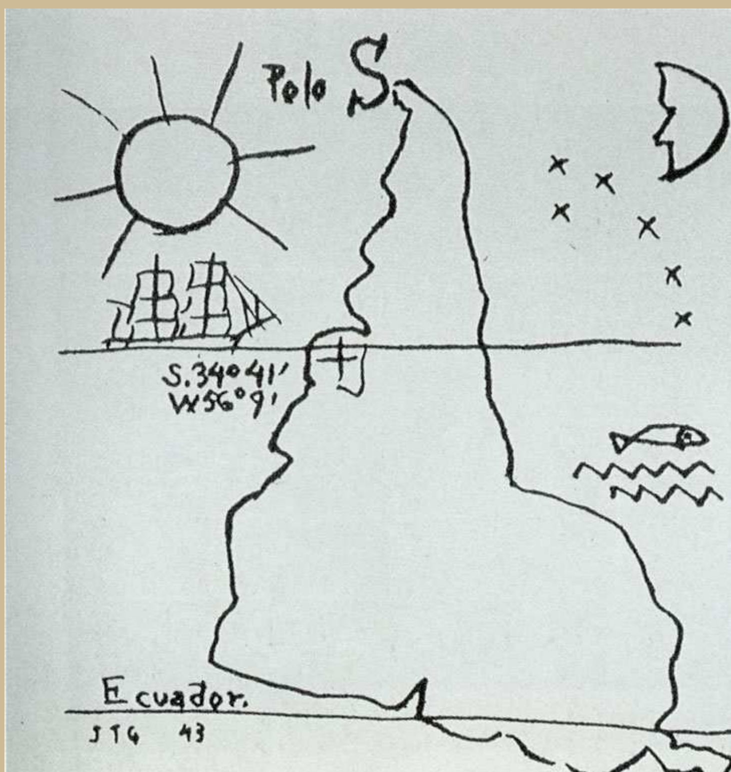
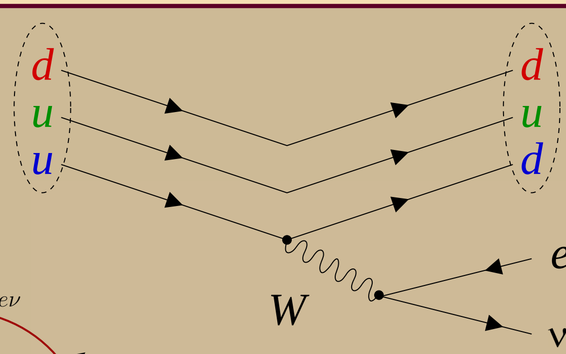
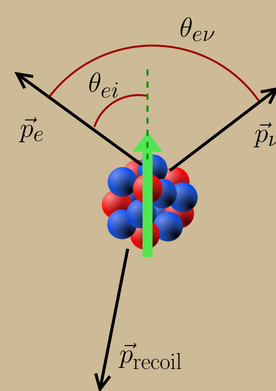
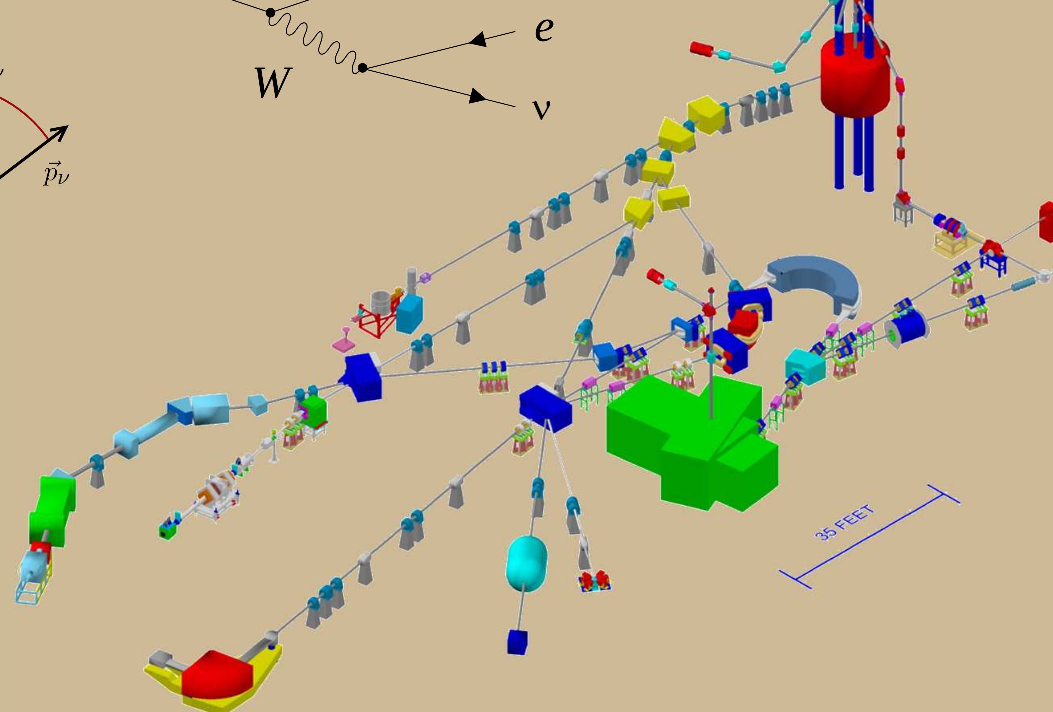
Precision Measurements of β-decay Correlation Parameters from Trapped Atoms and Ions









Dan Melconian

December 3, 2013

Overview

1. Fundamental symmetries

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

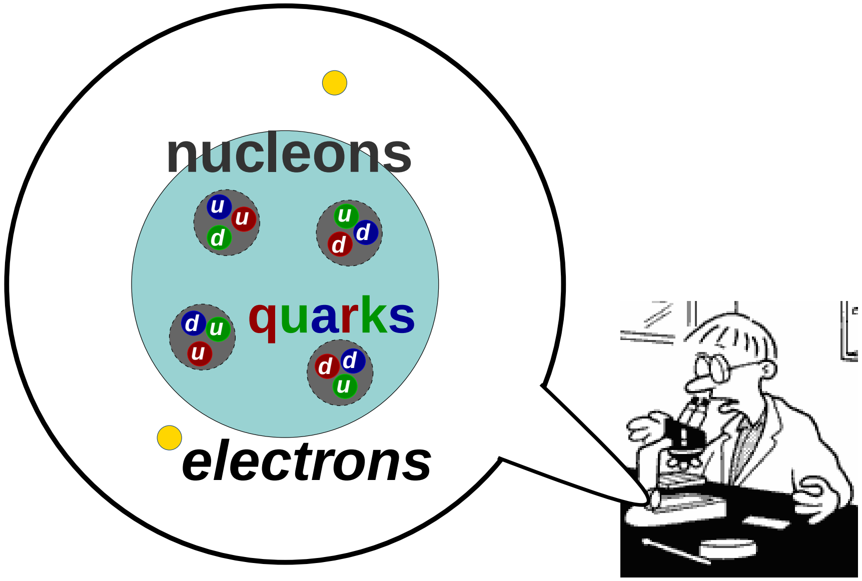
2. TAMU Penning Trap

- **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

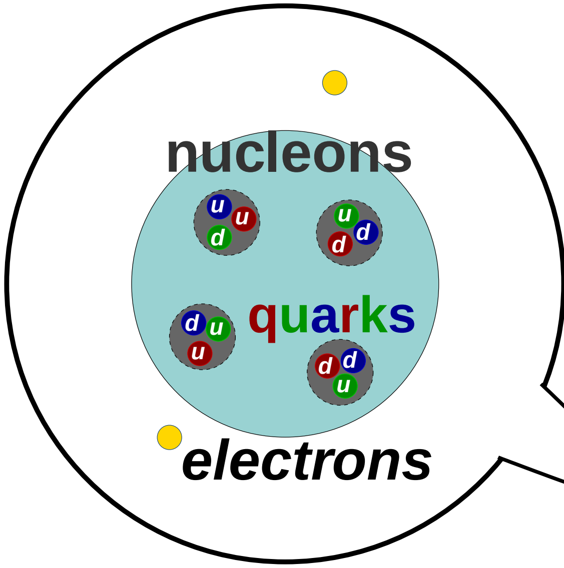
Scope of fundamental physics



the atom

from the very smallest scales . . .

Scope of fundamental physics



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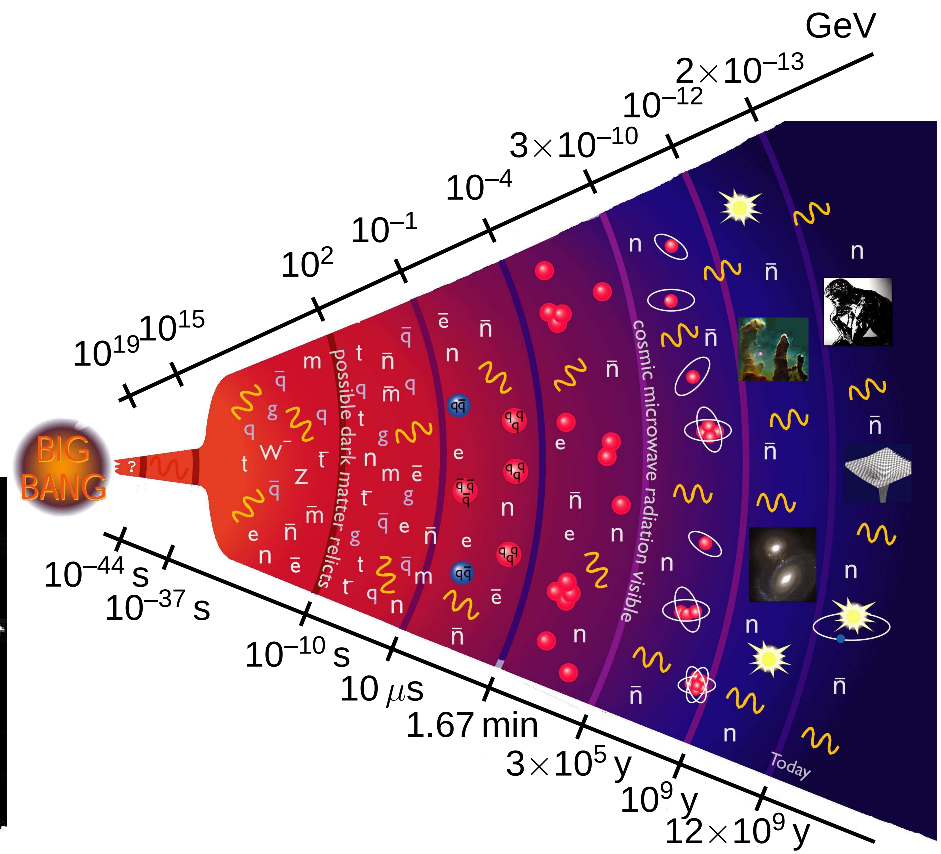

. . . to the very **largest**

The Standard Model

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

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The *new* Standard Model

12 elementary particles, **4 fundamental forces**
and (at least) **1 Higgs boson**

	1st	2nd	3rd	Q	mediator	force
leptons	ν_e	ν_μ	ν_τ	0	g	strong
	e	μ	τ	-1	$W^\pm$	weak ($W^\pm$, Z°)
quarks	u	c	t	$+2/3$	Z°	
	d	s	b	$-1/3$	γ	EM

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- ✔ it **predicted** the existence of the $W^\pm$, $Z_\circ$, g, c and t
- ✔ is a **renormalizable** theory $\rightsquigarrow$ and now **the Higgs!**
- ✔ GSW $\Rightarrow$ **unified** the **weak** force with **electromagnetism**
- ✔ QCD **explains** quark confinement

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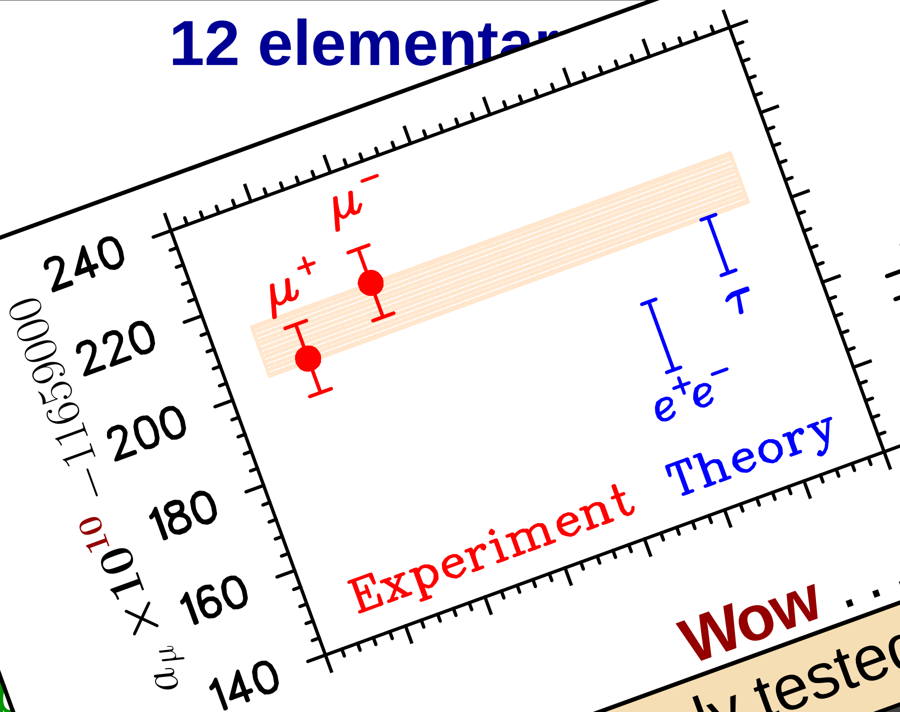

$a_\mu \equiv \frac{1}{2}(g-2)$

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

Wow . . . this is
the most precisely tested theory ever conceived!

...EM

✔ it ... , $Z_\circ$, g, c and t

✔ is a ... $\rightsquigarrow$ and now **the Higgs!**

✔ GSW ... e **weak** force with **electromagnetism**

✔ QCD ... **ains** quark confinement

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 do physicists test the SM?

- **colliders**: CERN, SLAC, FNAL, BNL, KEK, DESY . . .
- **nuclear physics**: traps, exotic beams, neutron, EDMs, $0\nu\beta\beta$, . . .
- **cosmology** & **astrophysics**: SN1987a, Big Bang nucleosynthesis, . . .
- **muon decay**: Michel parameters: ρ, δ, η, and ξ
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all of these techniques are **complementary** and **important**

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

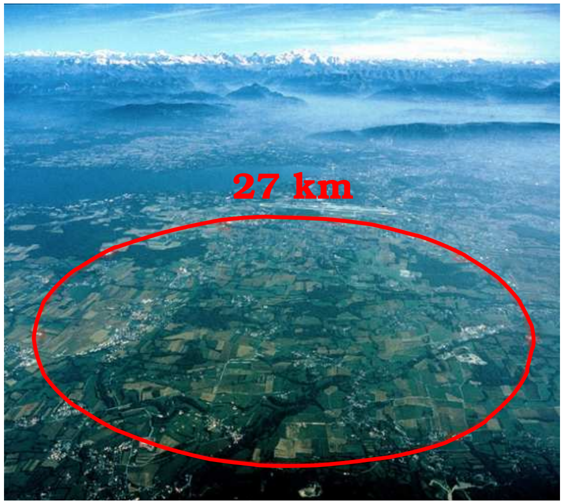
often they are **interdisciplinary**

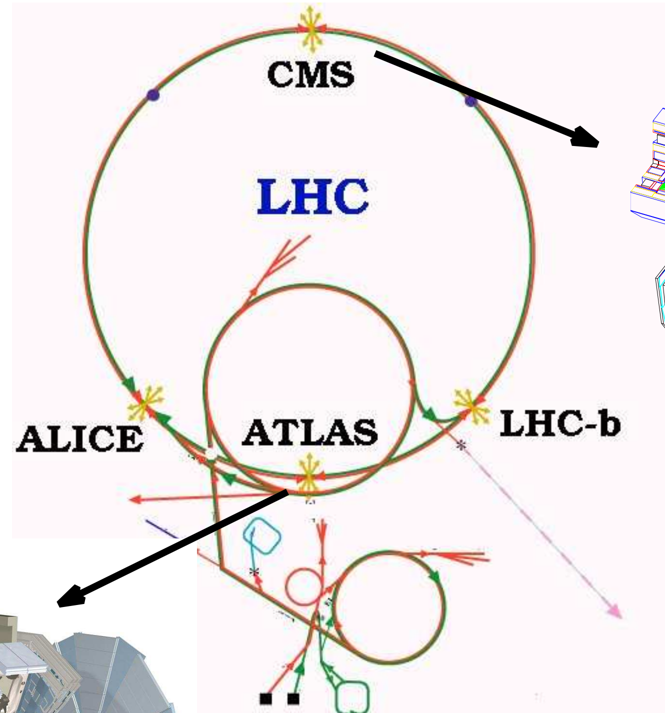
(fun and a great basis for graduate students!)

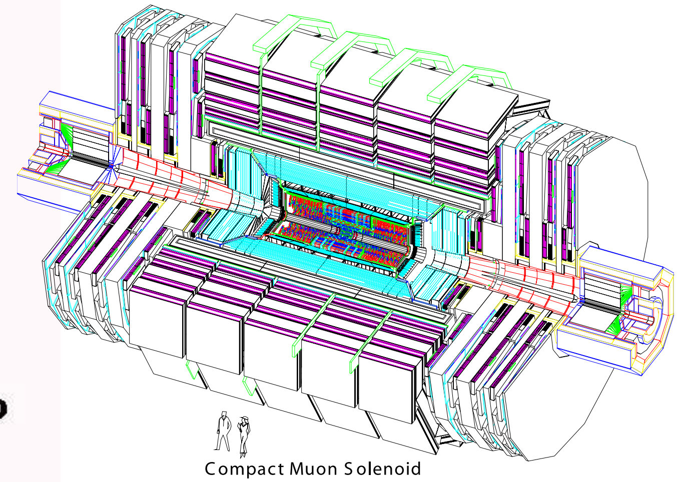
How does high-energy test the SM?

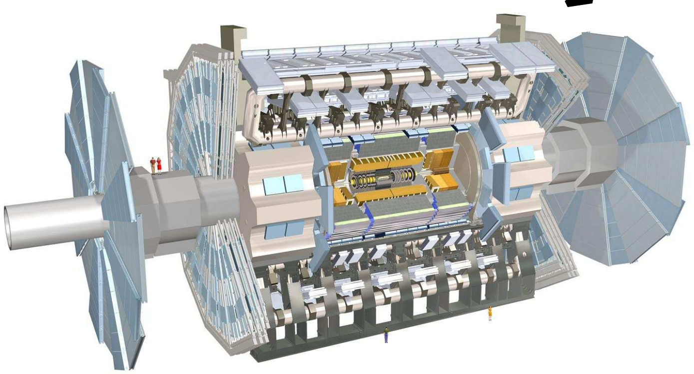
colliders: CERN, SLAC, FNAL, BNL, KEK, DESY, ...

direct search of particles









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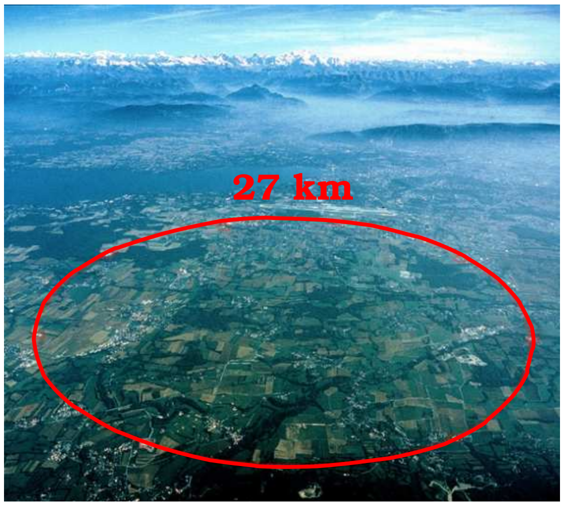
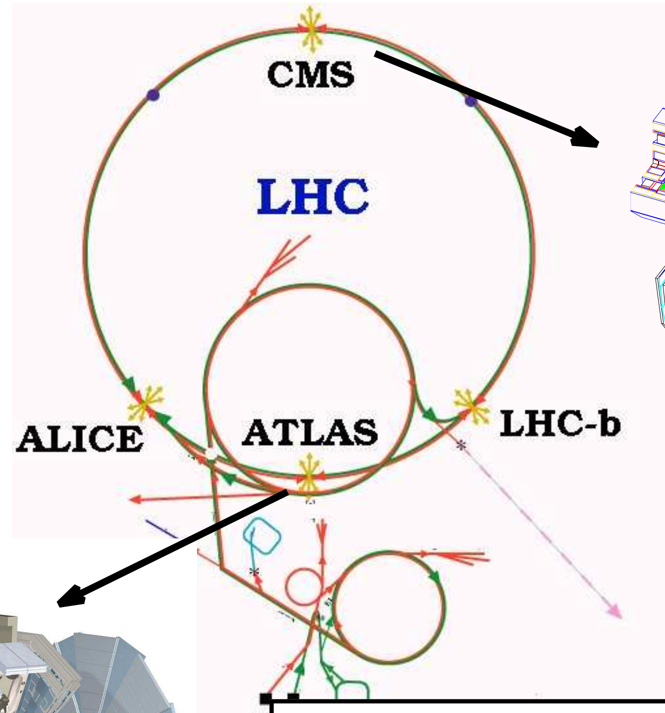
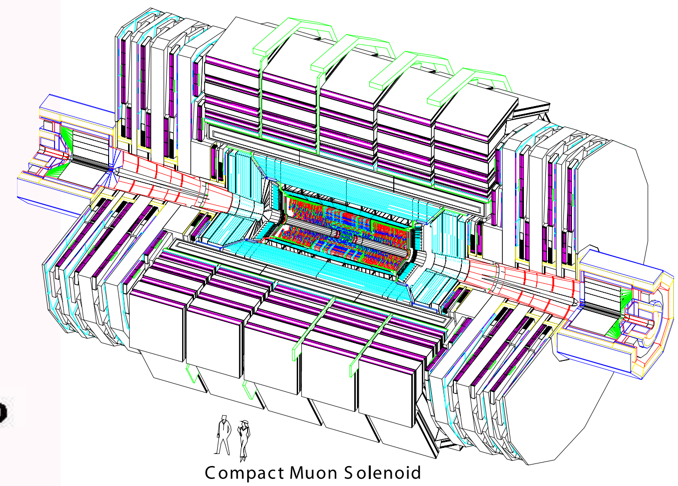
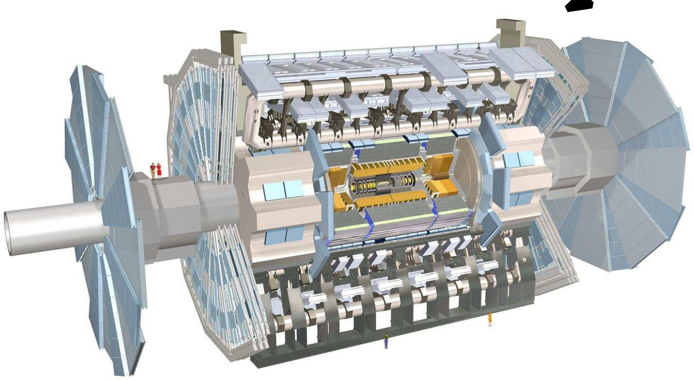








