0.0121$	$j_3 = 3.99 \times 10^5$

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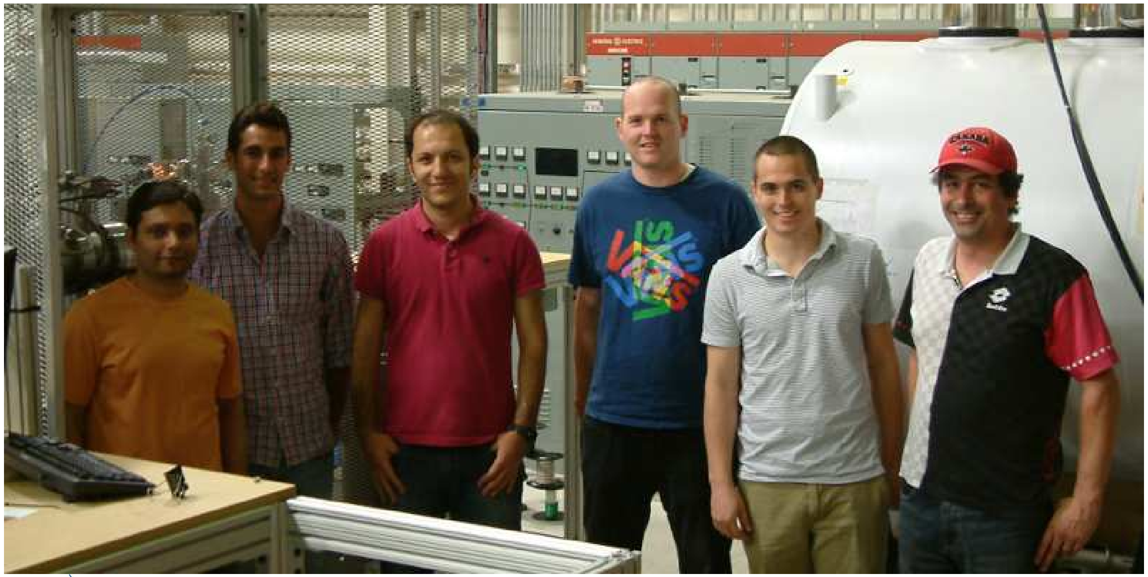
Summary

- Angular correlations in β decay can be used to probe physics beyond the standard model
  - to be competitive, precision must be 0.1%
- TAMUTRAP: unique facility to study β-delayed proton decays
  - scalar currents through $a_{\beta\nu}$: enhanced sensitivity
  - ft/V_{ud} and other applications
- TRINAT: unique facility to study polarized angular distributions in ^{37}K
  - with $t_{1/2}$ and B.R. measurements at TAMU, ρ well-determined
  - very clean A_β measurement; analyses underway

The Mad Trappers/Thanks

TAMU: Spencer Behling, Mike Mehlman, Ben Fenker, Praveen Shidling
+ TAMU/REU undergrads



TRINAT: TRIUMF M. Anholm, J.A. Behr, A. Gorelov,
L. Kurchananov, K. Olchanski, K.P. Jackson

D. Ashery, I. Cohen

G. Gwinner

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TAMU/Cyclotron Institute

also NSERC, NRC through TRIUMF, WestGrid, Israel Science Foundation

In case you haven't already heard. . .

TENURE-TRACK POSITION

PHYSICS & ASTRONOMY
TEXAS A&M UNIVERSITY

EXPERIMENTAL NUCLEAR PHYSICS
TEXAS A&M UNIVERSITY

The Physics and Astronomy Department at Texas A&M University seeks applications for a tenure-track assistant professor position in experimental nuclear physics under the auspices of the Nuclear Solutions Institute. This institute combines basic and applied nuclear science with nuclear security technology and policy; it already encompasses a broad spectrum of faculty members drawn from across the university. A selected candidate must hold an earned Ph.D. in physics or a related area. The appointment is expected to begin on or before September 1, 2015.

The successful candidate for this position will assume a tenure-track position in the Department of Physics and Astronomy with a joint appointment in the Cyclotron Institute and the Nuclear Solutions Institute. More senior candidates may be considered at the associate professor or professor level. He/she is expected to assume full teaching responsibilities at the graduate and undergraduate levels and is also expected to conduct a vigorous research program based at the Cyclotron Institute and employing the facilities there, which include two cyclotrons – a newly refurbished K150 and a superconducting K500 – together with a wide variety of modern experimental equipment. An upgrade project, nearing completion, will utilize the two accelerators to make radioactive beams available to all target locations.

Each application should include:

- a cover letter specifying that the application is for the nuclear physics position,
- a *curriculum vita*,
- a list of publications,

In case you haven't already heard. . .

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TEXAS A&M UNIVERSITY

EXPERIMENTAL NUCLEAR PHYSICS
TEXAS A&M UNIVERSITY

The Physics and Astronomy Department at Texas A&M University seeks applications for a tenure-

- Open search: no specific subfield
- Just need to have (big part of) your program based locally at the CI
- Application review will begin early October

Let people know who are good and may be interested!

dmelconian@comp.tamu.edu

- a list of publications,

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