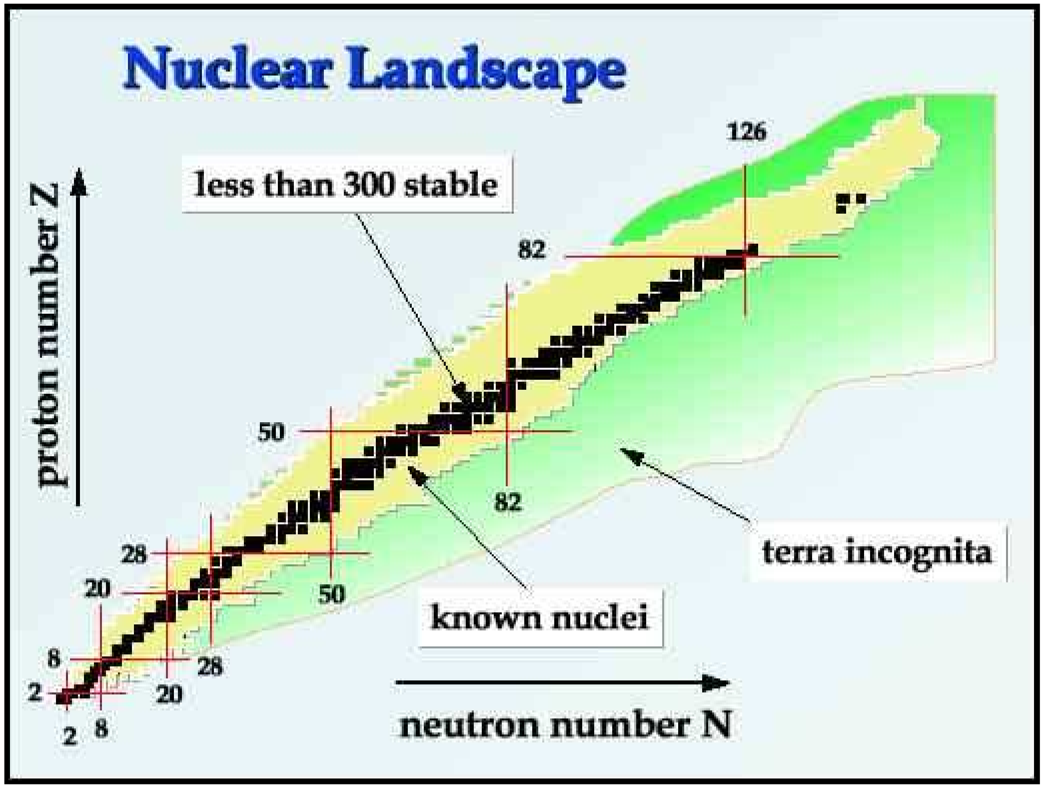
"go big or go home"

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

One way we can test the SM?

nuclear physics: radioactive ion beam facilities

indirect search via precision measurements



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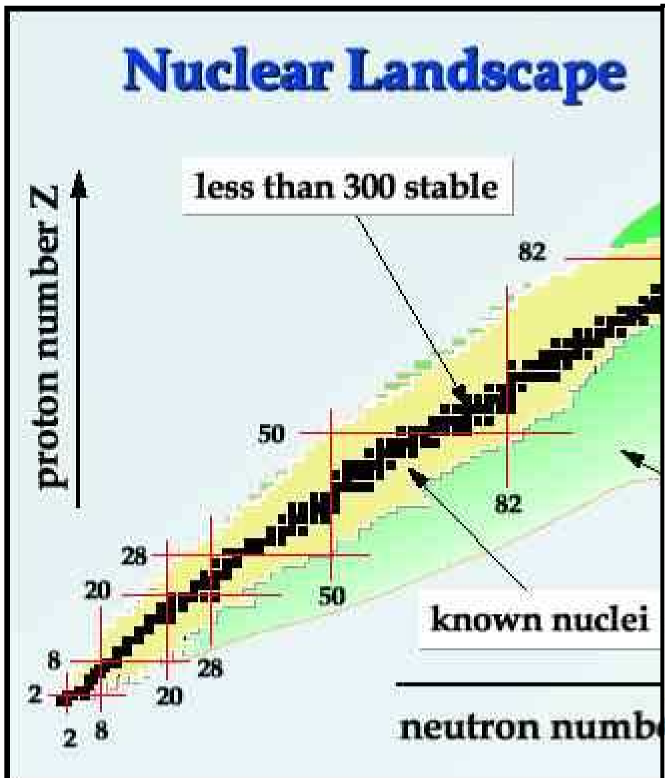

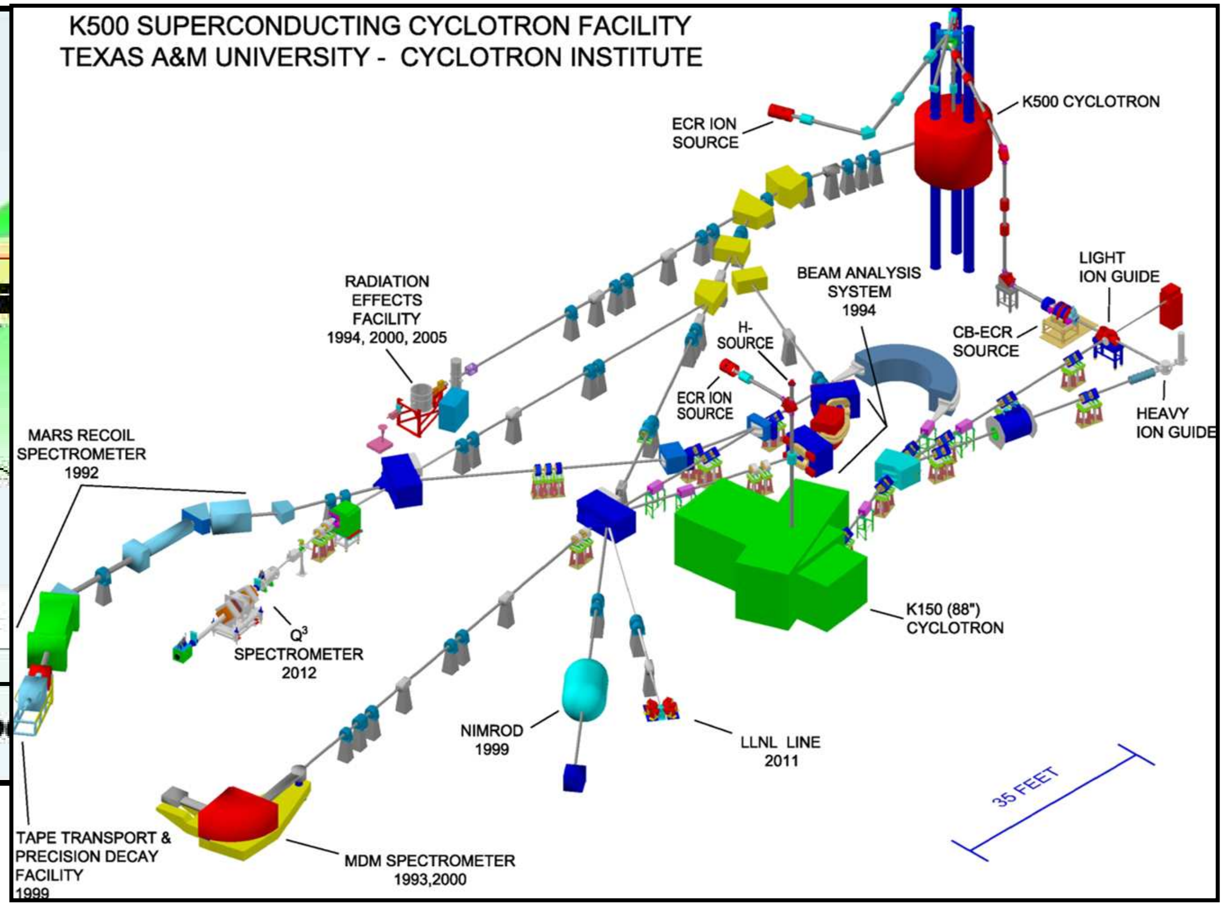

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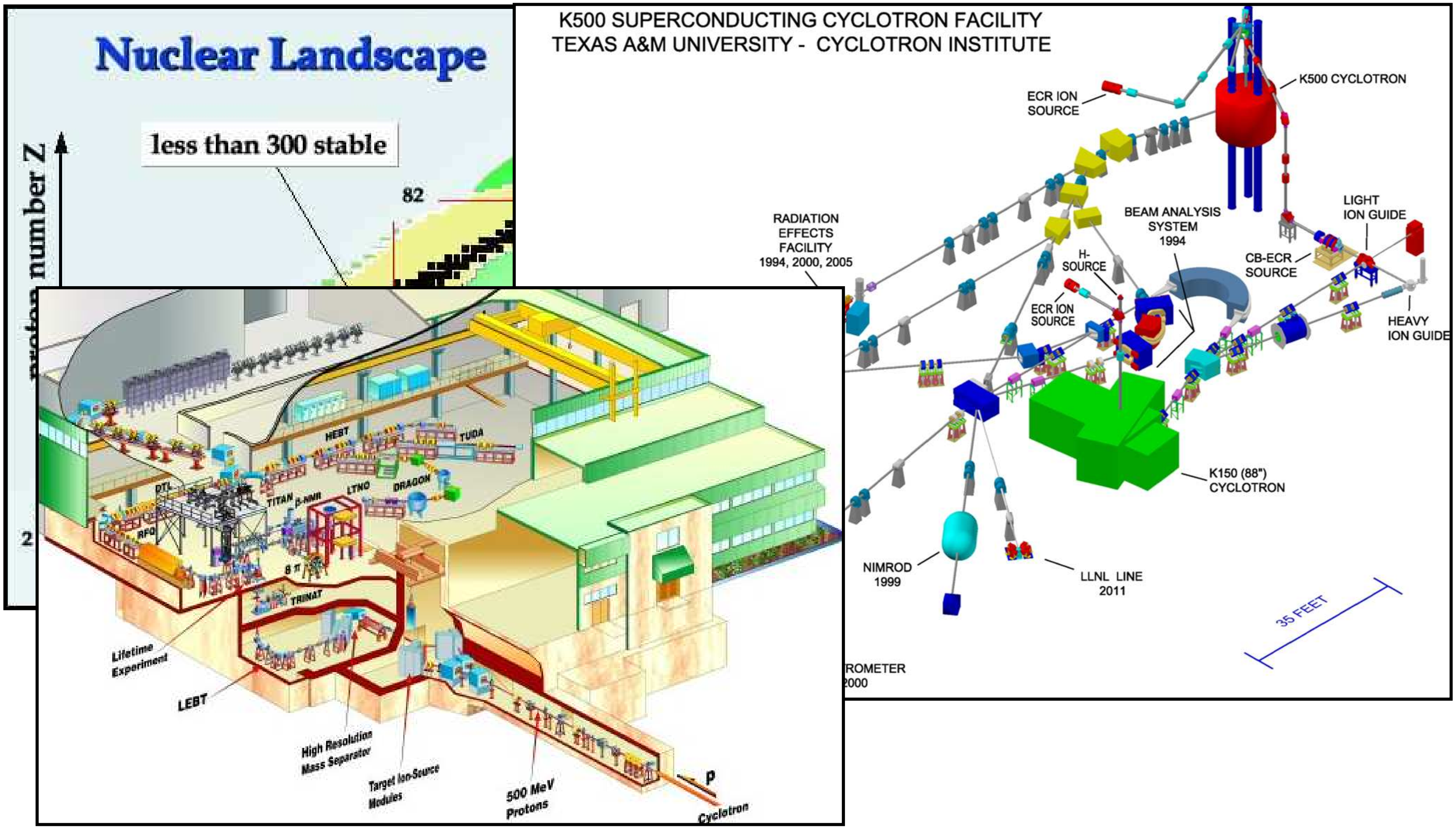

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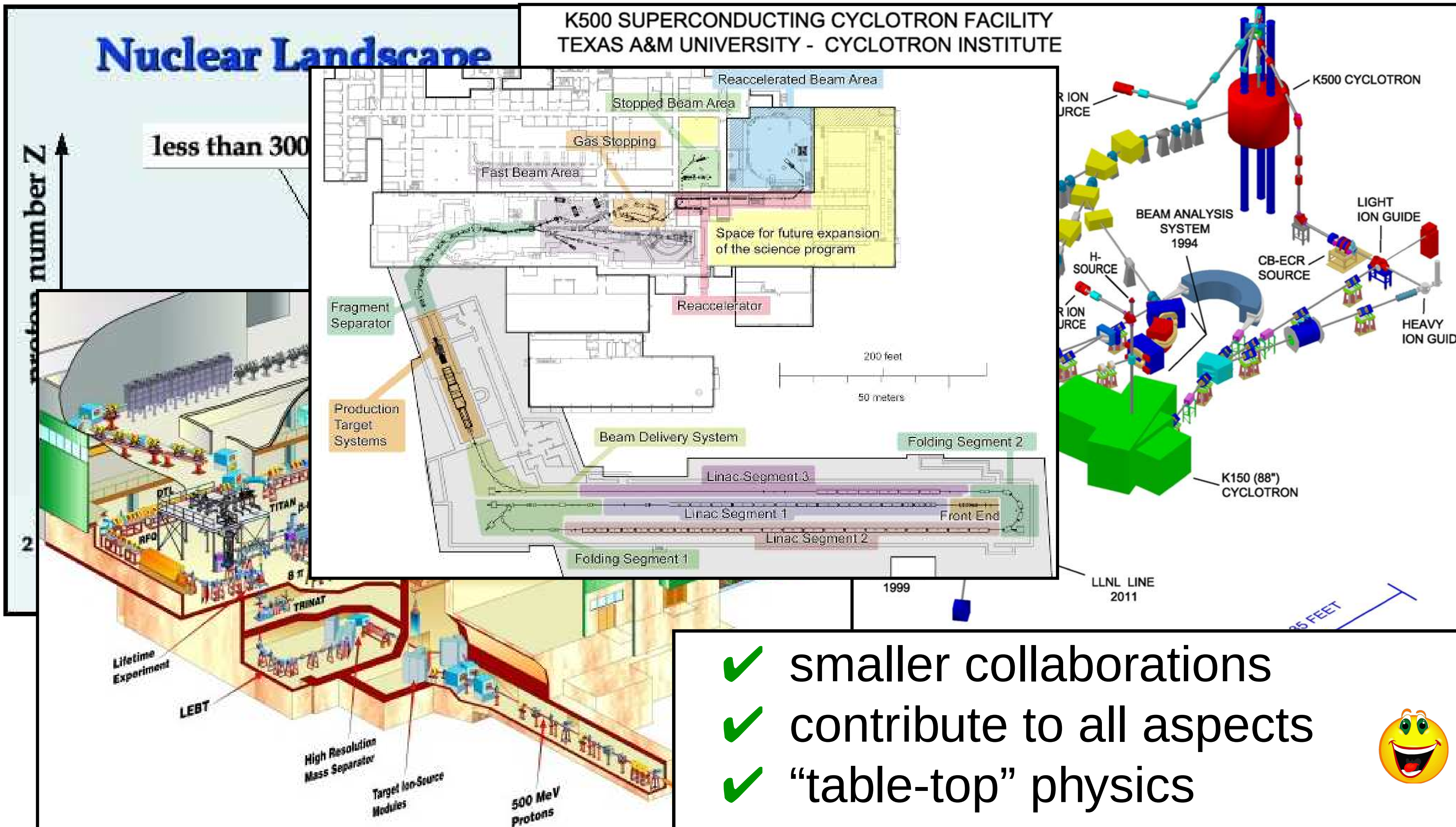
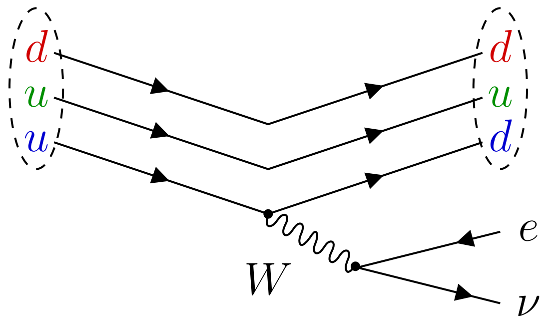
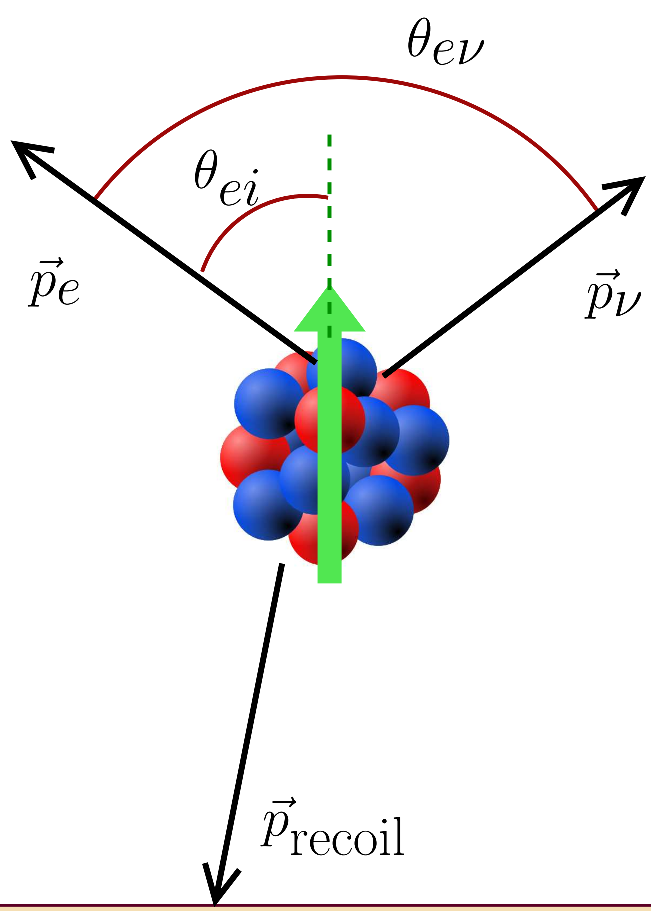


- ✔ smaller collaborations
- ✔ contribute to all aspects
- ✔ “table-top” physics

How do I plan to test the SM?



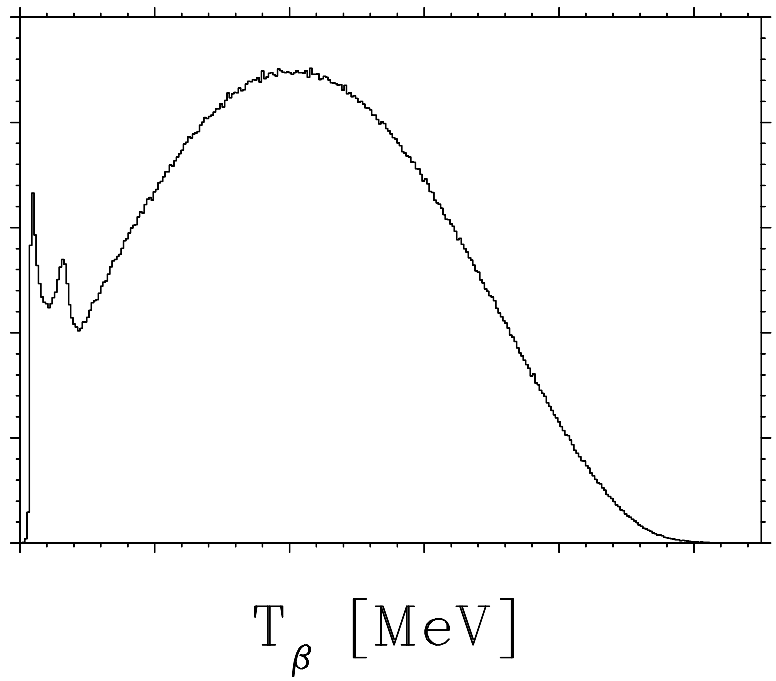


- perform a β decay experiment on **short-lived** isotopes
- make a **precision measurement** of the angular correlation parameters
- **compare** the SM predictions to observations
- look for **deviations** as an indication of **new physics**

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)

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



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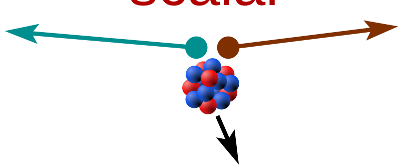
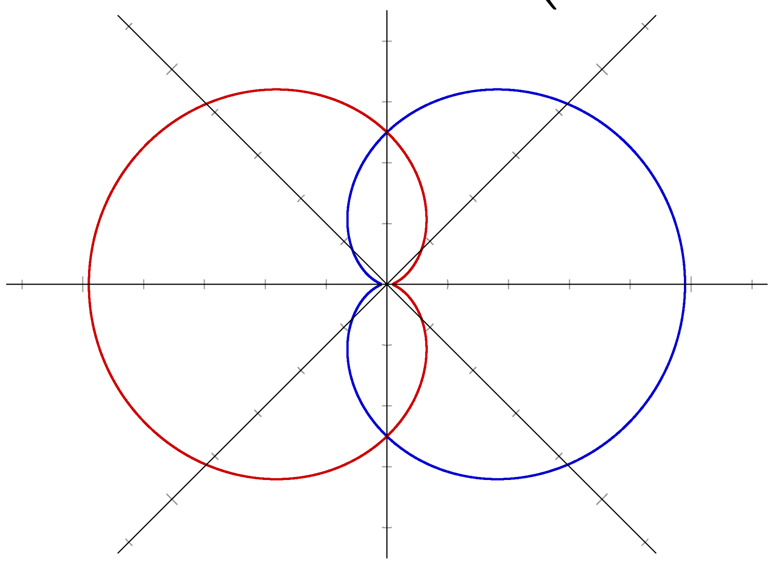
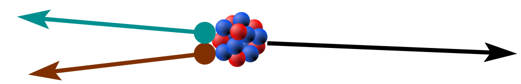
scalar



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



vector



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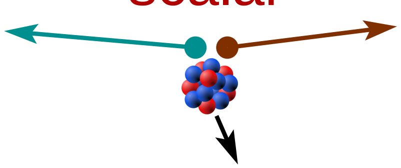

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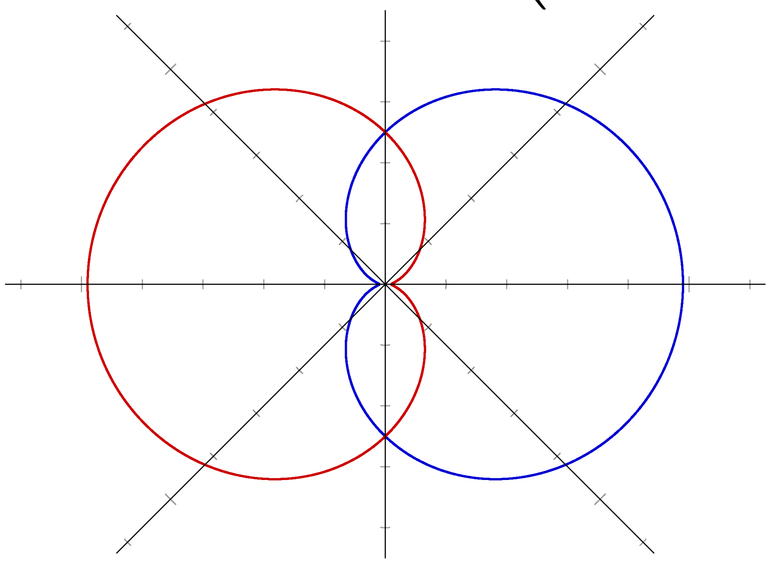

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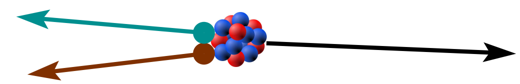

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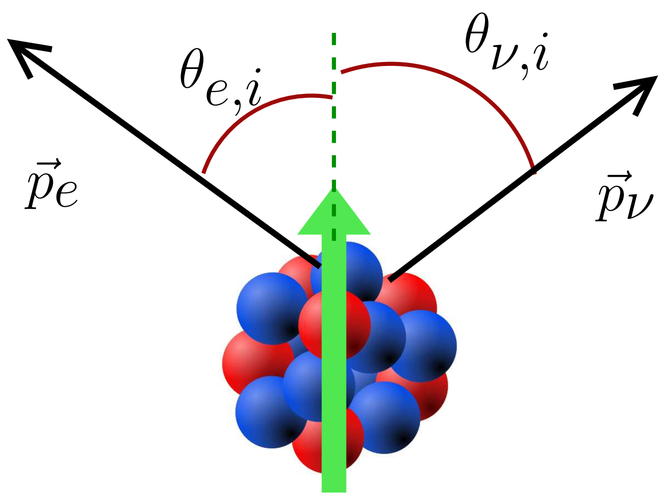

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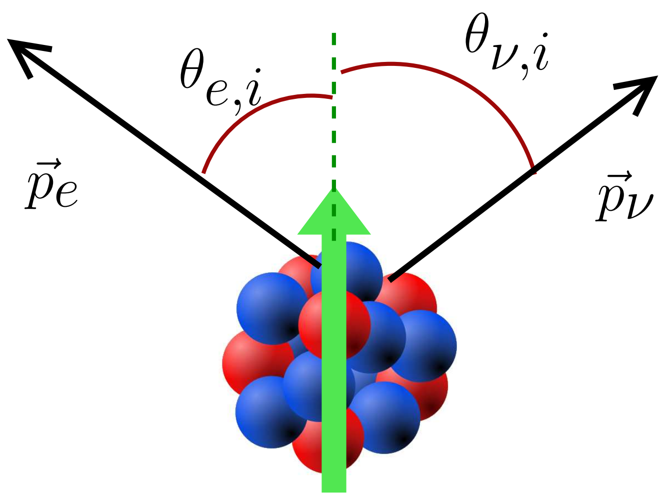

$$A_\beta = \frac{-2\rho}{1+\rho^2} \left[(1 - xy) \sqrt{\frac{3(1+x^2)}{5(1+y^2)}} - \frac{\rho(1-y^2)}{5(1+y^2)} \right]$$

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

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

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

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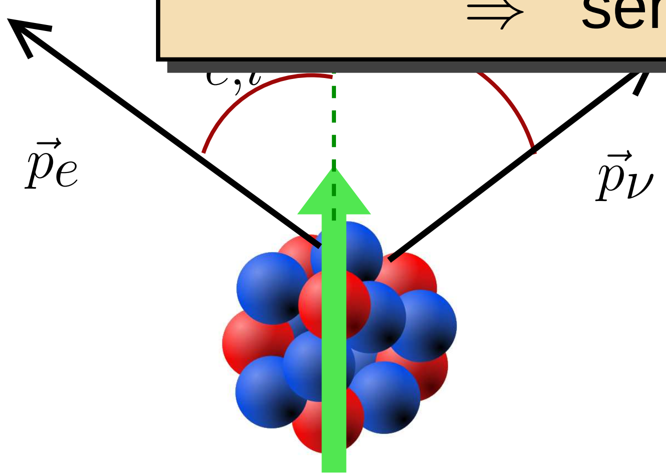
β-decay parameters depend on the currents mediating the weak interaction
$\Rightarrow$ sensitive to new physics $\Leftarrow$



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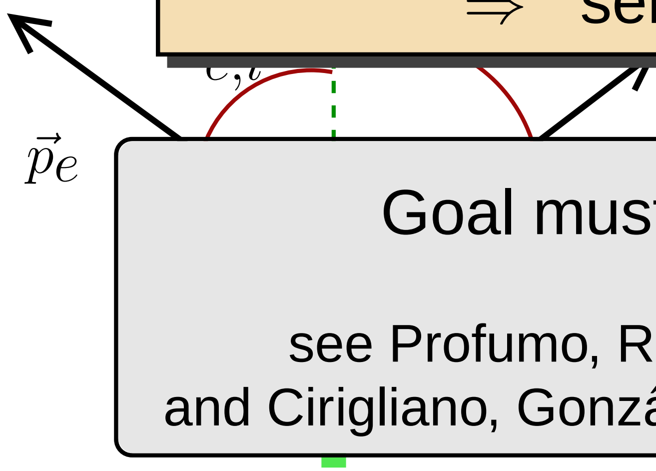

Goal must be **0.1%** to complement LHC

see Profumo, Ramsey-Musolf and Tulin, PRD **75** (2007)
and Cirigliano, González-Alonso and Graesser, JHEP **1302** (2013)

Overview

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- 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

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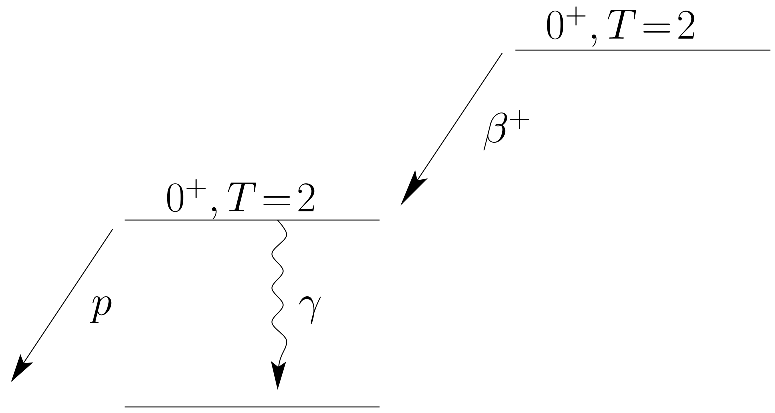
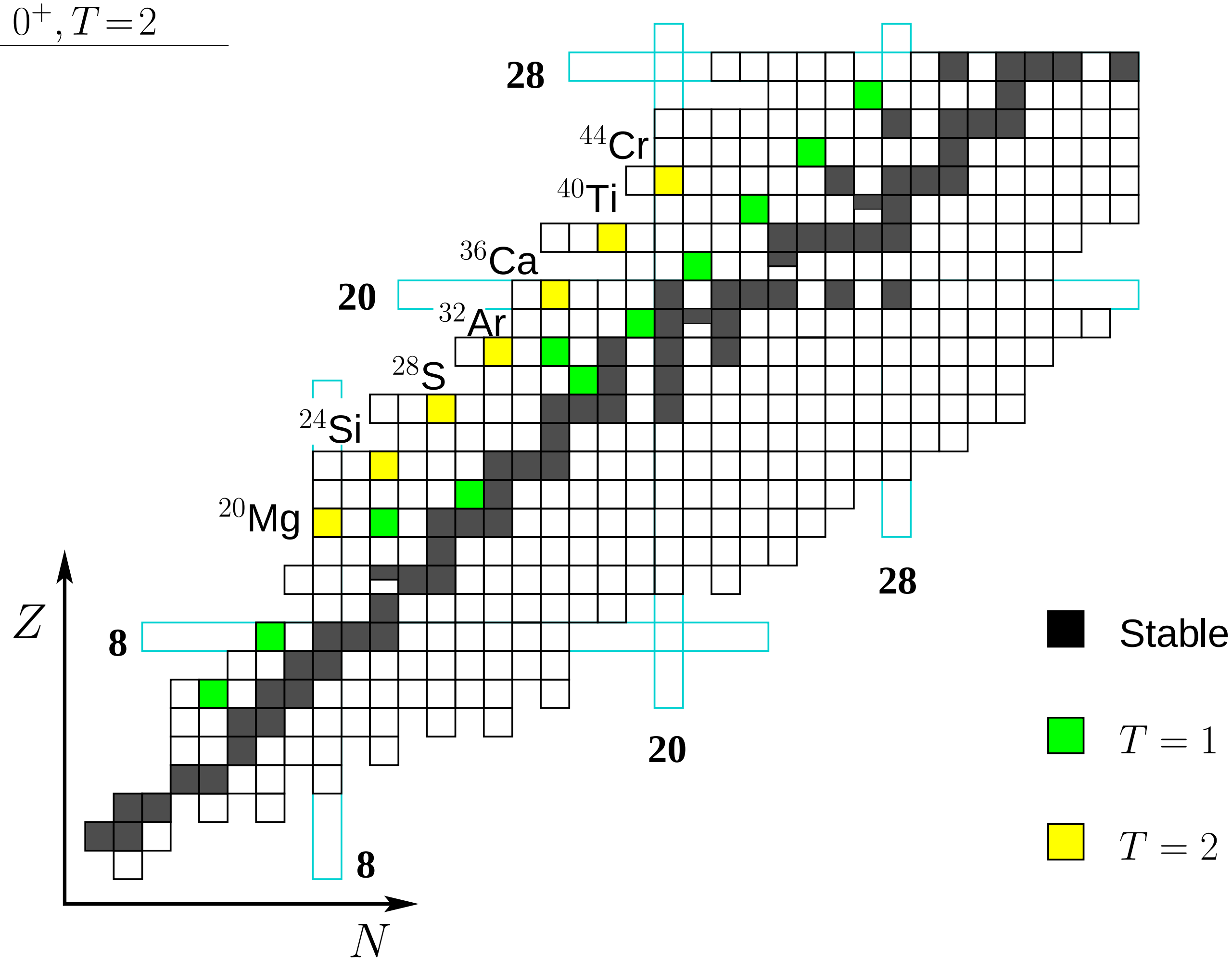
- **preliminary results** of a recent run

$T = 2$ superallowed decays





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

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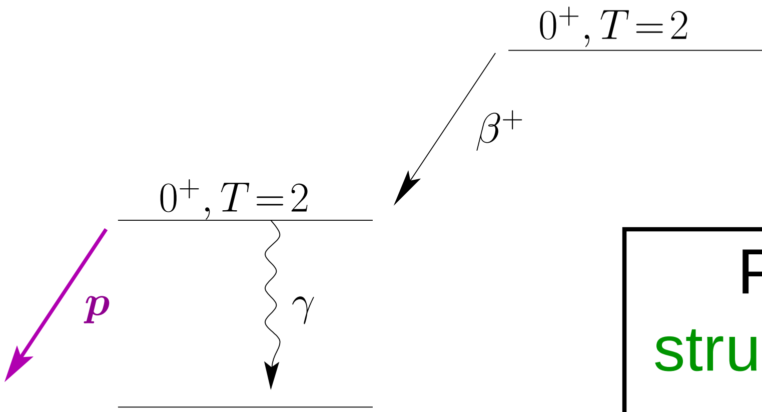

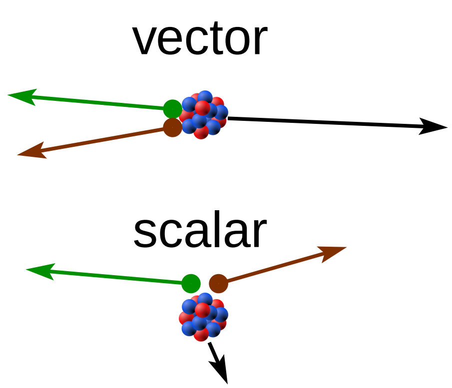

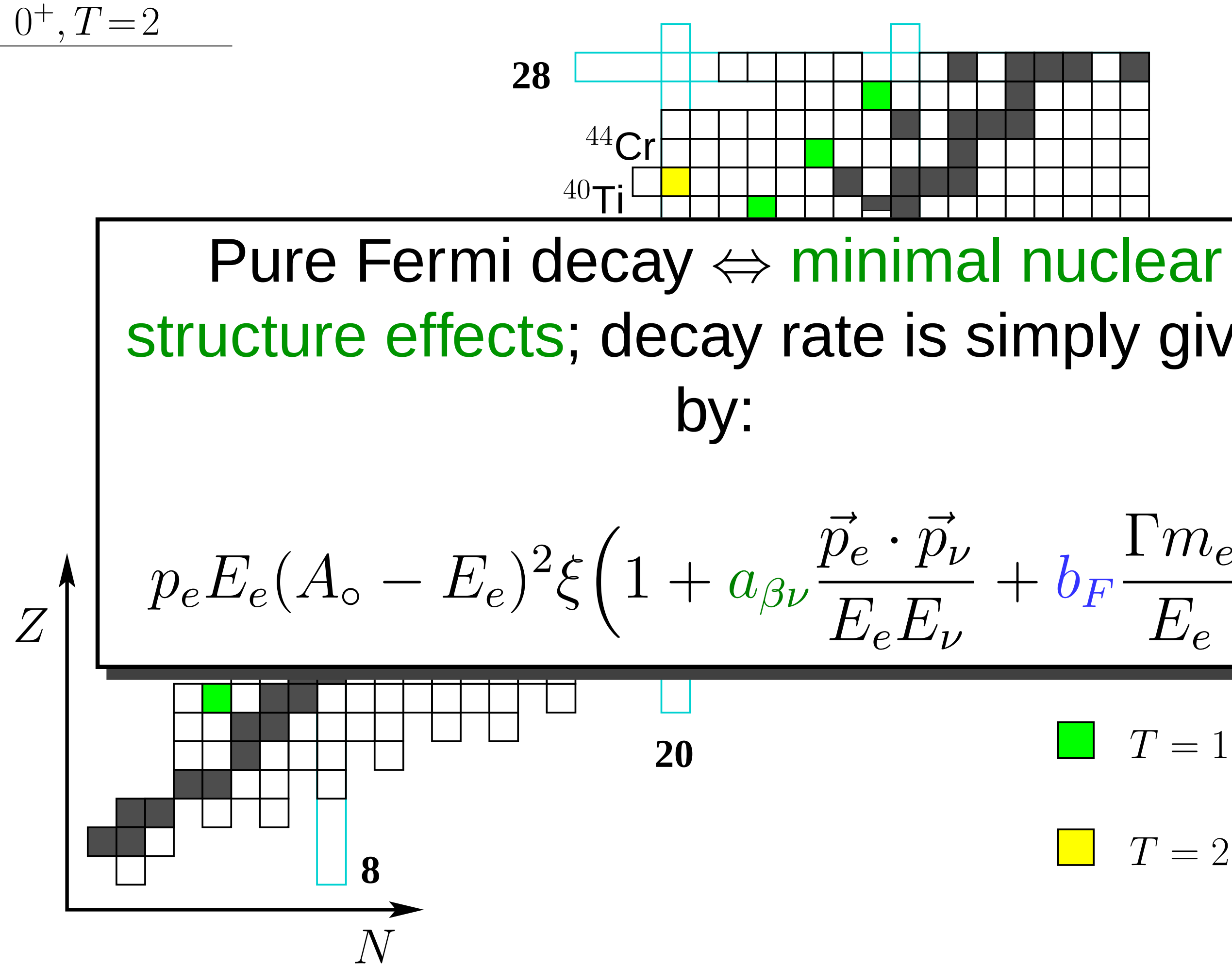

Pure Fermi decay $\Leftrightarrow$ minimal nuclear structure effects; decay rate is simply given by:

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

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- 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

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[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 $\vec{p}_e \cdot \vec{p}_\nu$!

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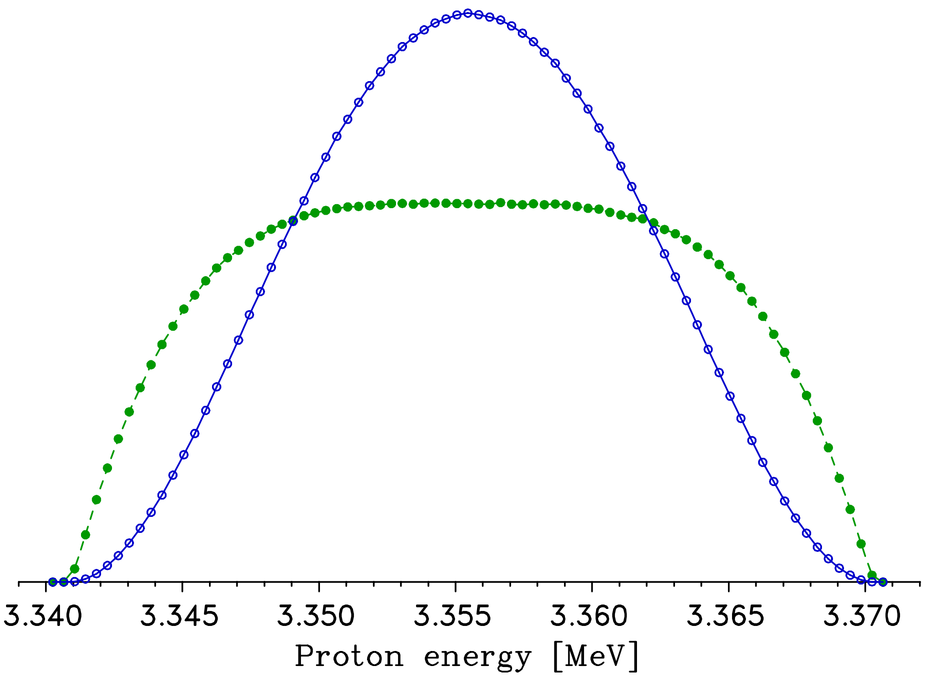

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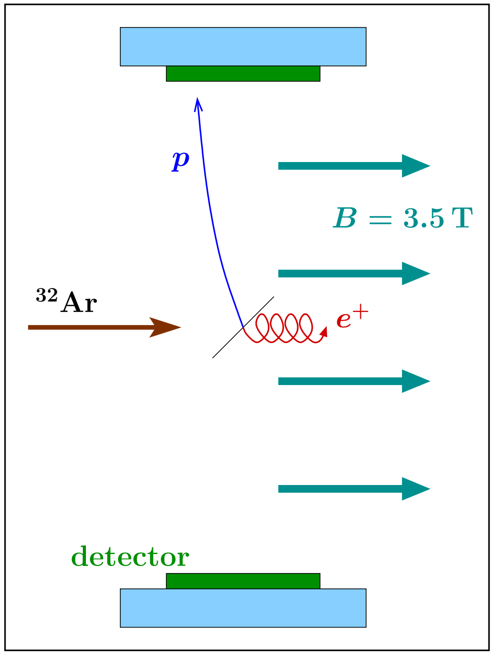

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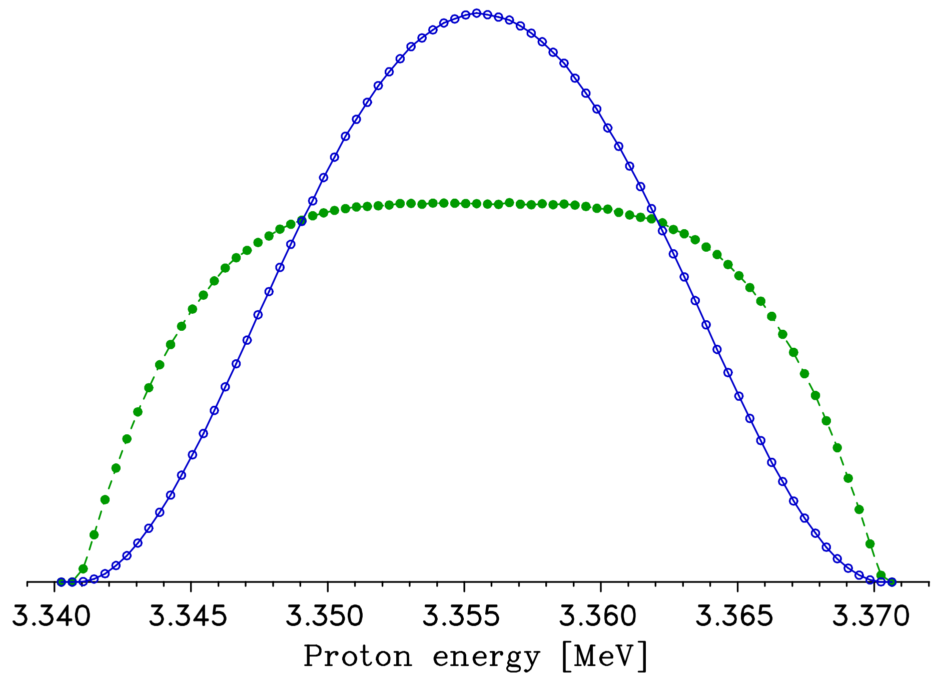

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But why throw away useful information??

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

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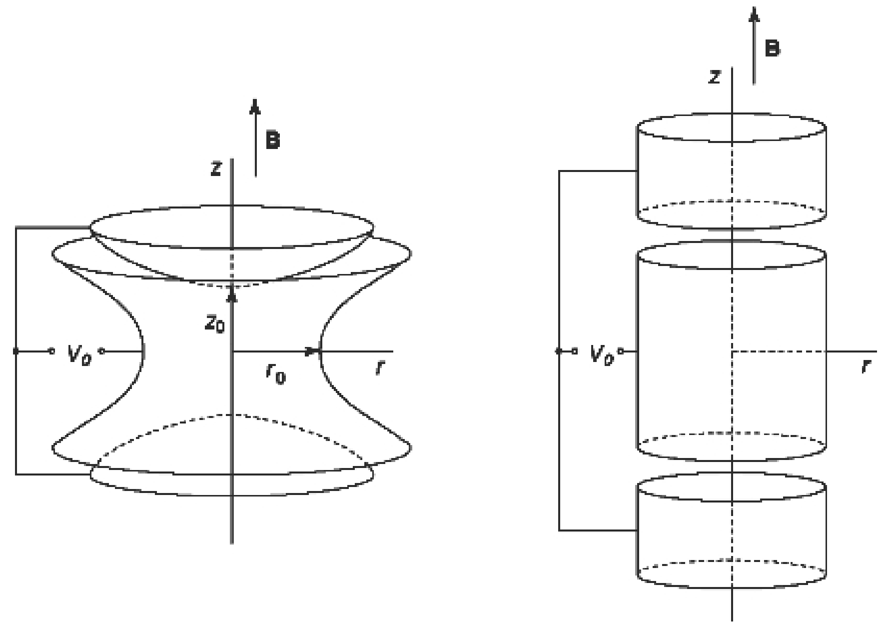

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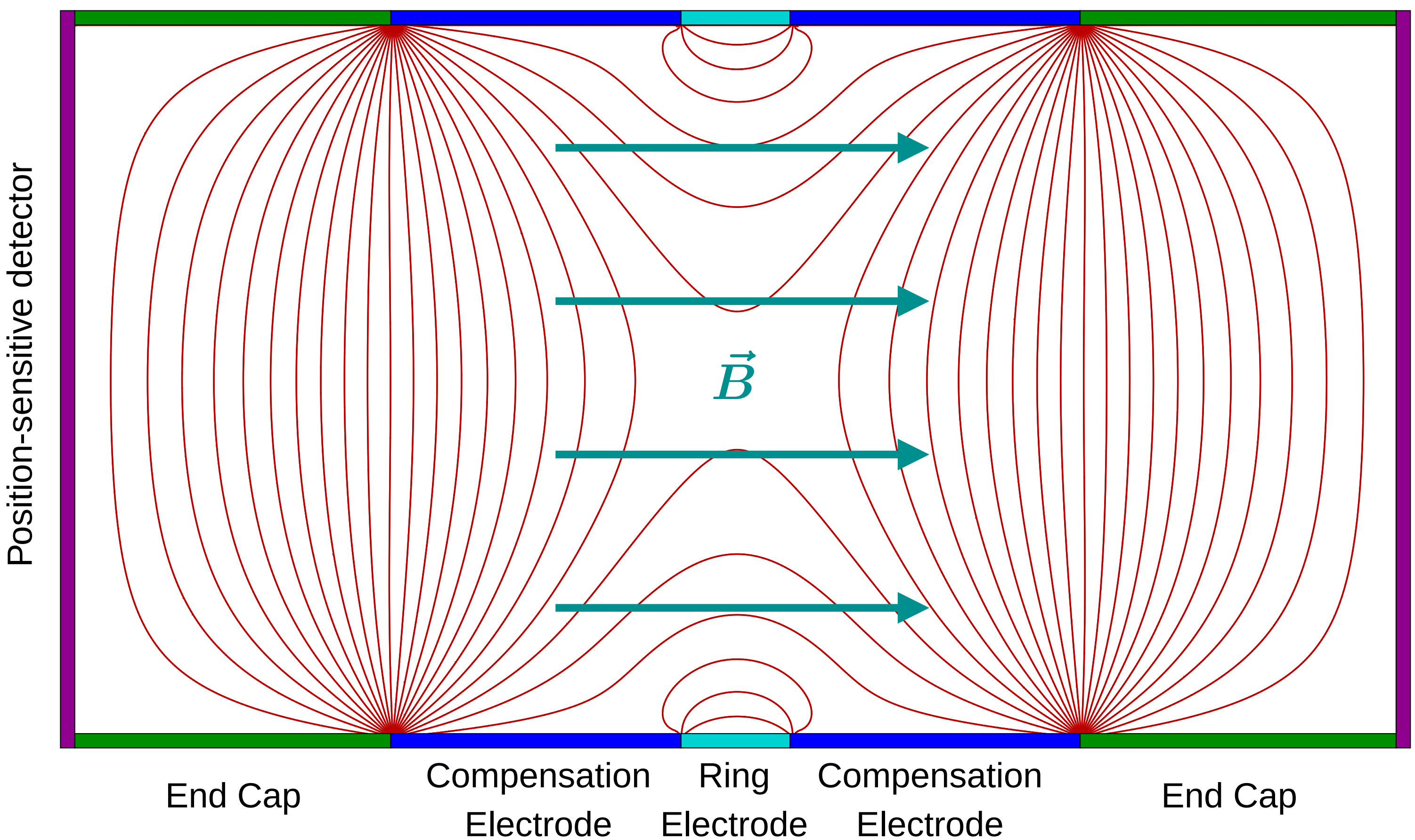

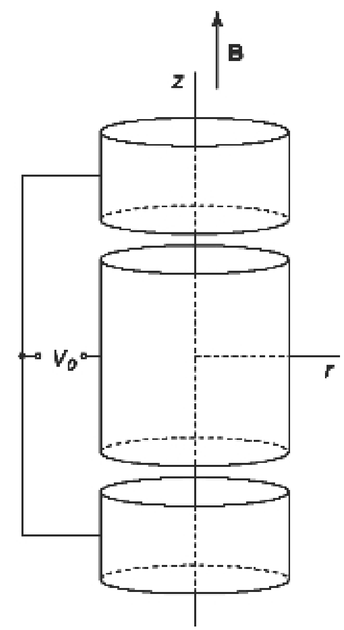

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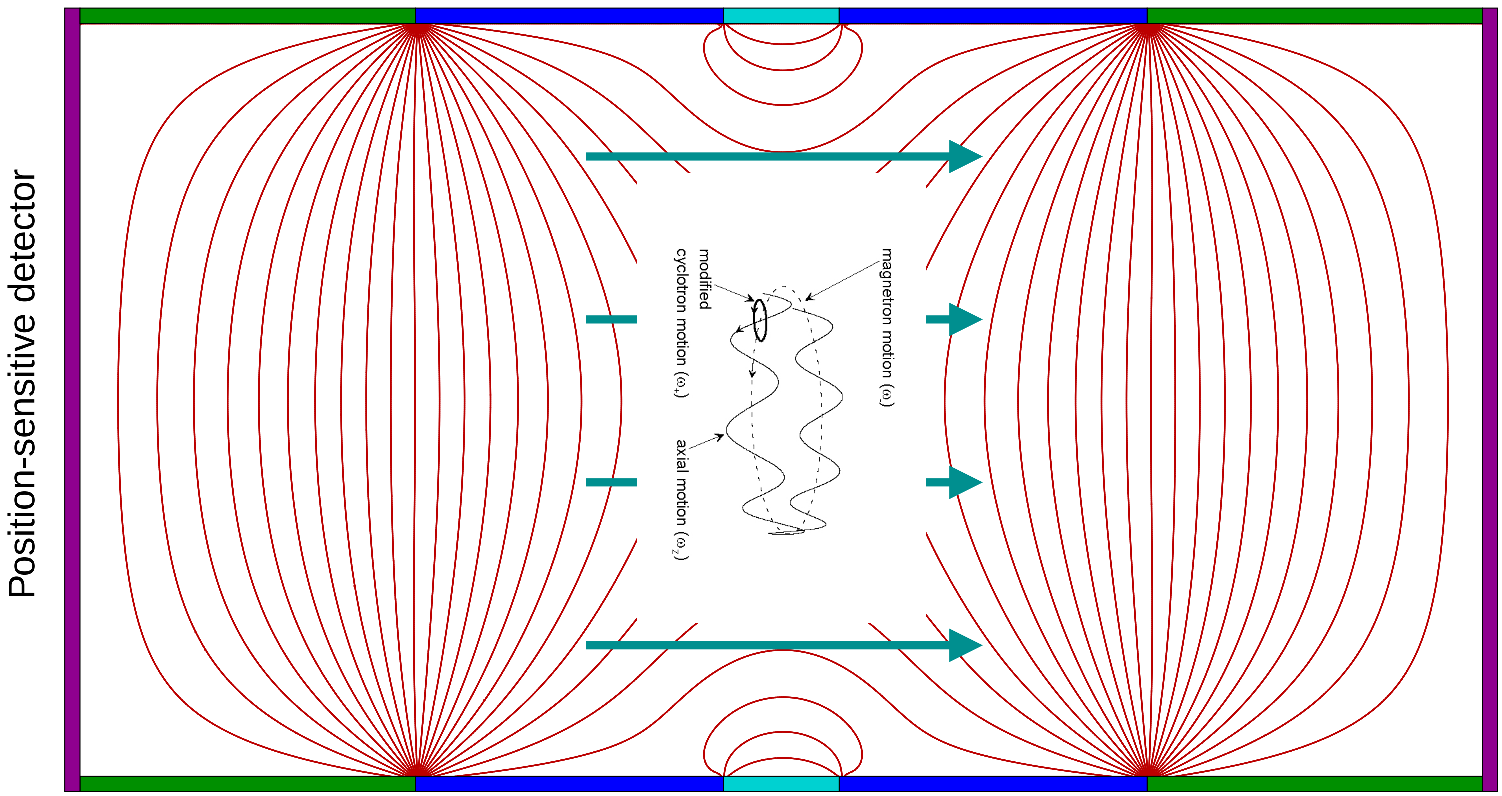

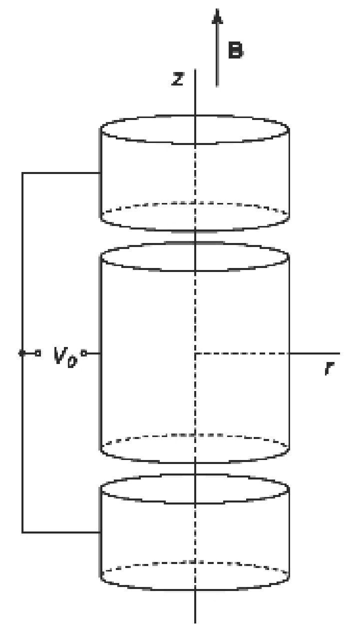

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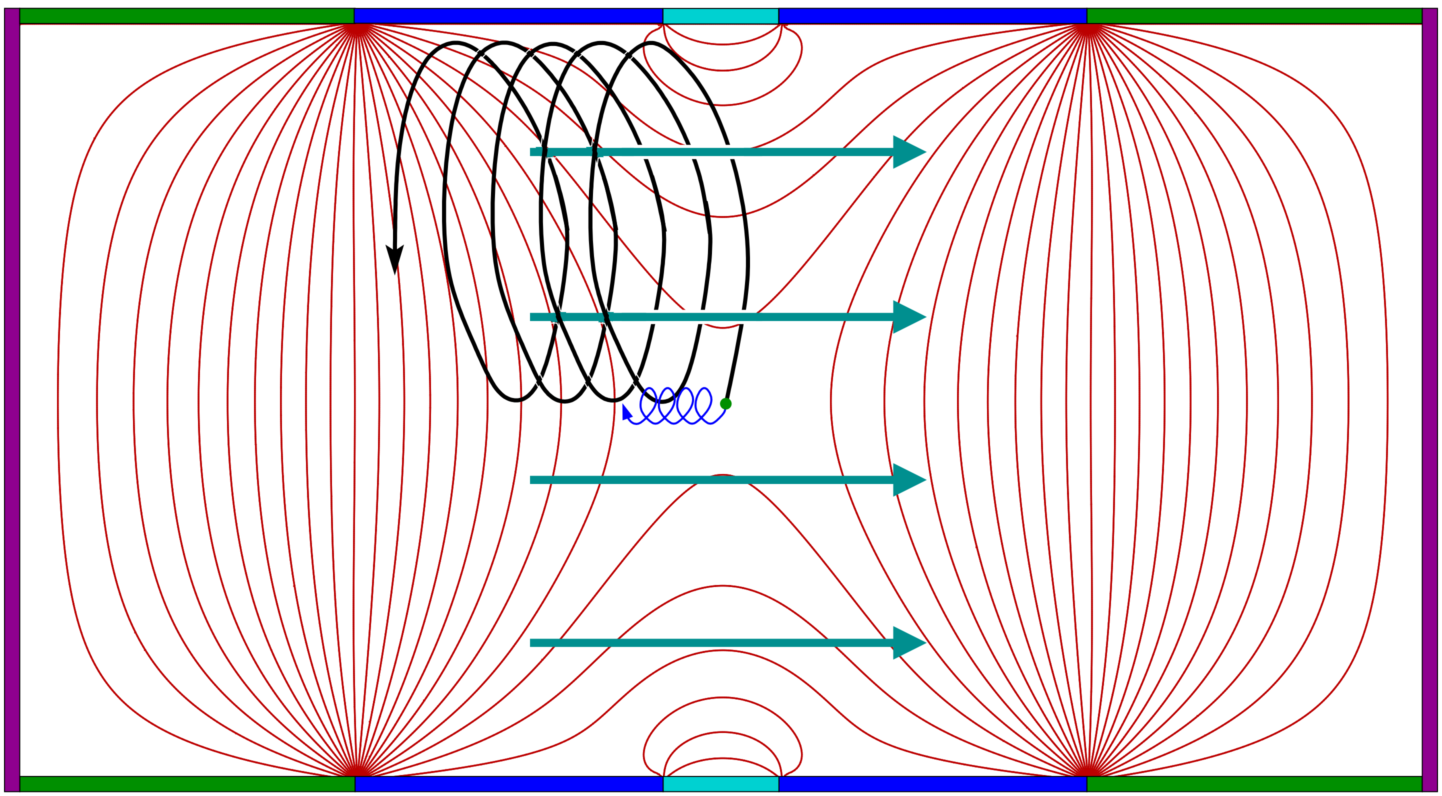

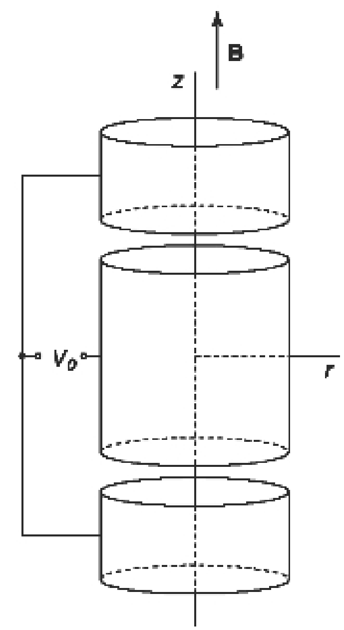

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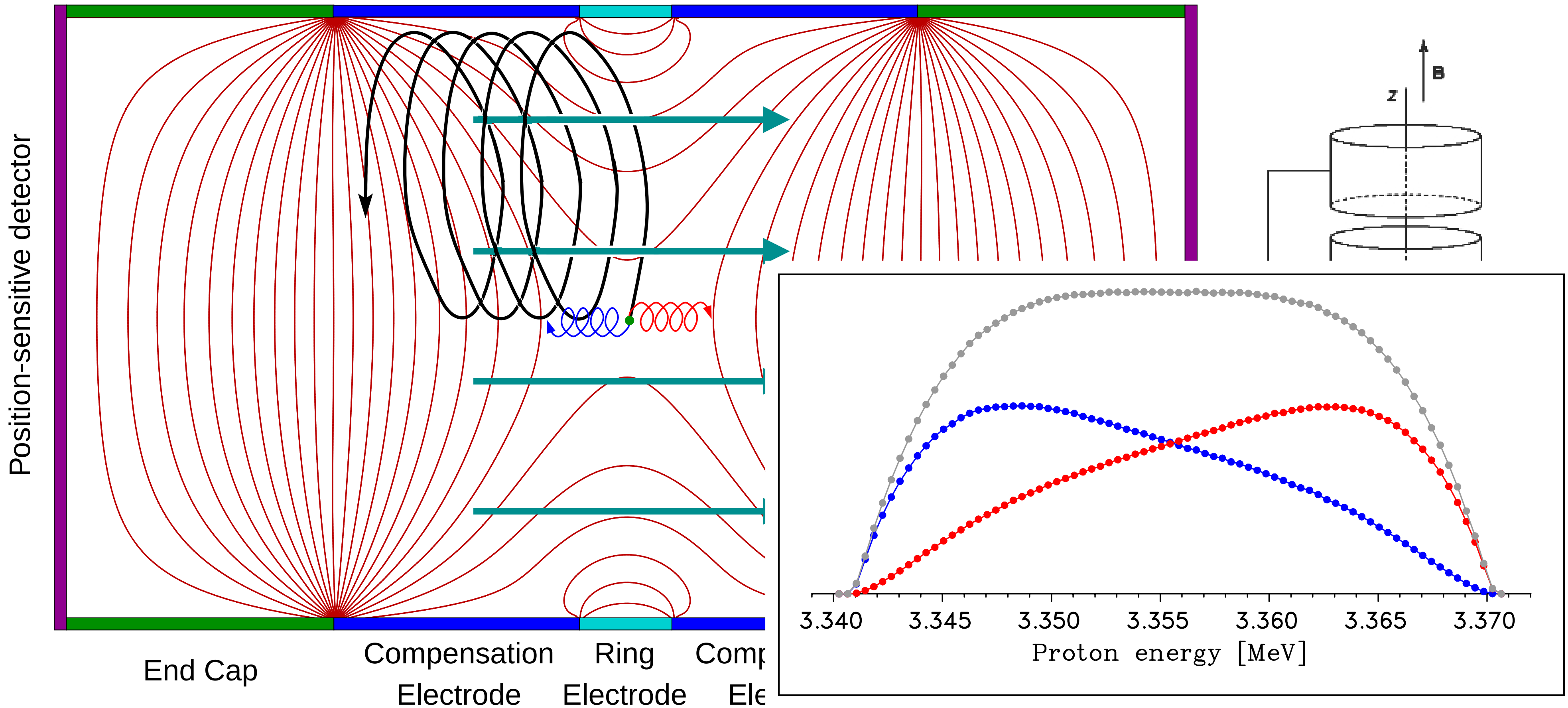
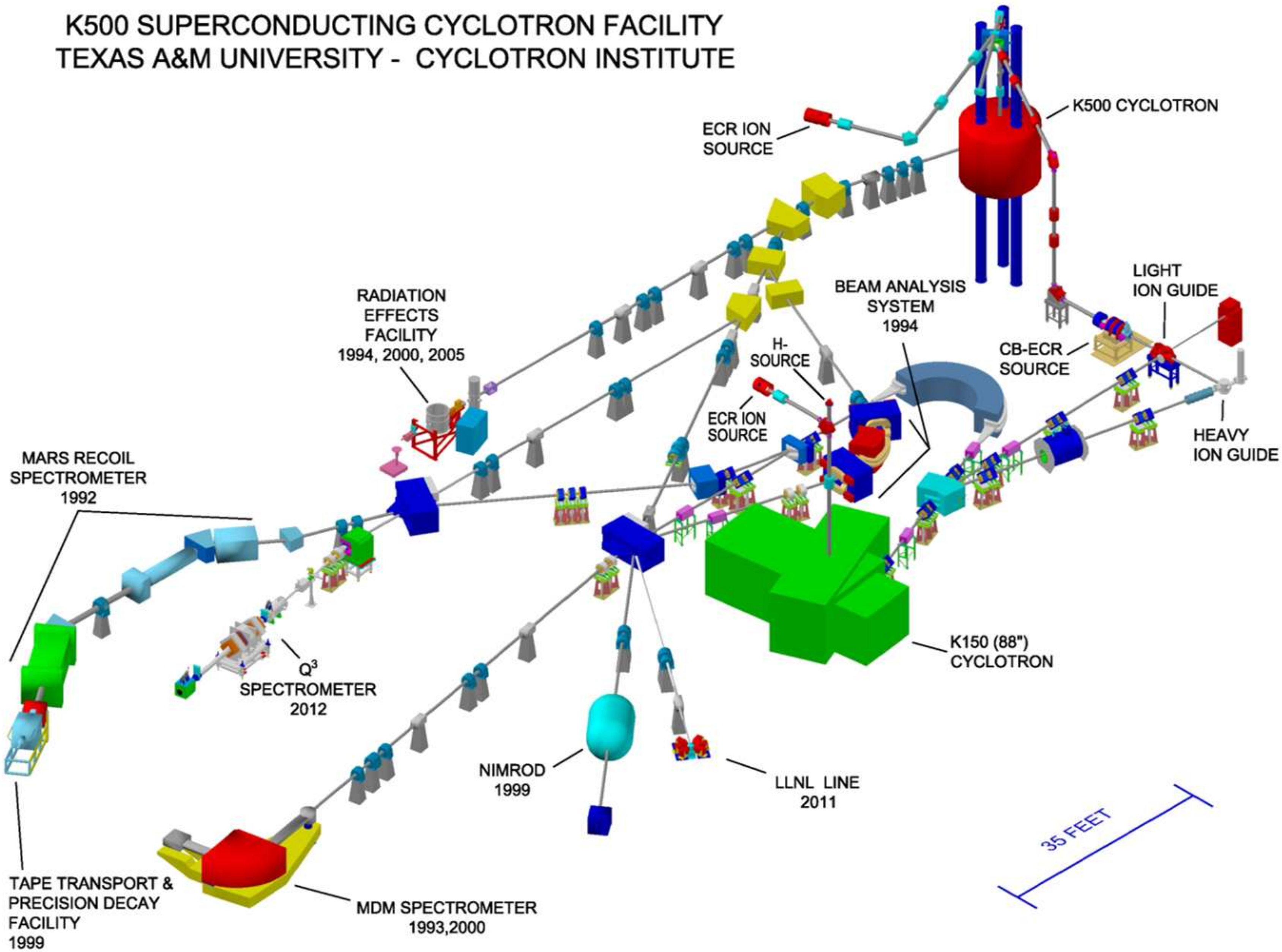
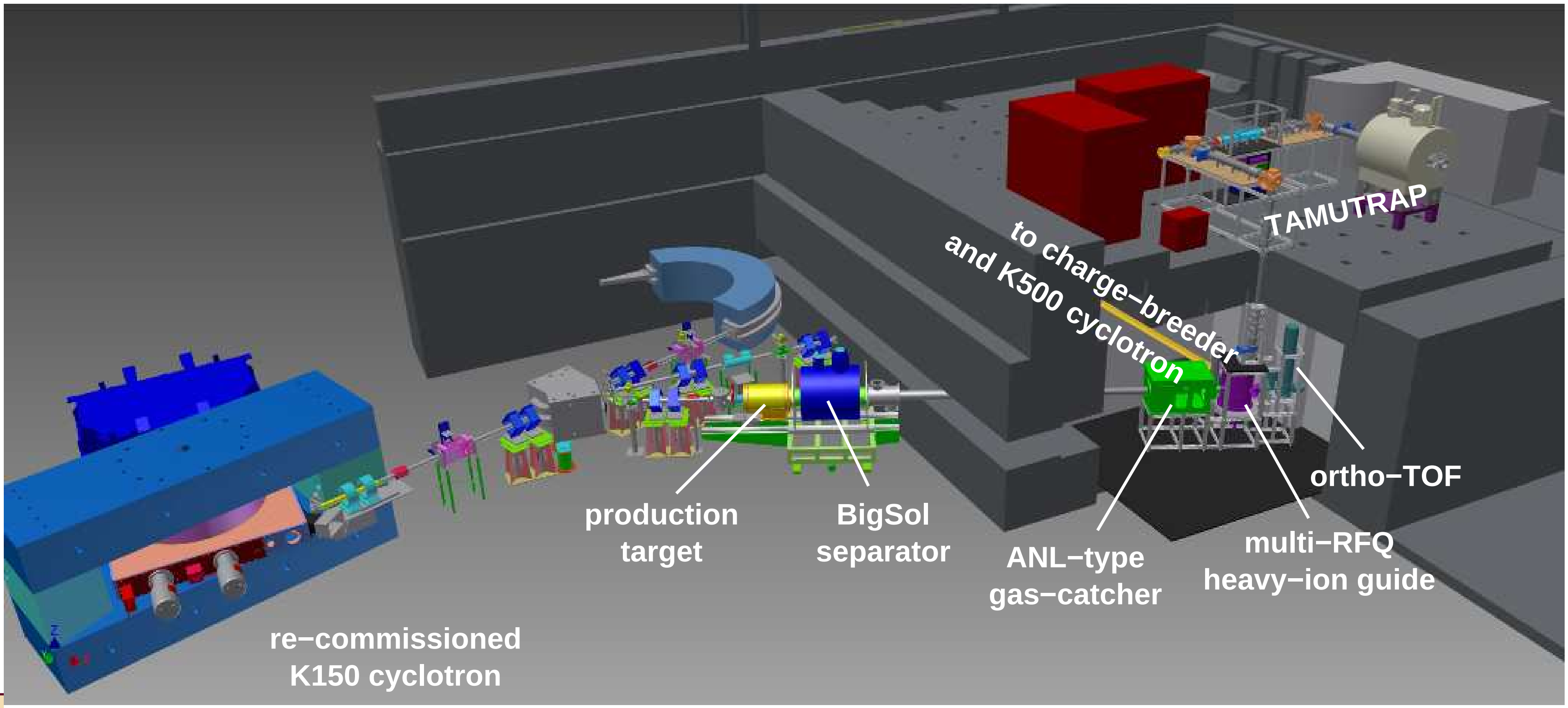


A Penning trap at T-REX CI/TAMU



The Texas A&M University Penning Trap

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



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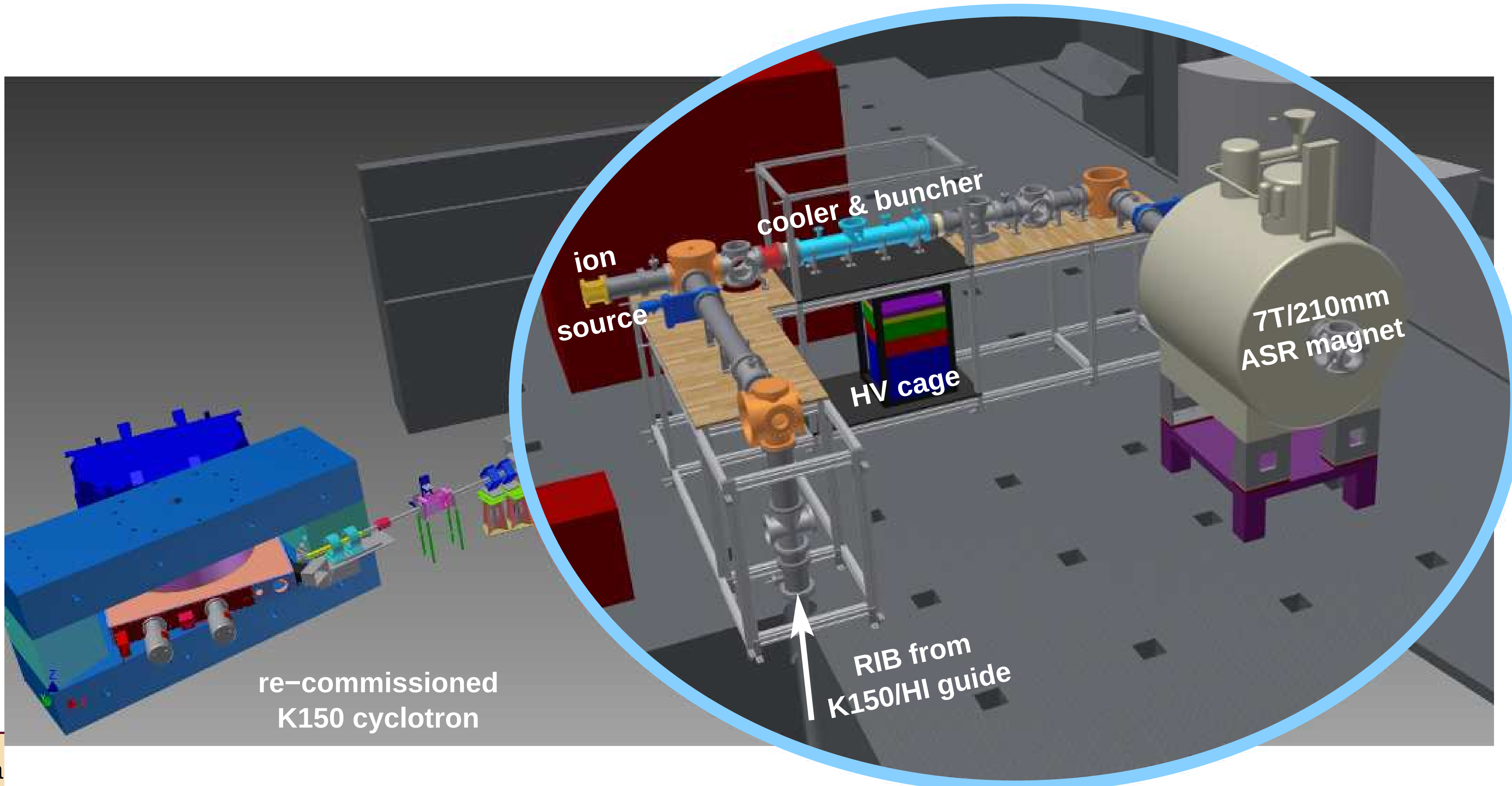

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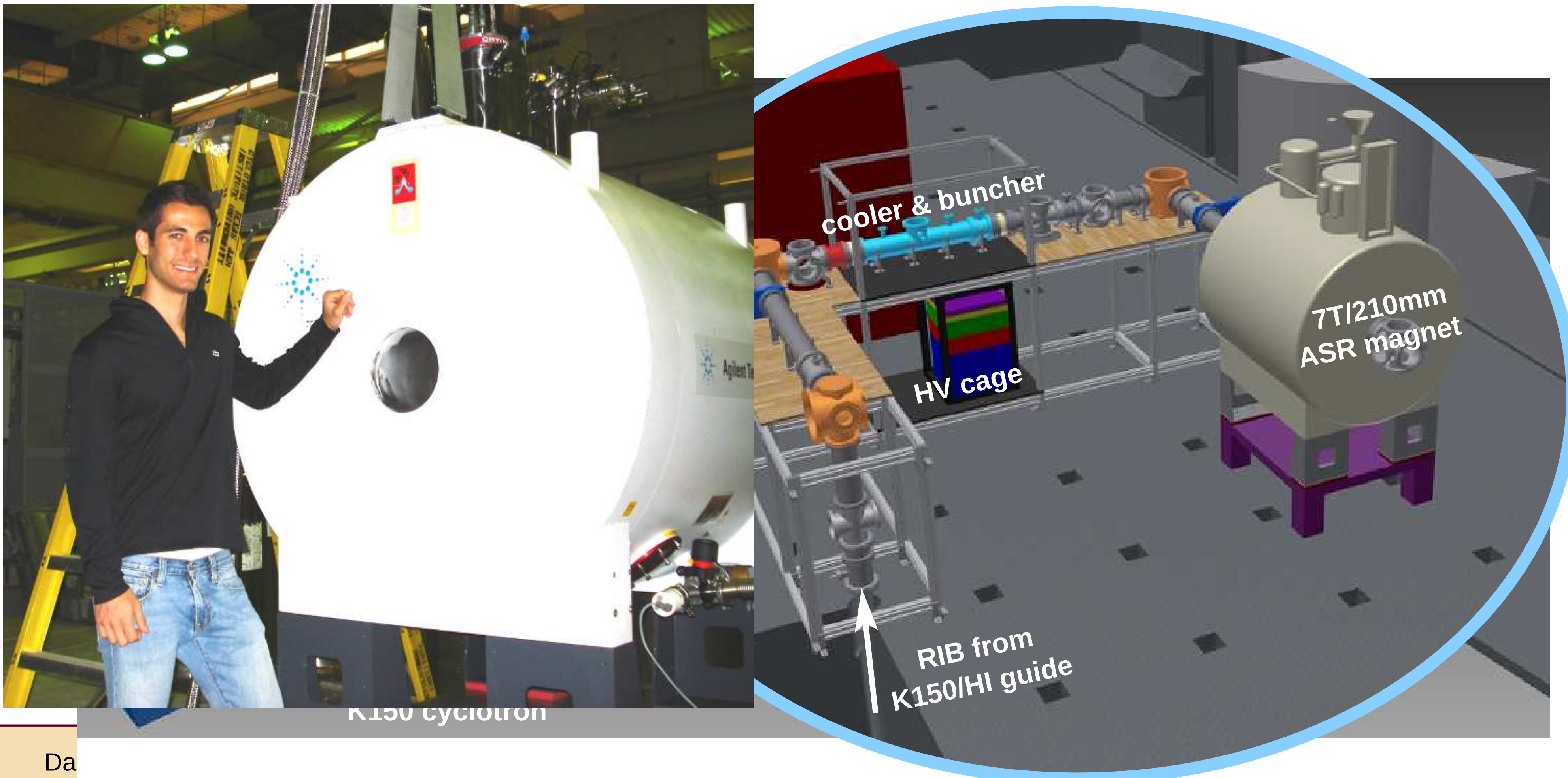

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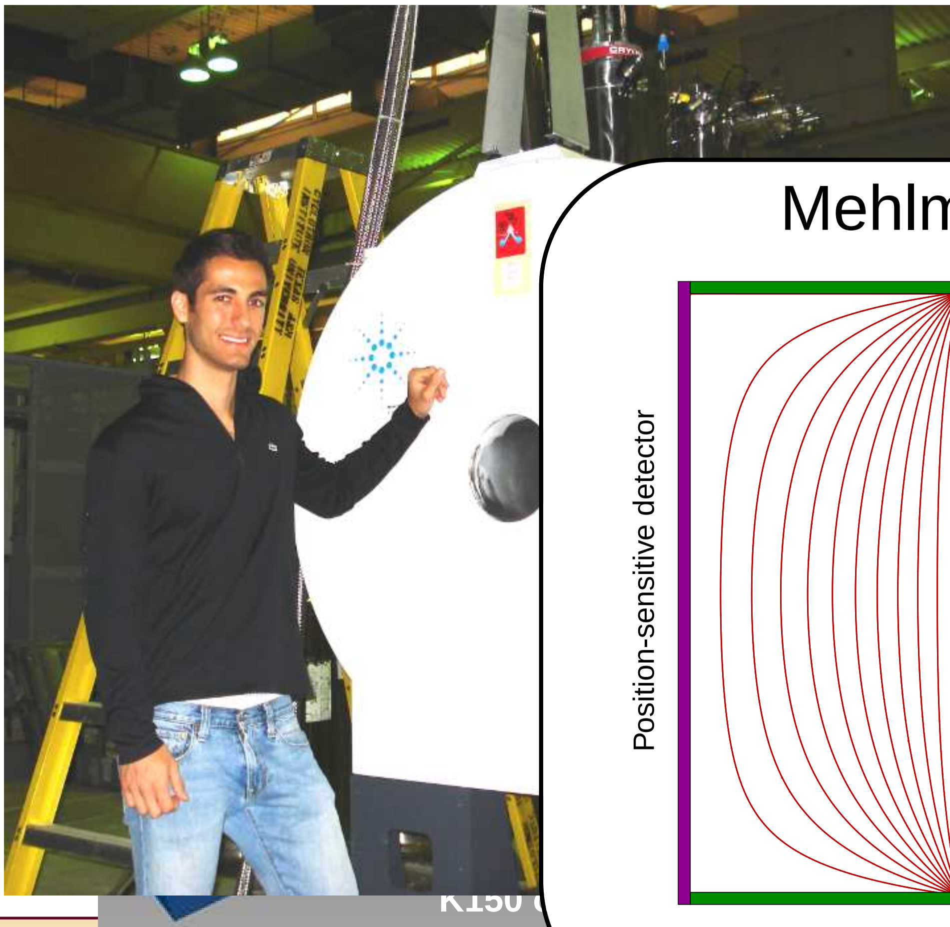
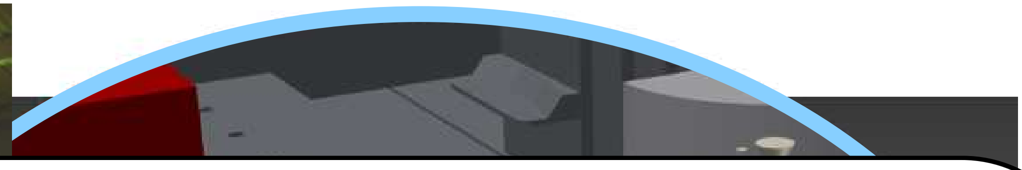
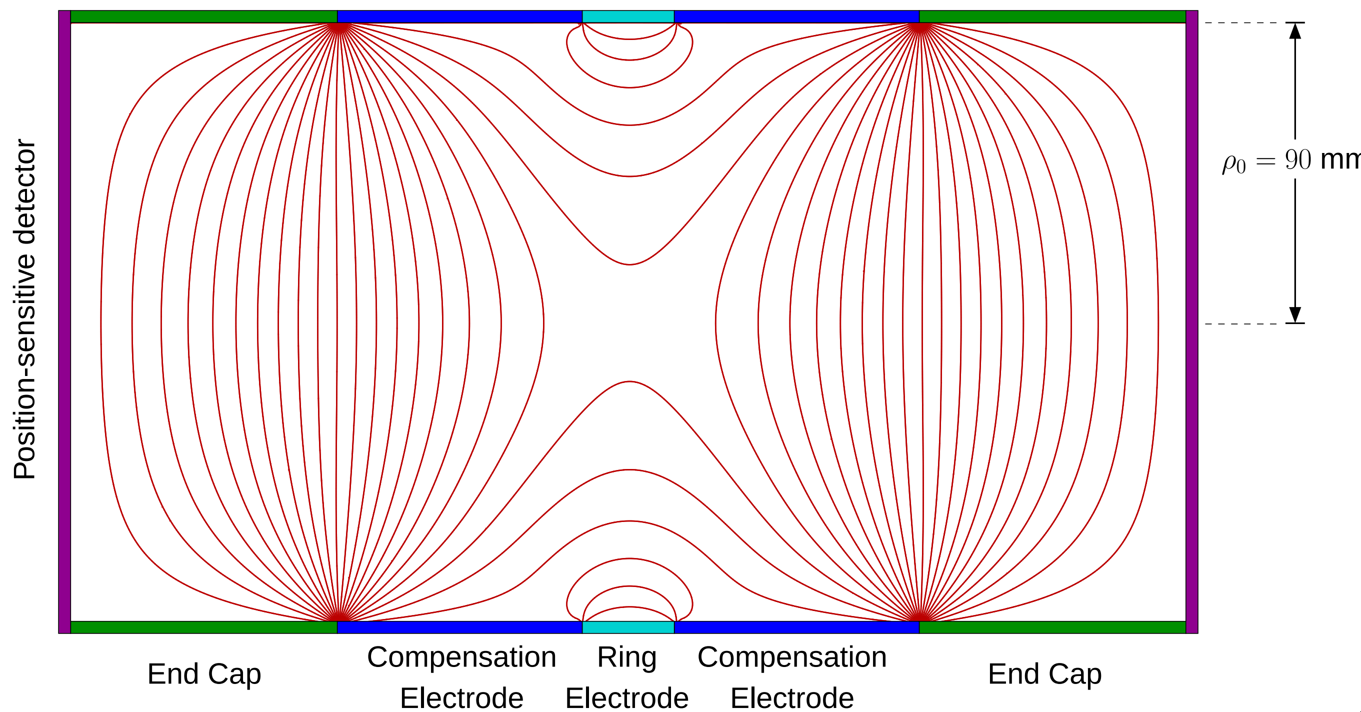
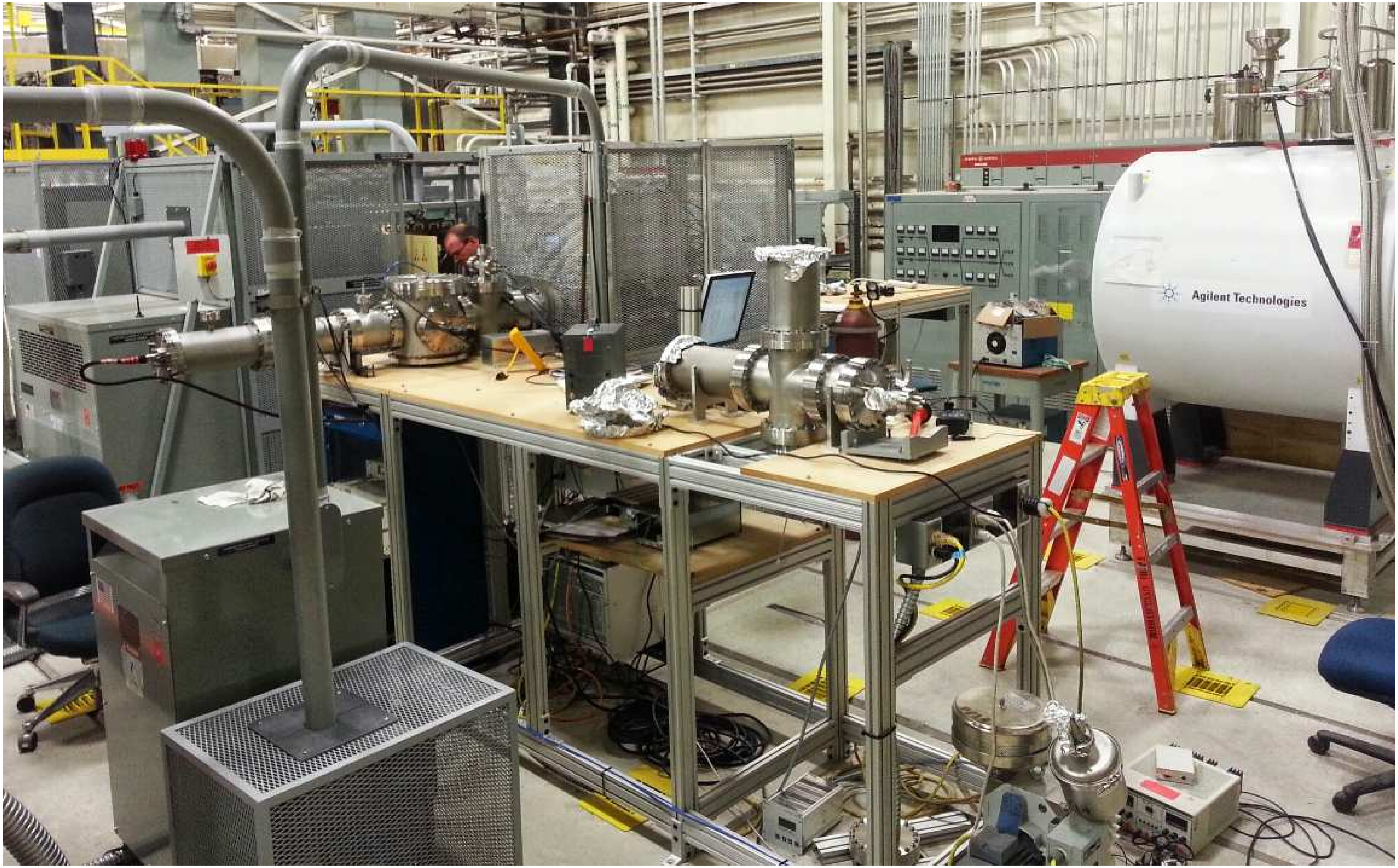




Mehlman *et al.*, NIM **A712**, 9 (2013)



Current status (come visit and see!)



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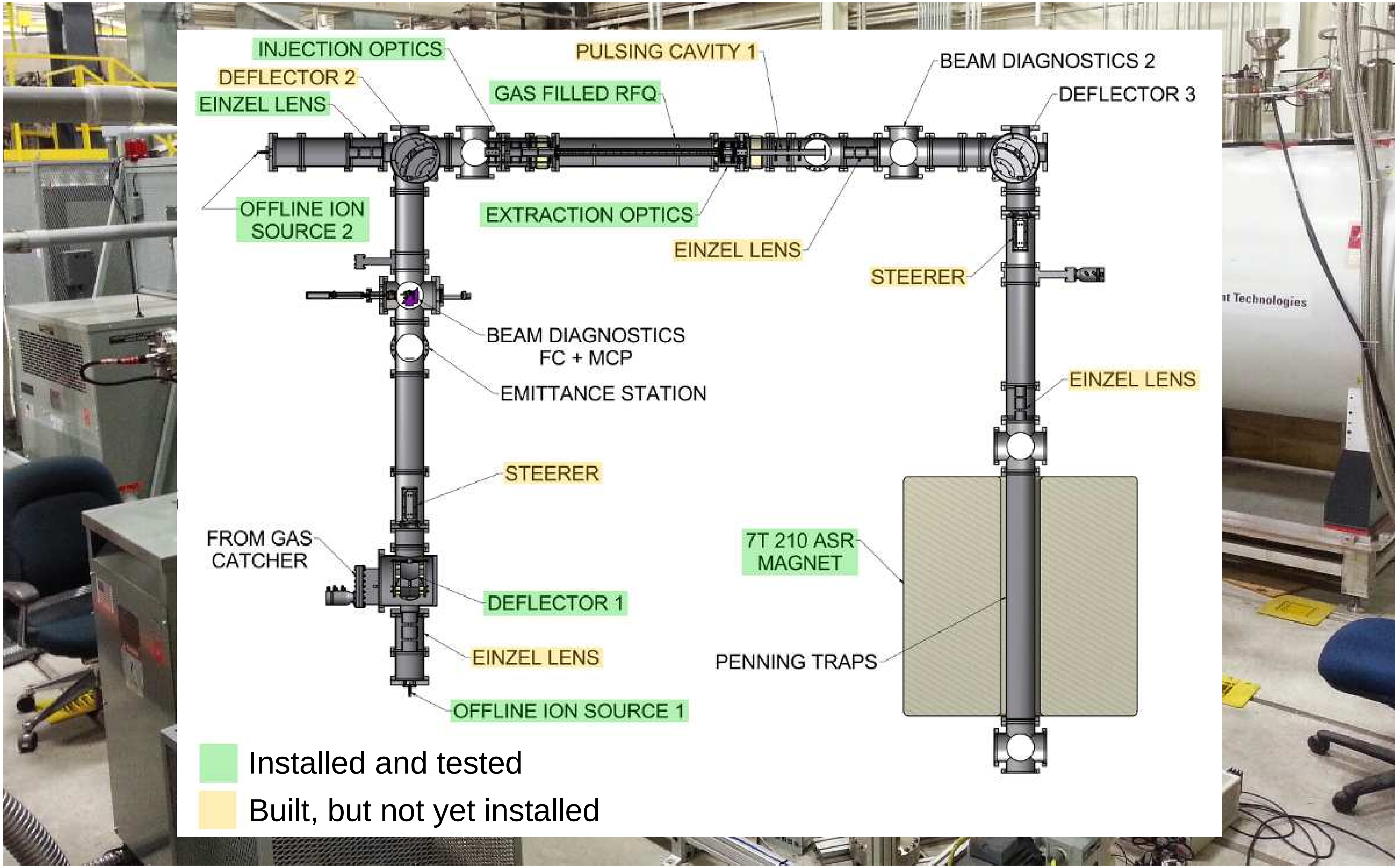

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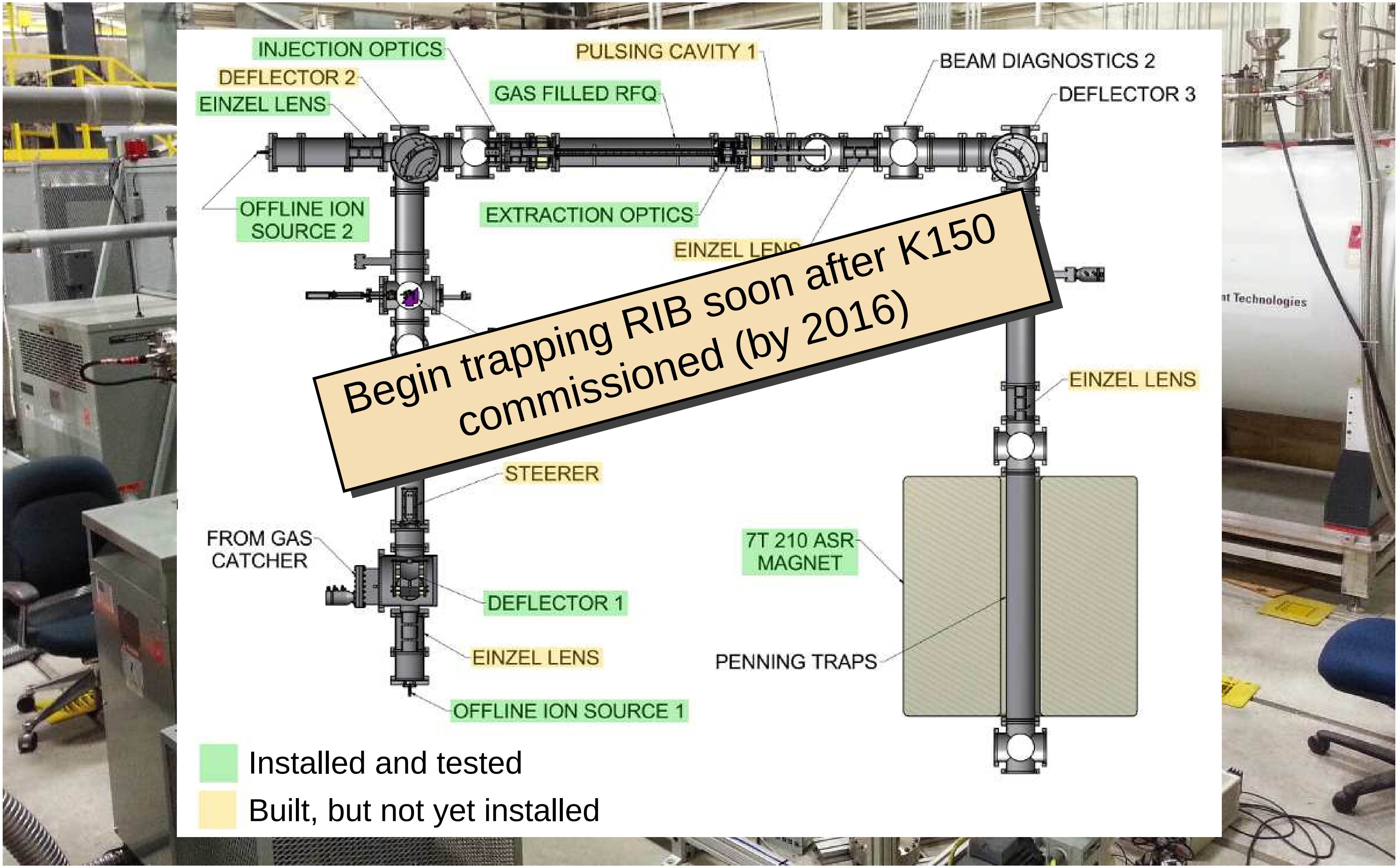
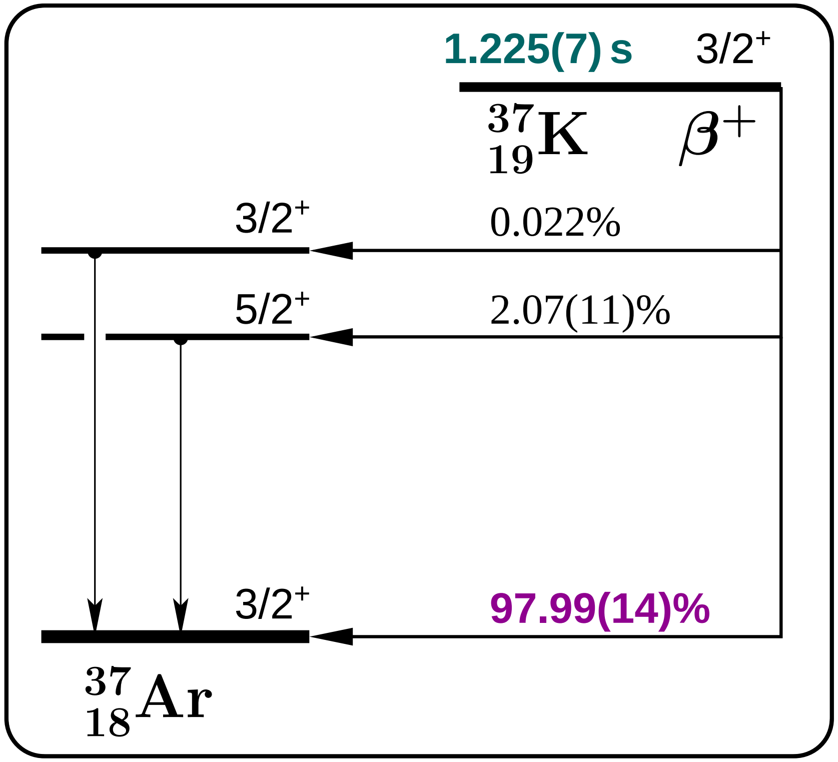


Overview

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 the neutron:



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- **strong** branch to g.s.

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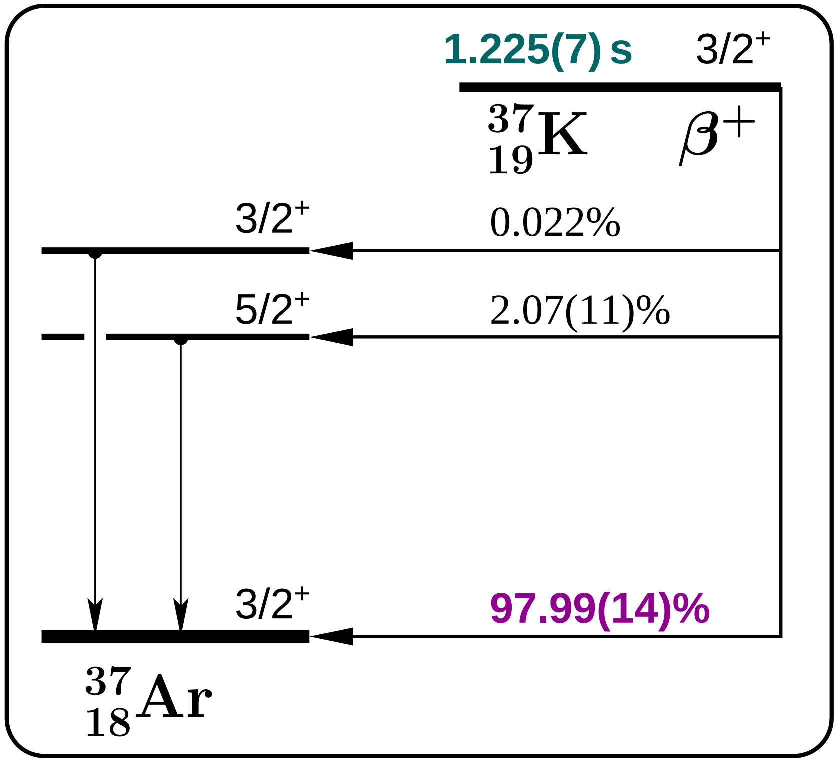

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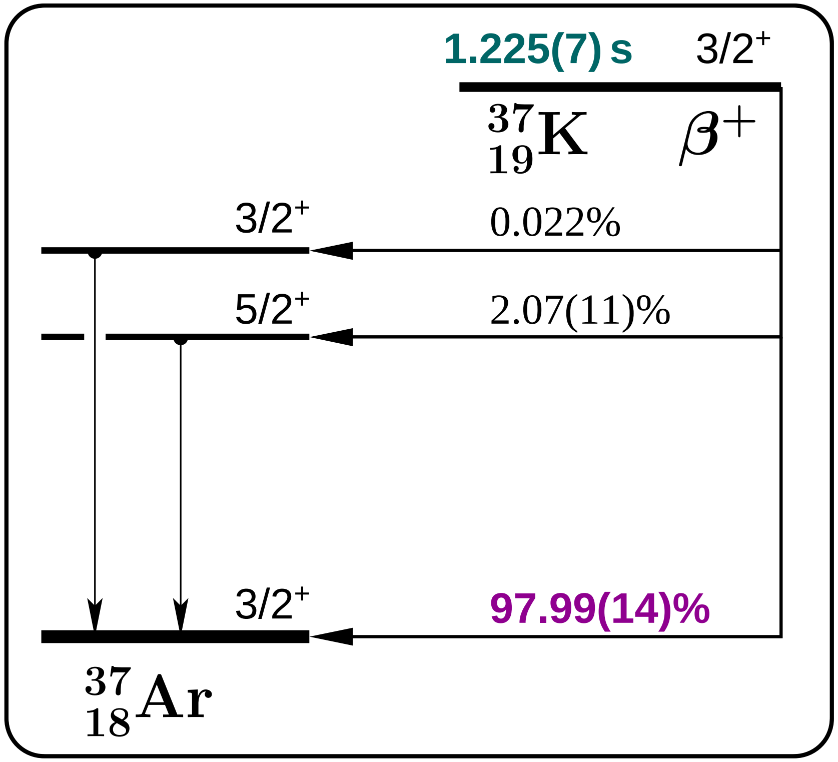

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$$\rho^2 = \frac{2\mathcal{F}t^{0^+\to 0^+}}{\mathcal{F}t} - 1$$

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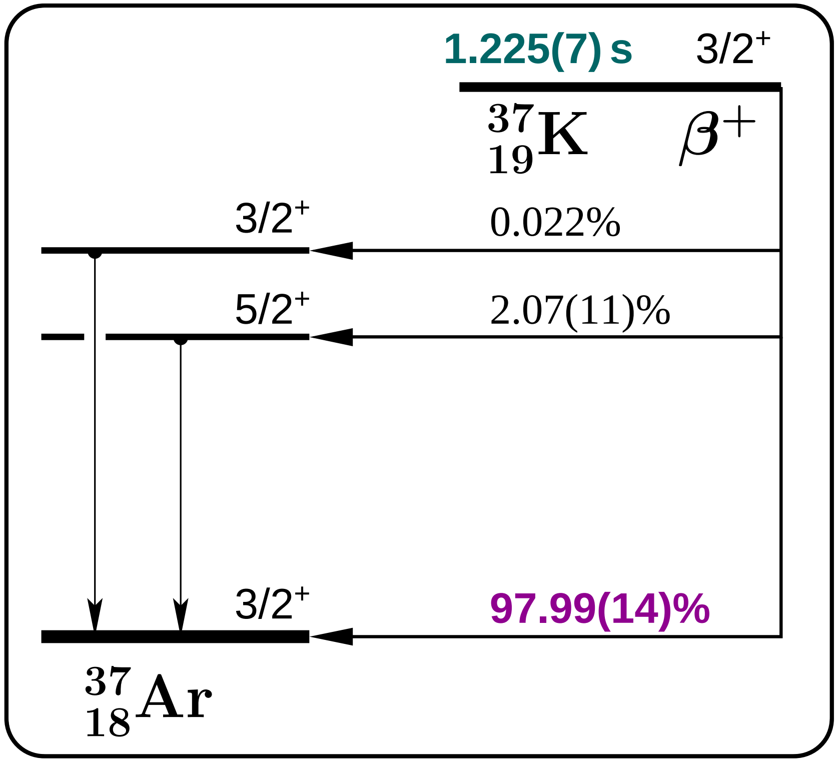

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$$\rho^2 = \frac{2\mathcal{F}t^{0^+\rightarrow 0^+}}{\mathcal{F}t} - 1$$

Q_{EC}: $\pm$0.003%

BR: $\pm$0.14%

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

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

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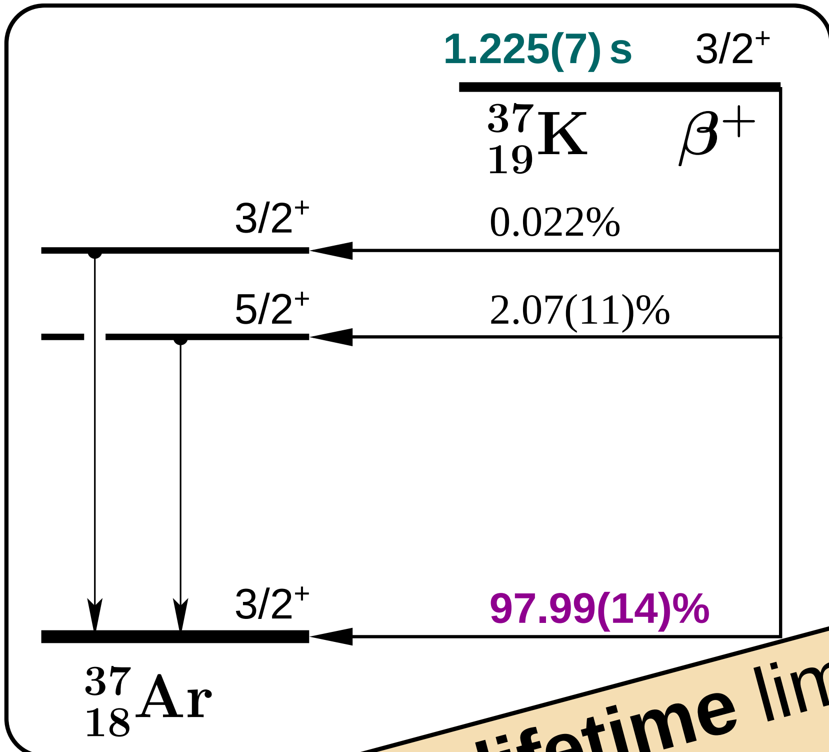

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$\Rightarrow$ need $\rho \equiv$ [illegible] $/G_V M_F$

to [illegible] 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 [illegible] $- 1$, with $\mathcal{F}t$ in the denominator

Q_{EC}: [illegible]

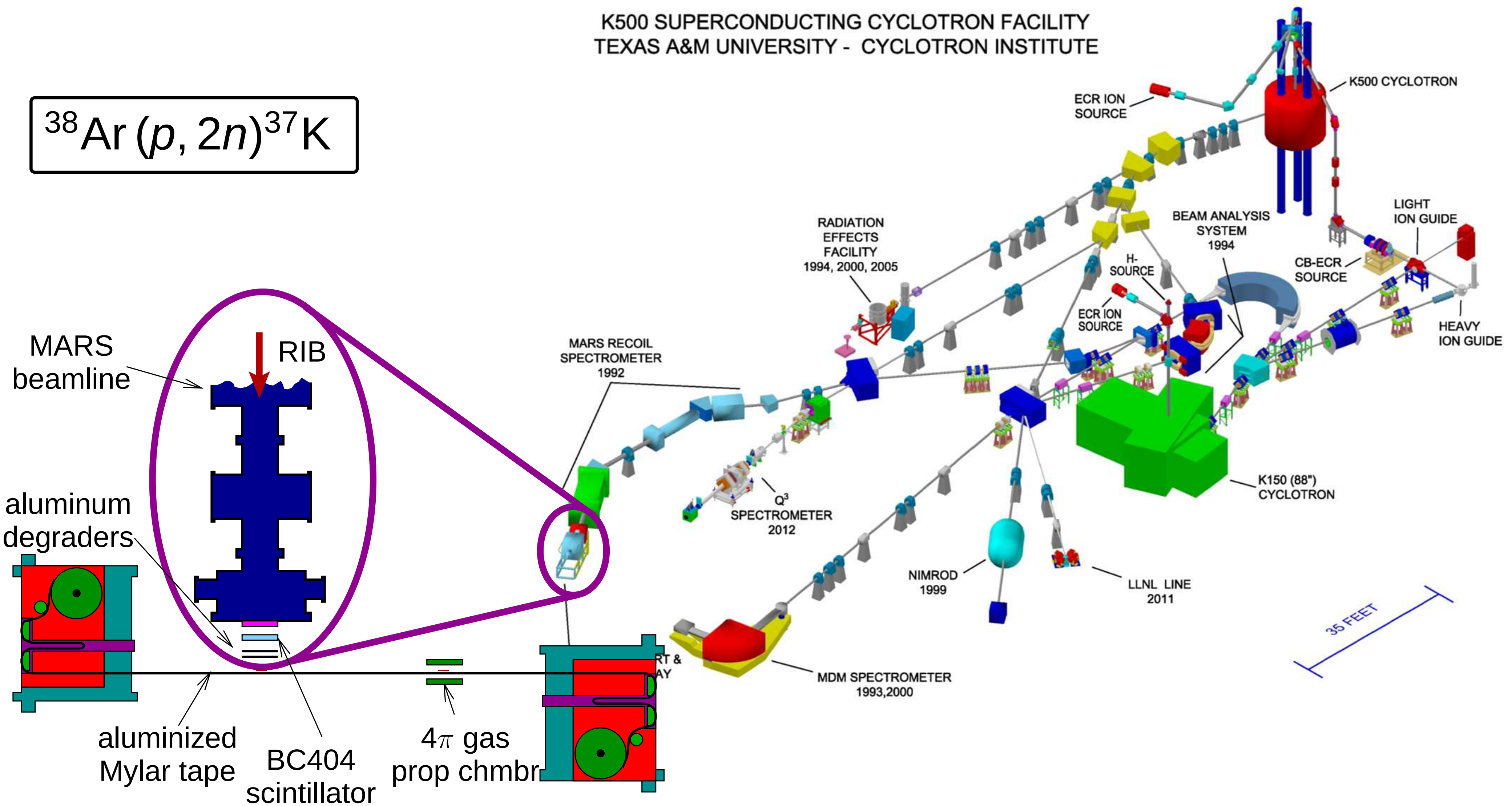
BR: [illegible]

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

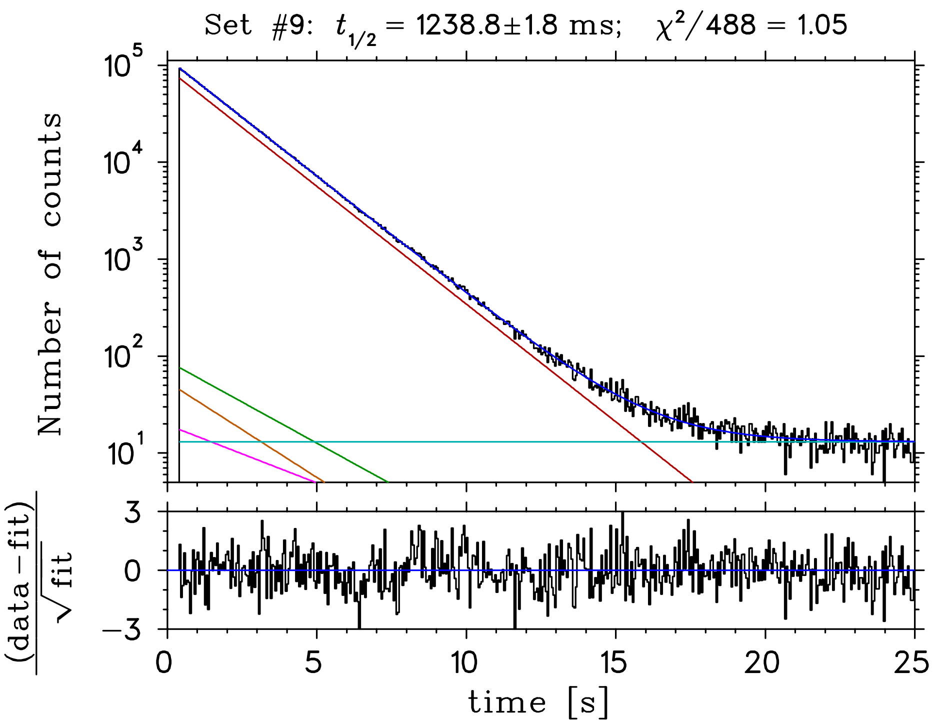
$\mathcal{F}t = 4562(28) \Rightarrow \rho = 0.5874(\mathbf{71})$

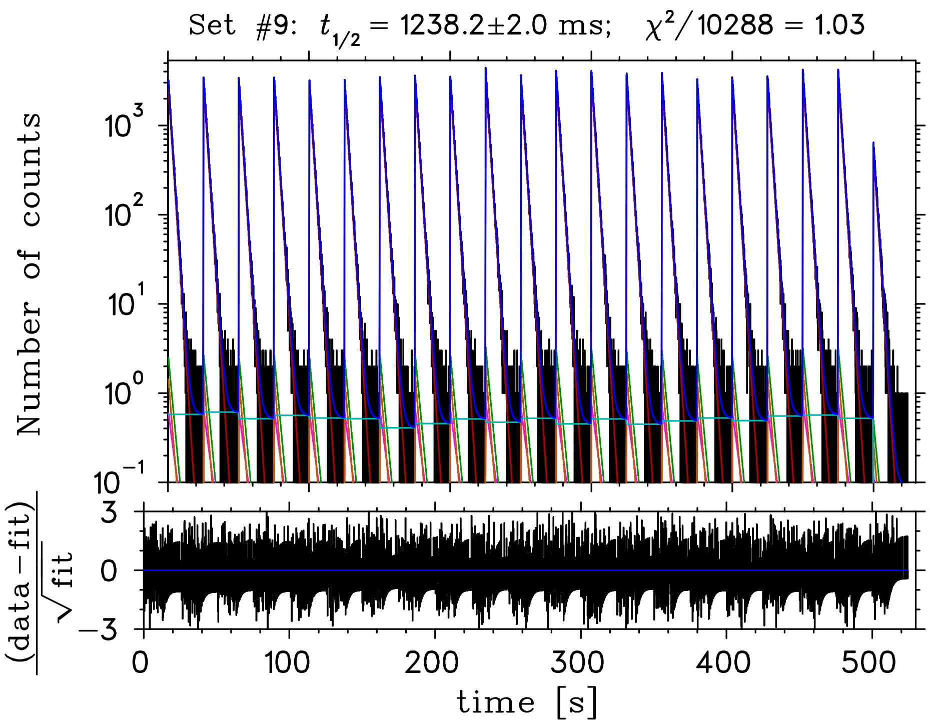
Measuring the lifetime at the CI

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



Improving the lifetime





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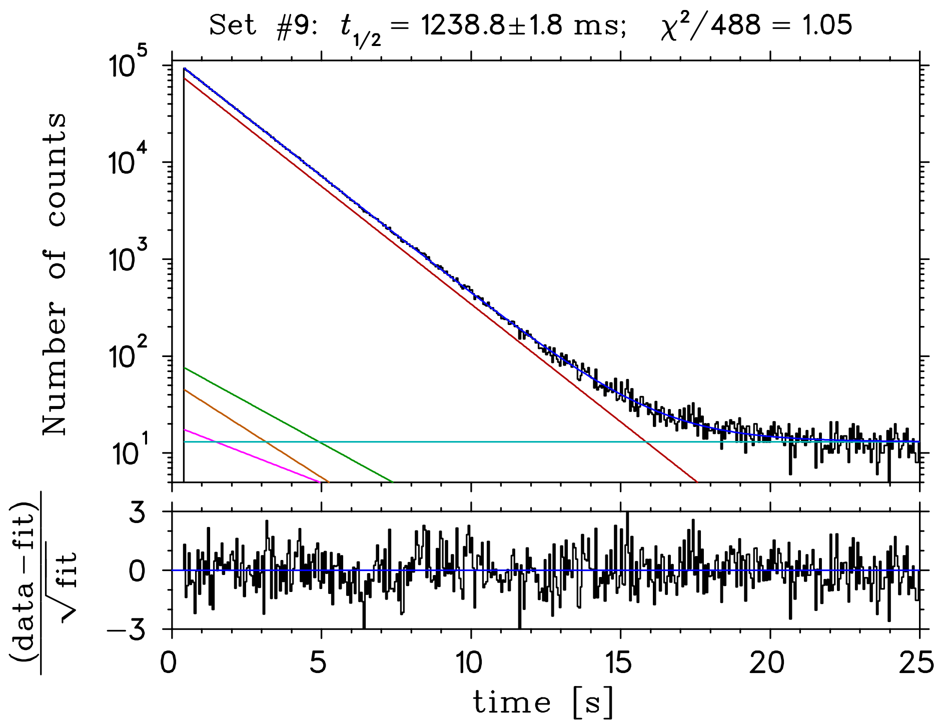

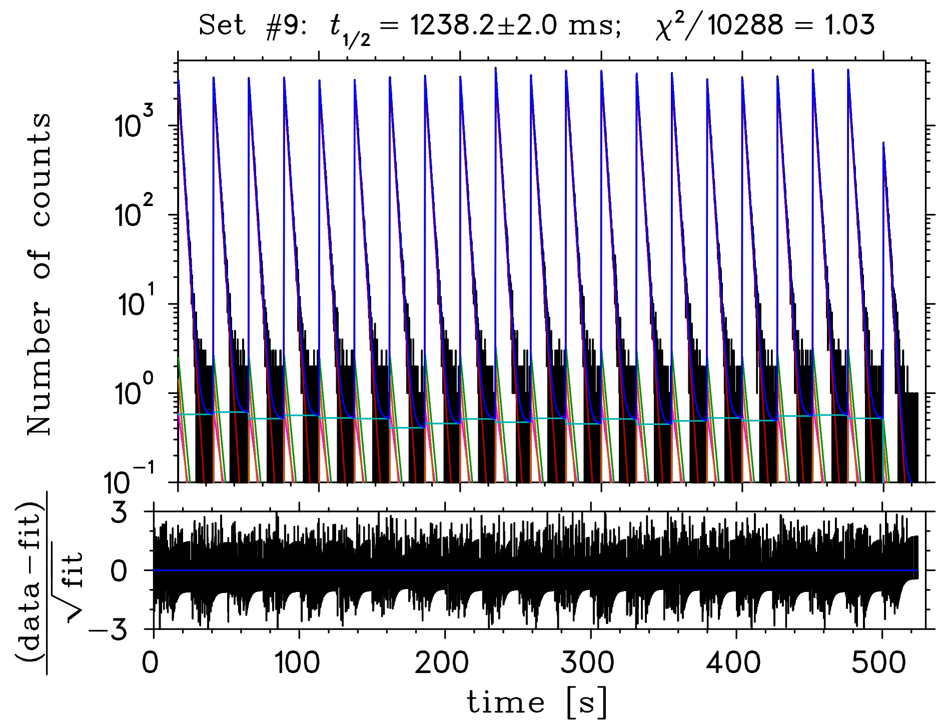

nearly a $10\times$ improvement: $t_{1/2} = 1236.51 \pm 0.47 \pm 0.83$ ms

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

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

P. Shidling *et al.*, in preparation

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

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

Correlation	SM prediction
$\beta-\nu$ correlation:	$a_{\beta\nu} = 0.6580(\mathbf{61})$
Fierz interference parameter:	$b = 0$ (sensitive to scalars and tensors)
β asymmetry:	$A_\beta = -0.5739(\mathbf{21})$
ν asymmetry:	$B_\nu = -0.7791(\mathbf{58})$
Time-violating D coefficient:	$D = 0$ (sensitive to imaginary couplings)

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

see Profumo, Ramsey-Musolf and Tulin, PRD **75** (2007)
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β asymmetry:	$A_\beta = -0.5739(\mathbf{21}) \rightarrow -0.5719(\mathbf{7})$
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Thank you, AMO physicists!!

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

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

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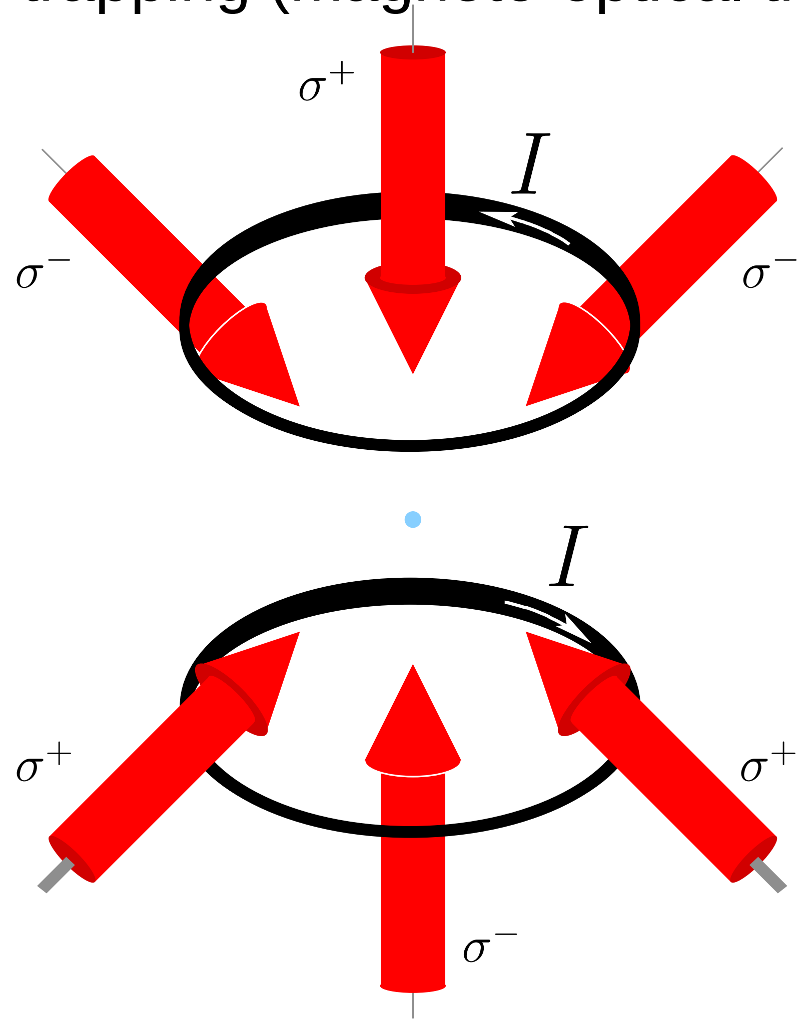

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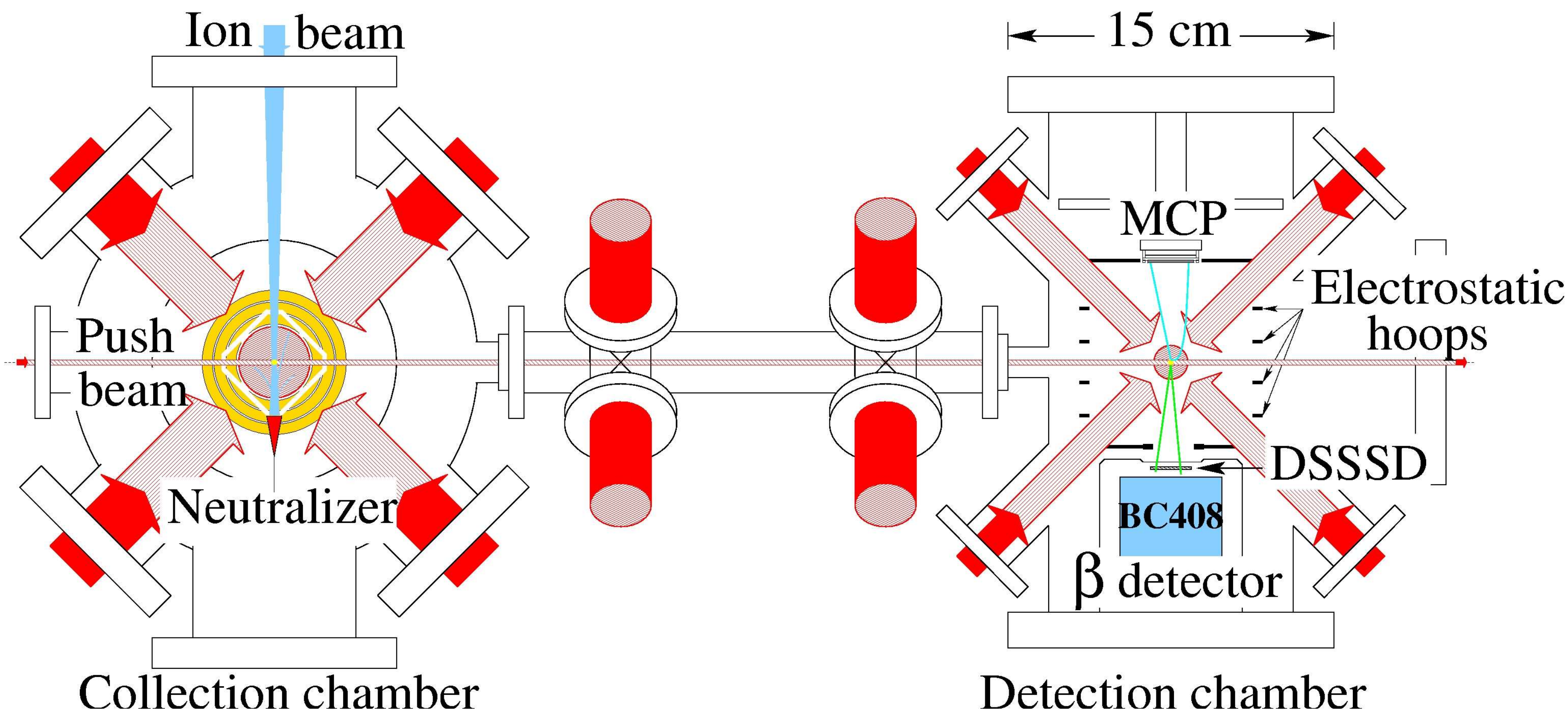

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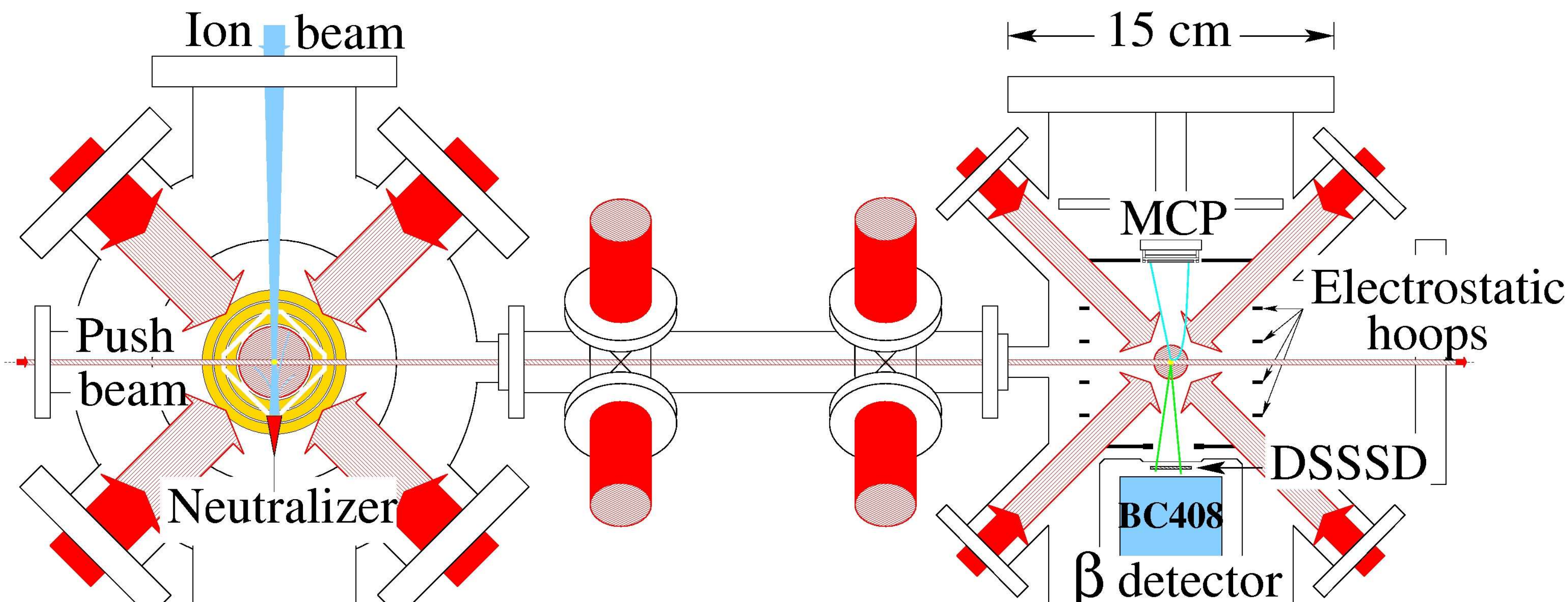

Traps provide a **backing-free**, very **cold** ($\lesssim 1$ mK), **localized** ($\sim 1\ \mathrm{mm}^3$) source of **isomerically-selective**, **short-lived** radioactive atoms

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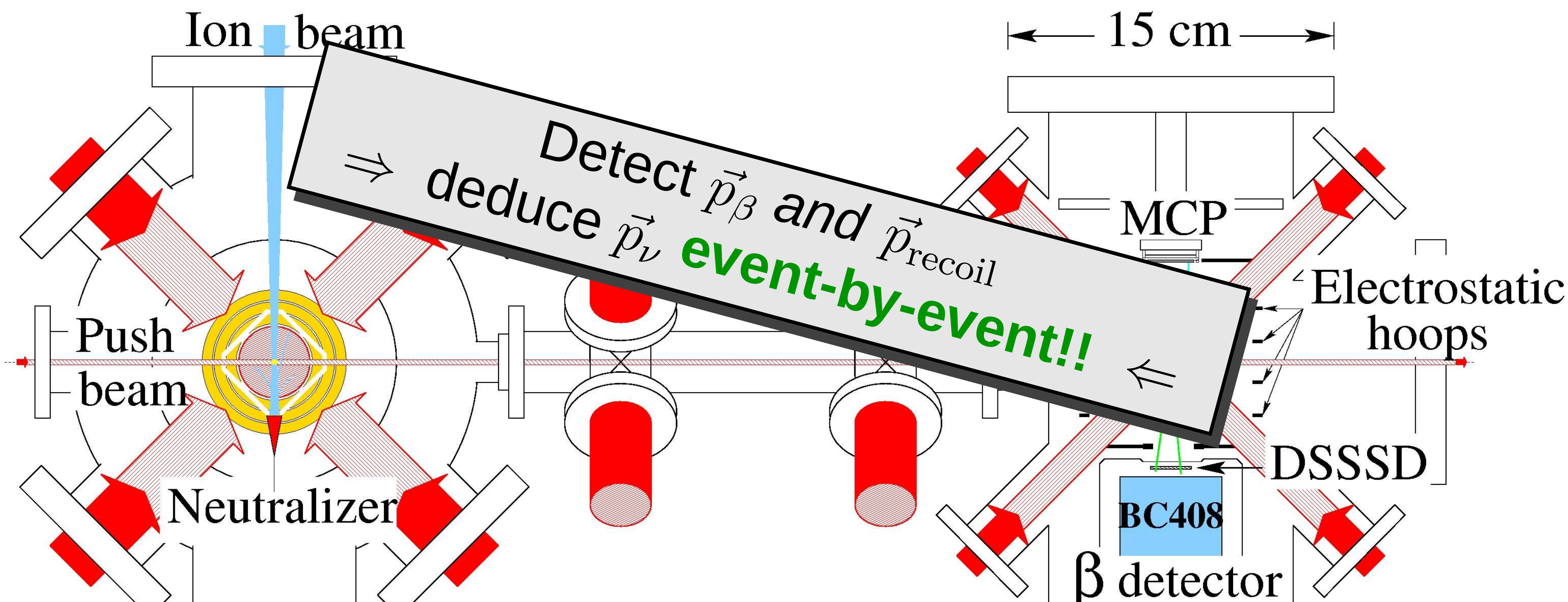

Detect $\vec{p}_\beta$ and $\vec{p}_{\rm recoil}$
$\Rightarrow$ deduce $\vec{p}_\nu$ **event-by-event!!** $\Leftarrow$

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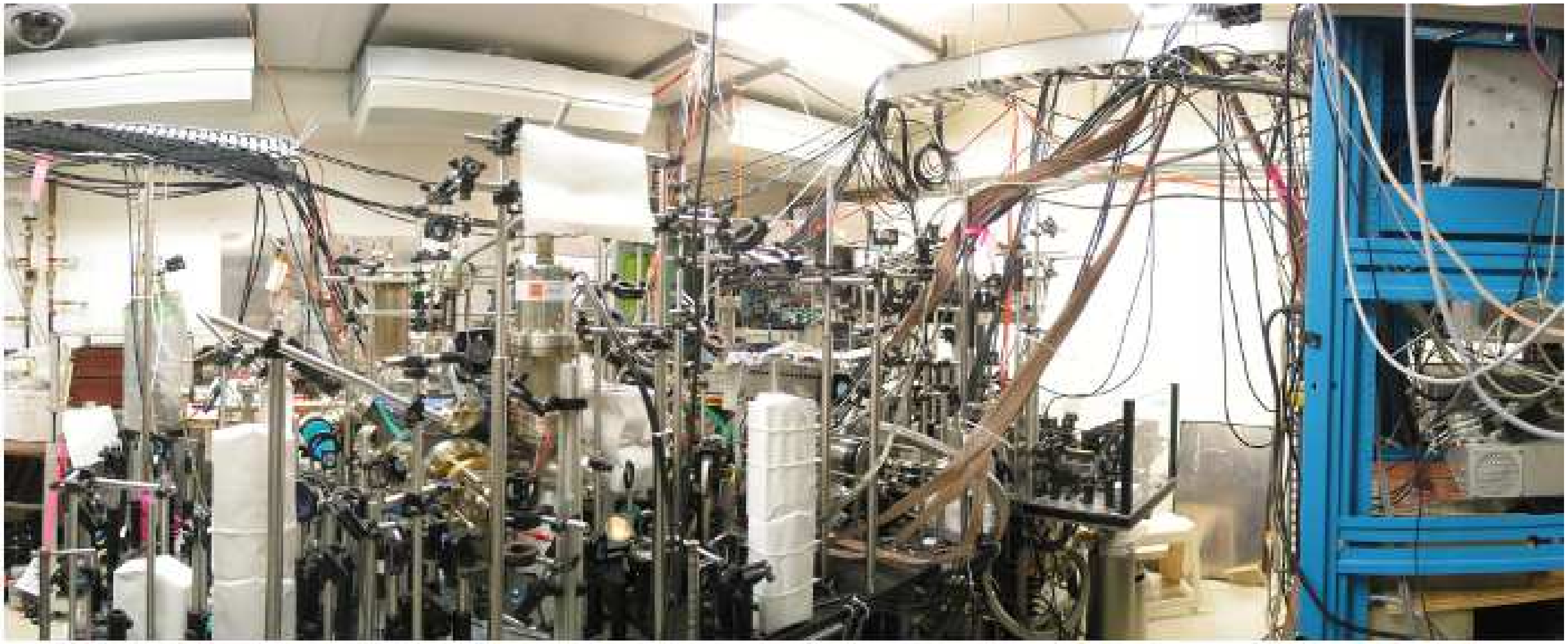
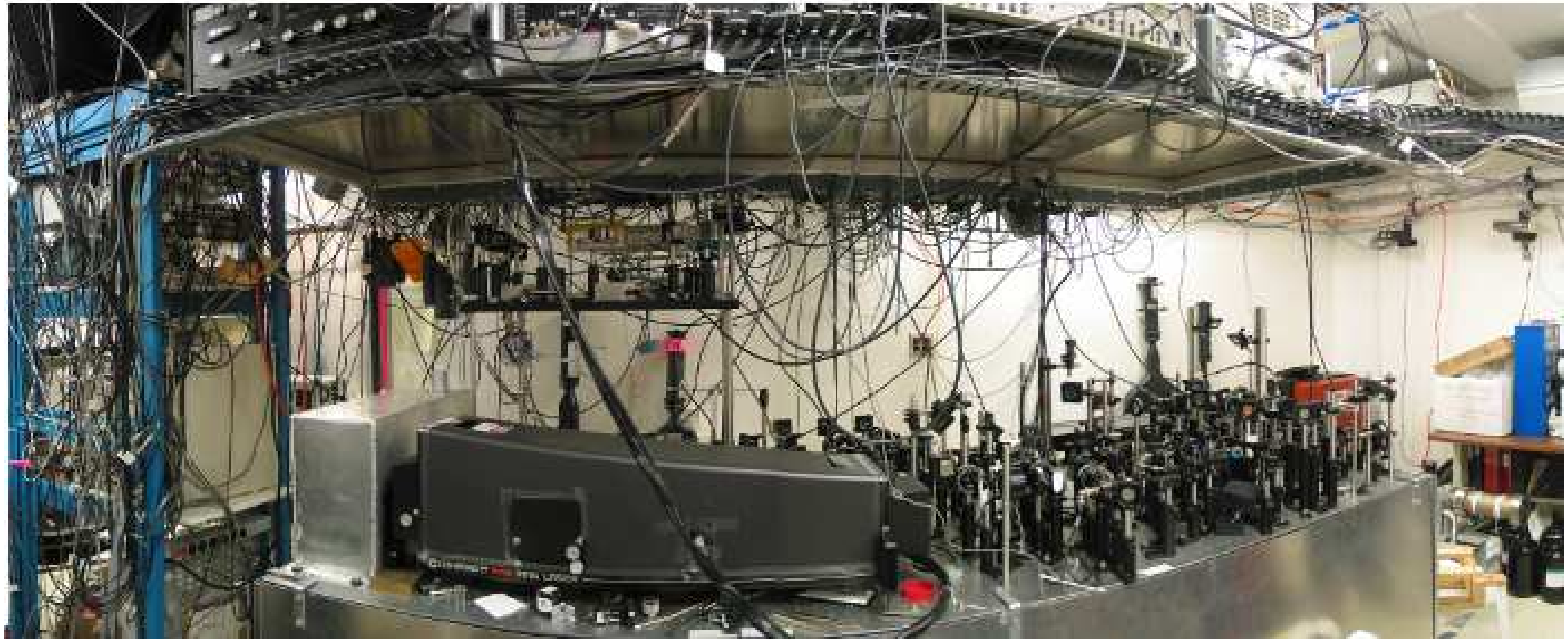
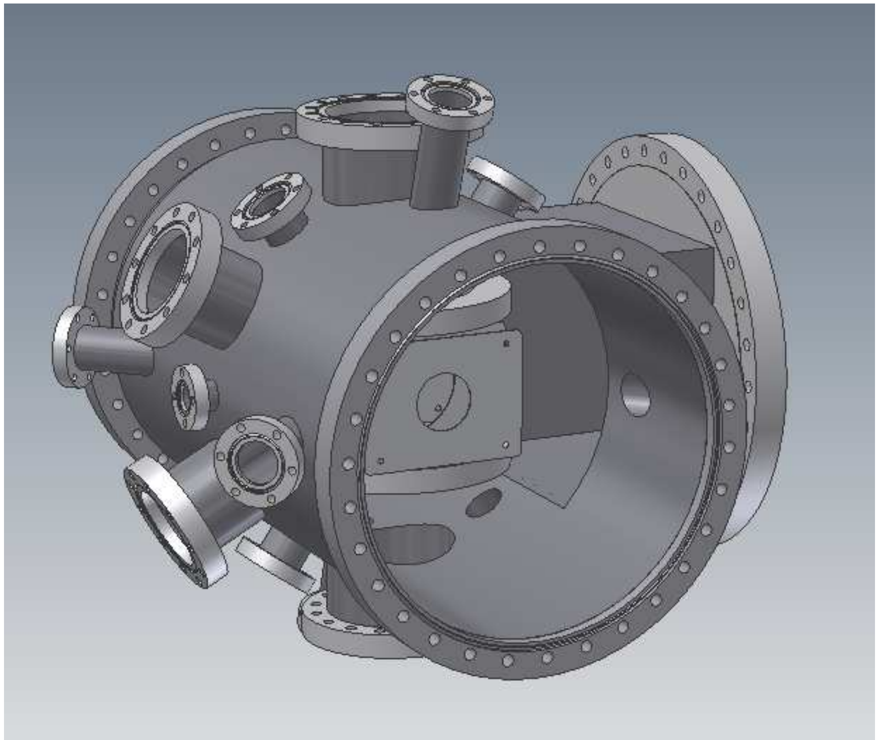
The TRINAT lab



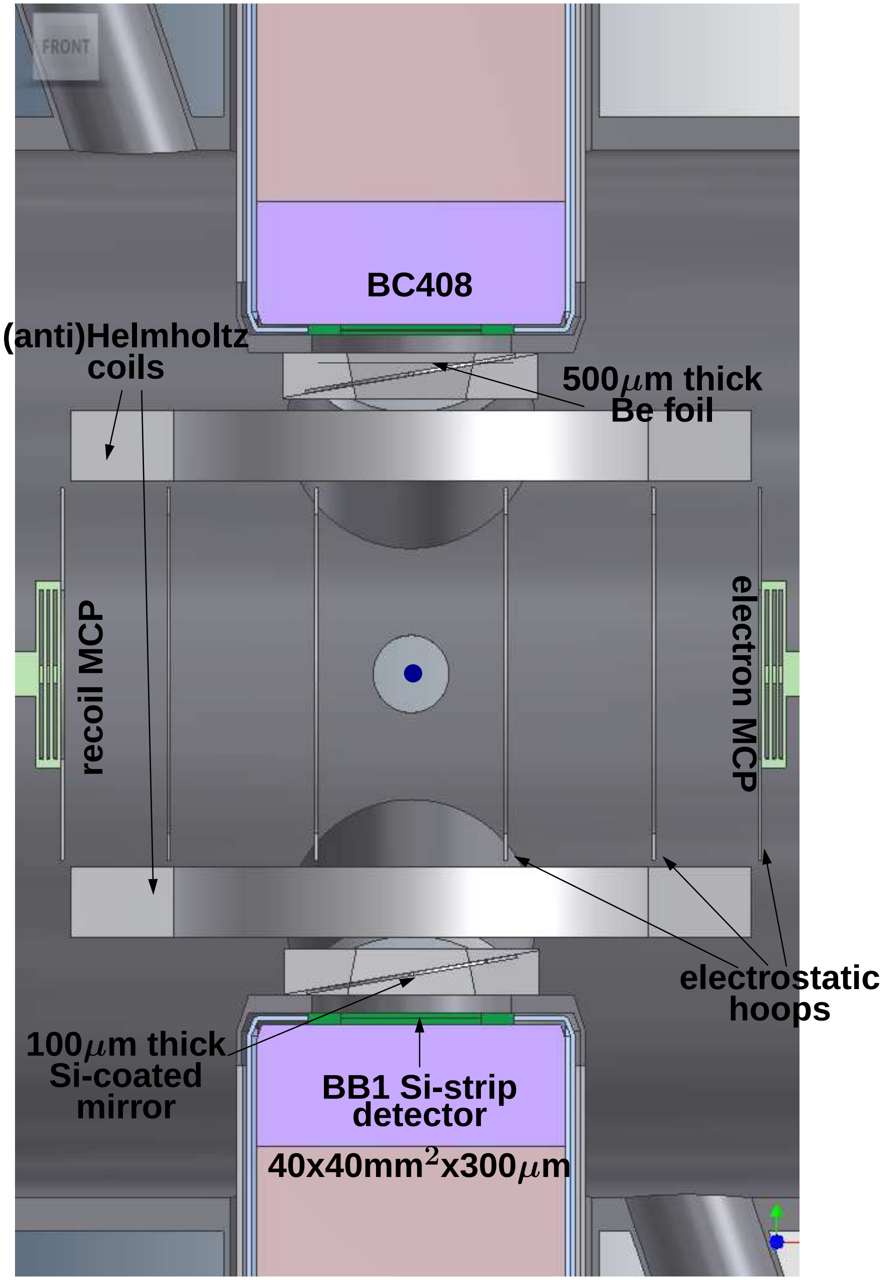


The new chamber

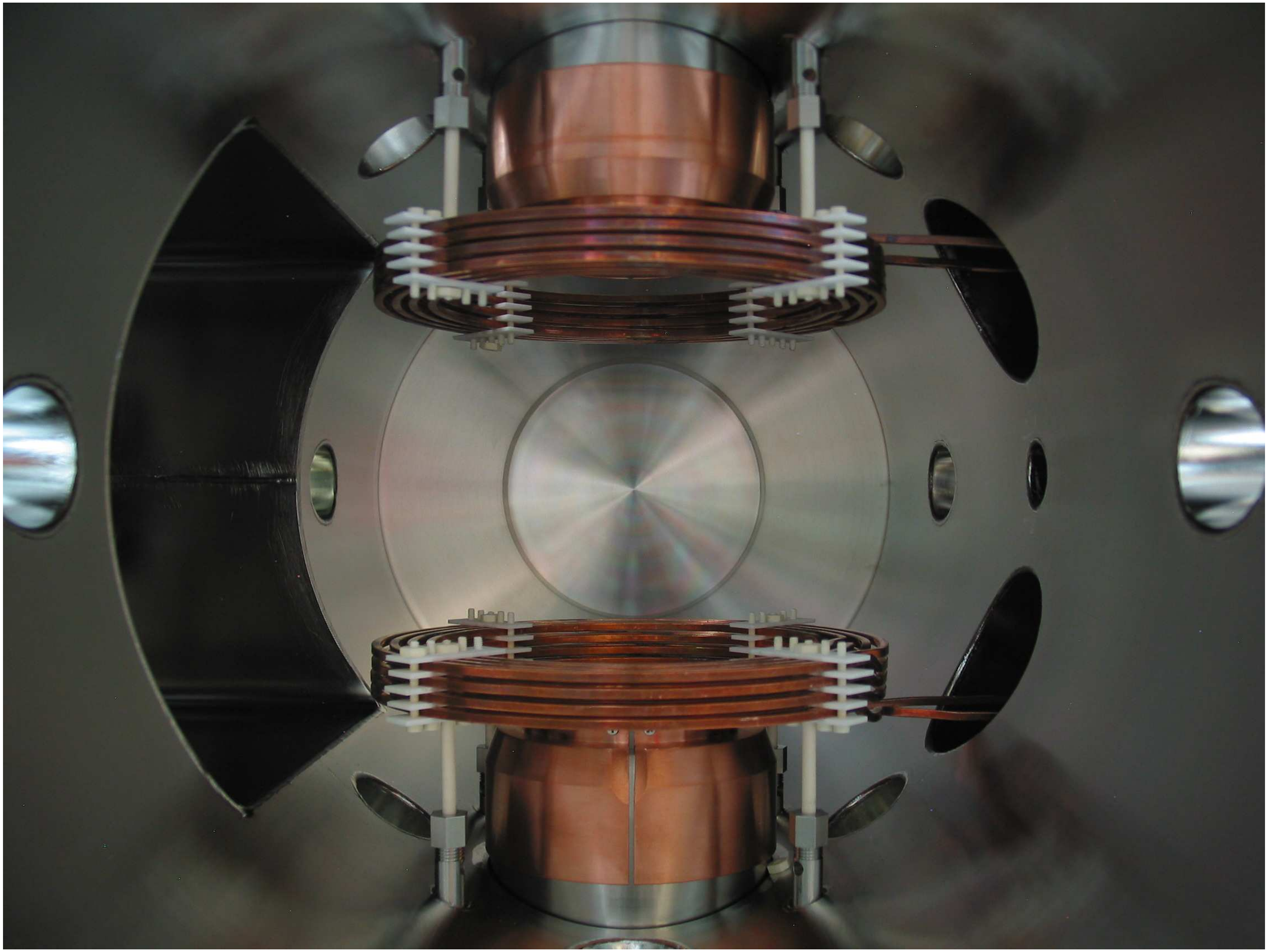


- Shake-off e^- detection
- Better control of OP beams
- $B_{\text{quad}} \rightarrow B_{\text{OP}}$ quickly: AC-MOT (Harvery & Murray, PRL **101** (2008))
- Increased β/recoil solid angles
- Stronger E-field

$\vdots$



Outline of polarized experiment



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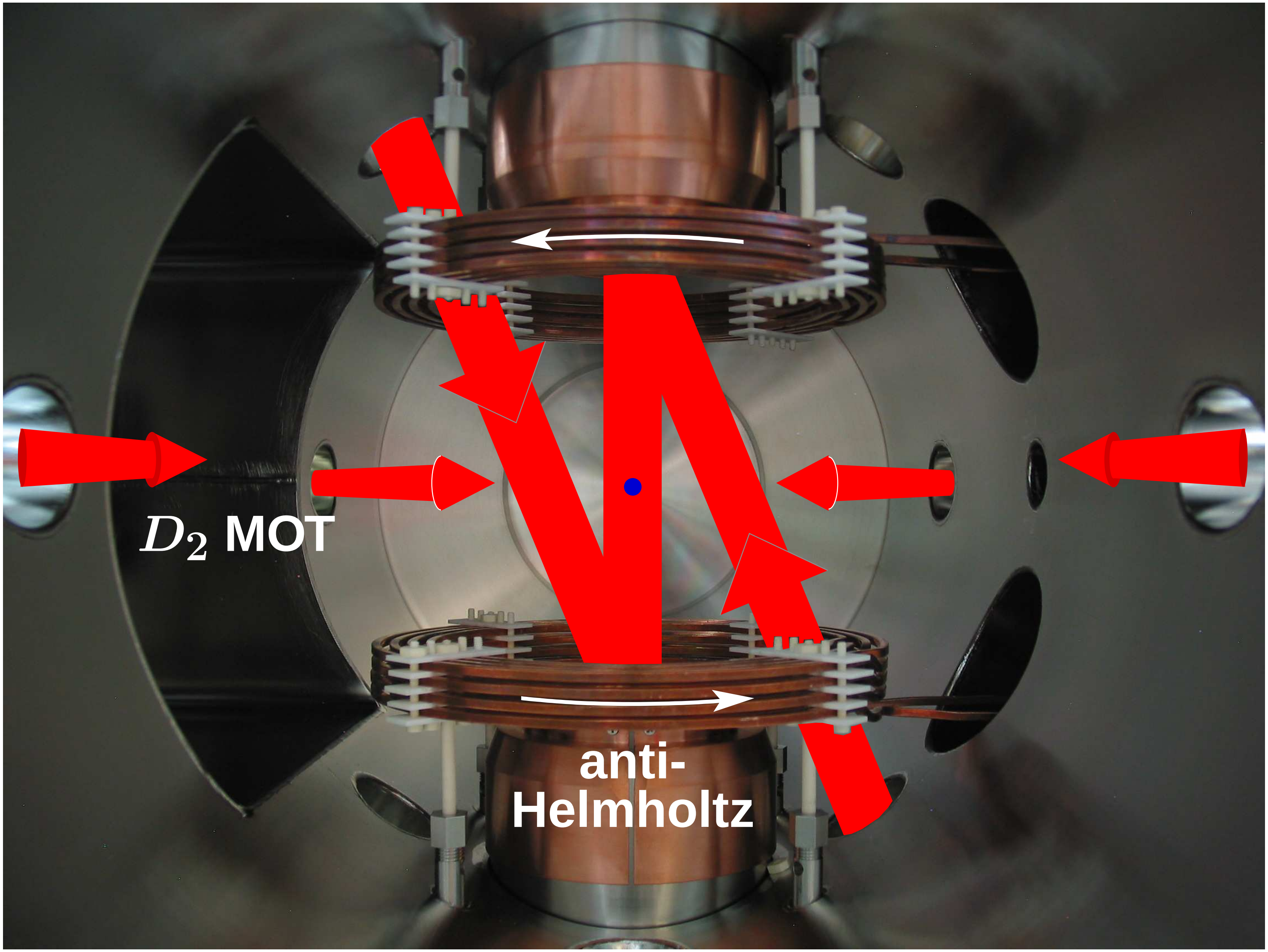

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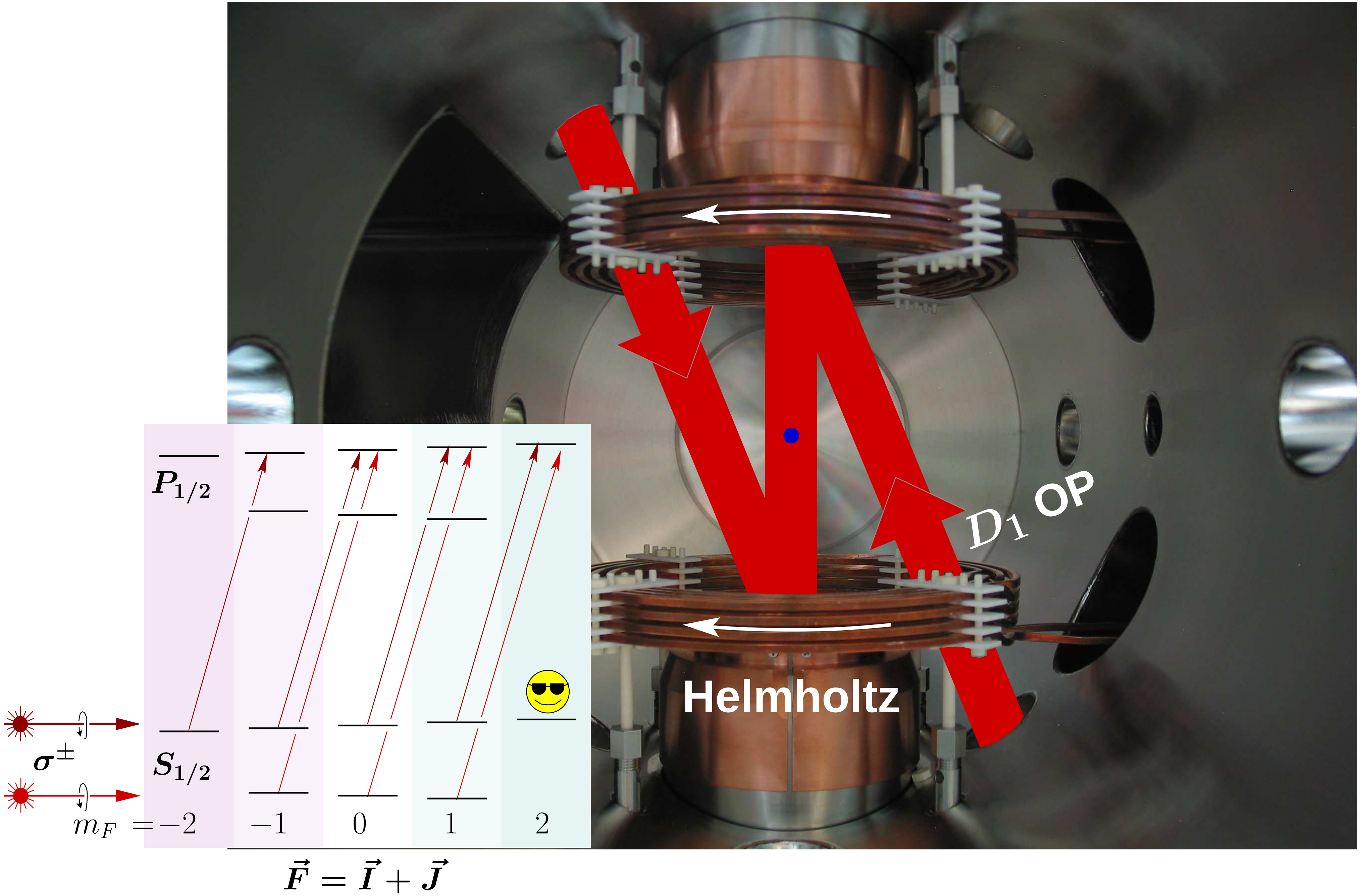

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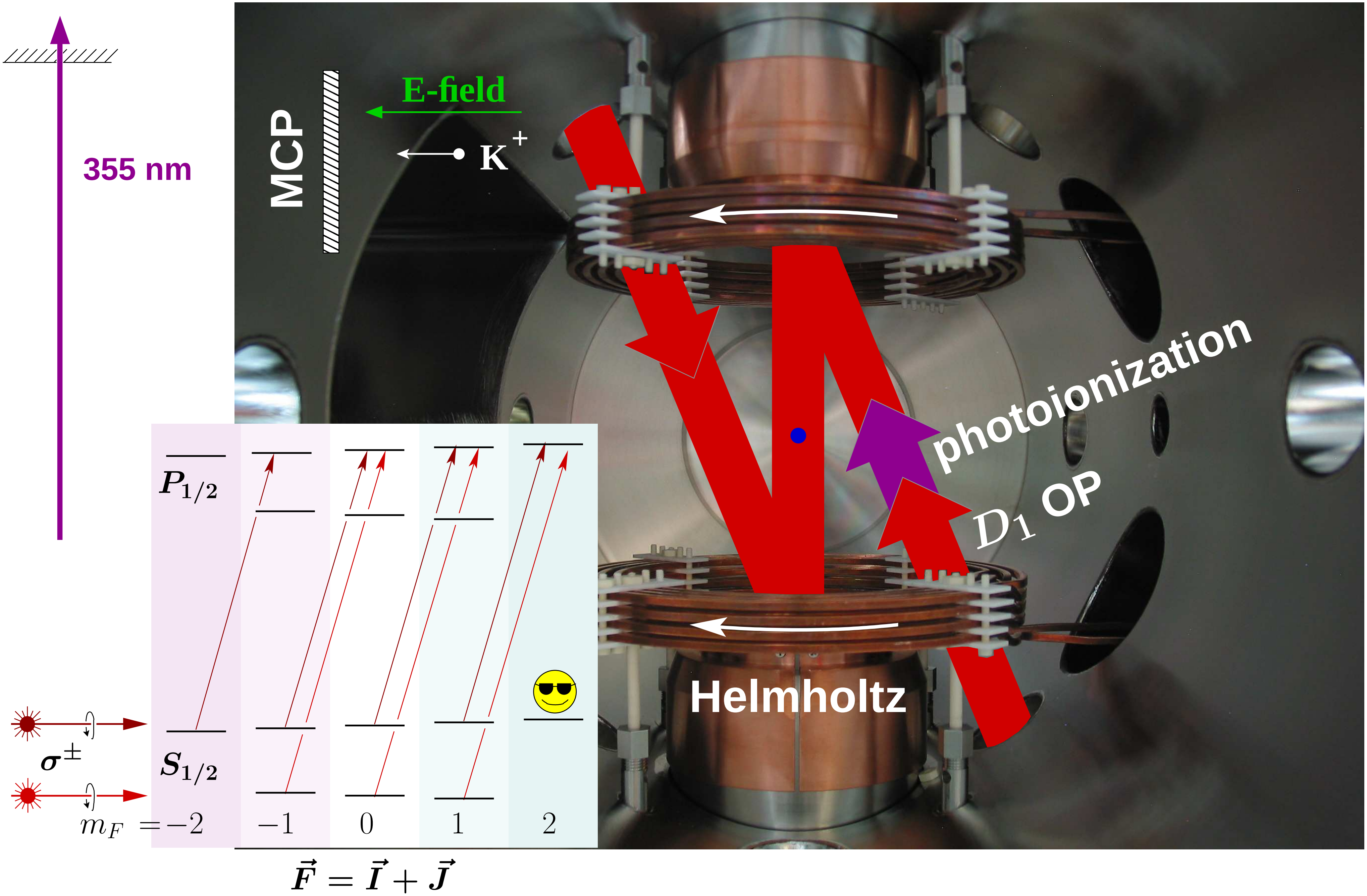
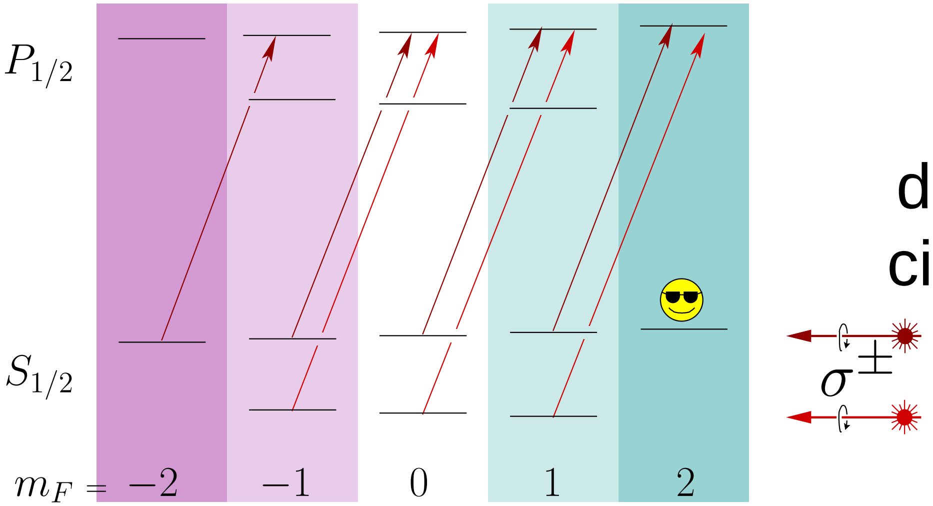
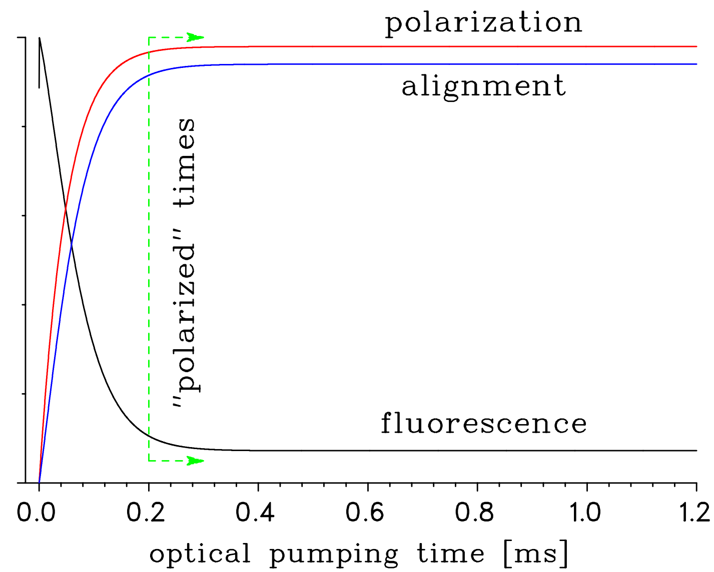


Atomic measurement of P



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



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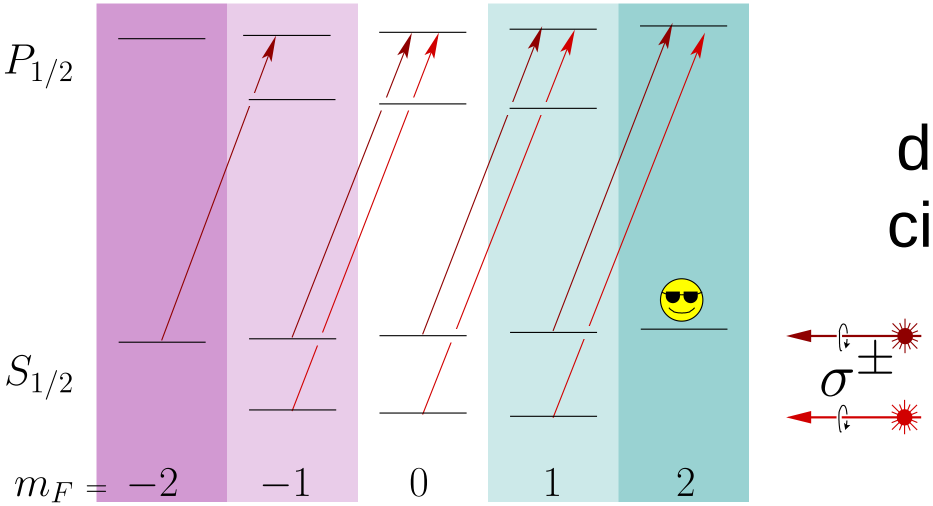

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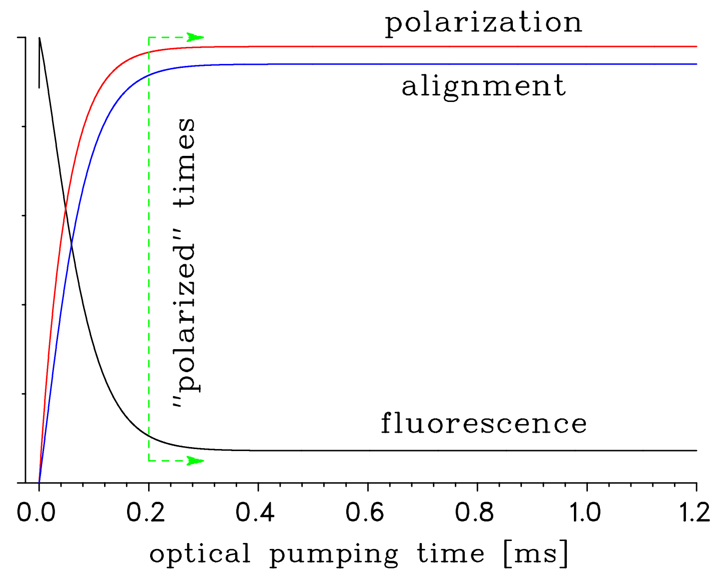
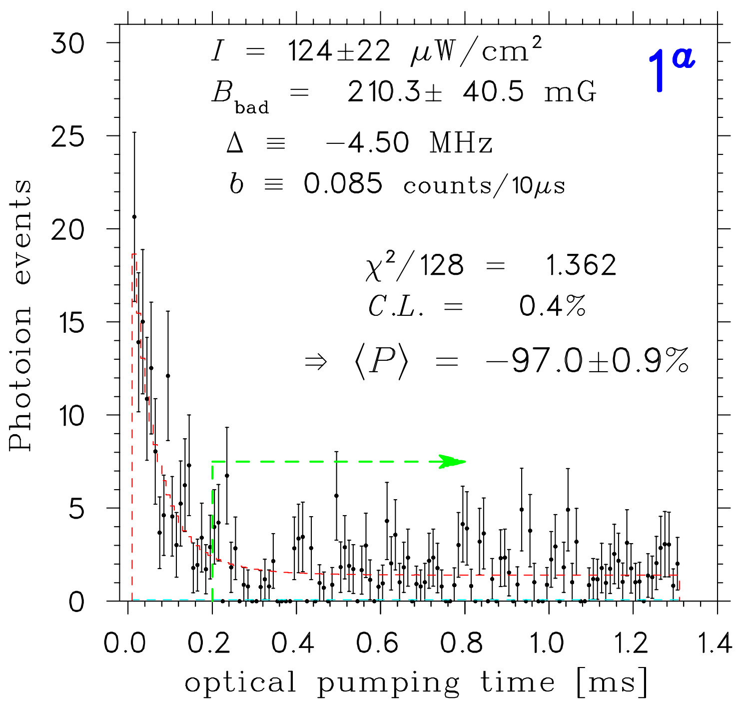
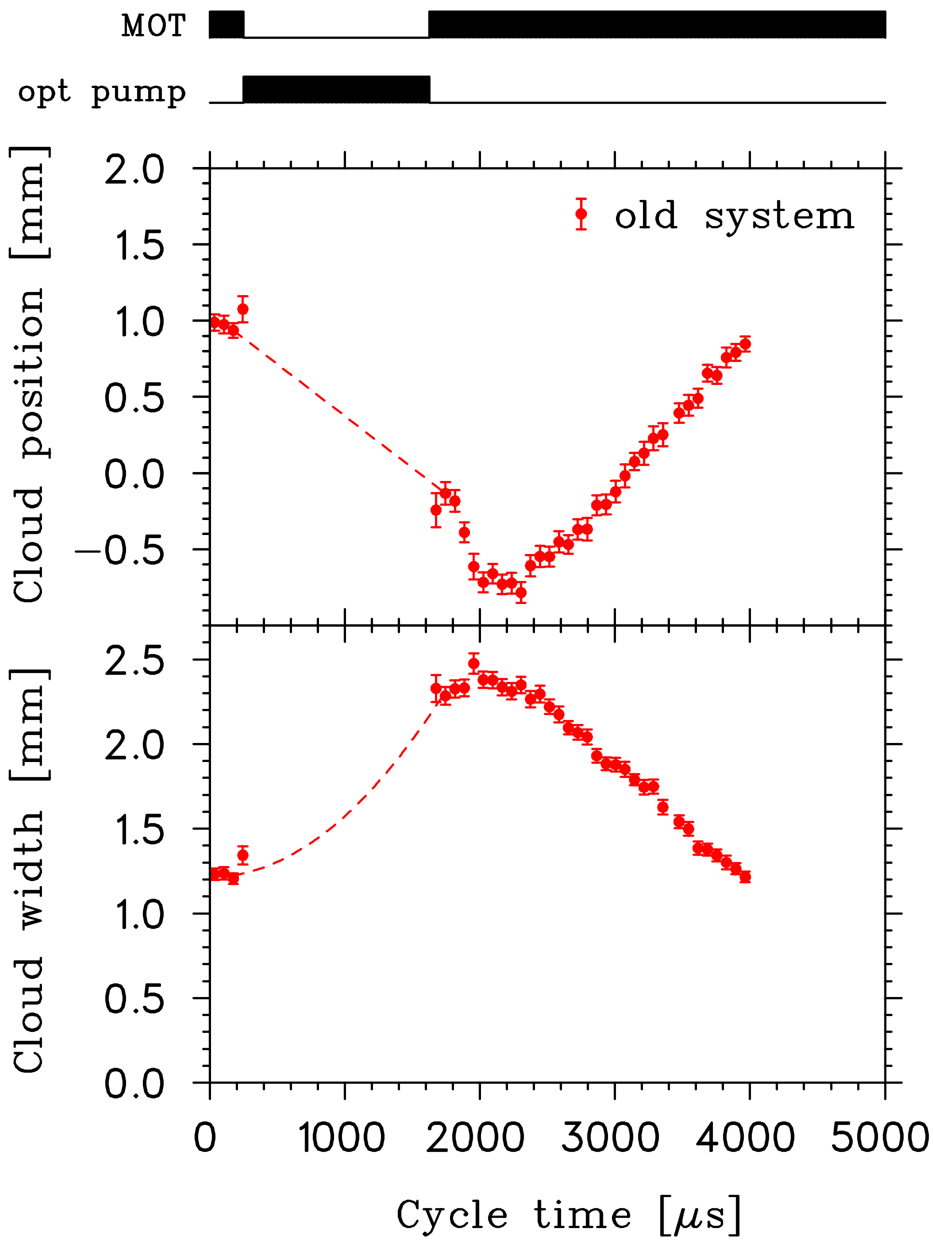




$$\Rightarrow P_{\mathrm{nucl}} = 96.74 \pm 0.53^{+0.19}_{-0.73}$$

The cloud is better controlled now!



- old system:
  - retroreflected beams
  - kludged "Helmholtz" coils
  - eddy currents

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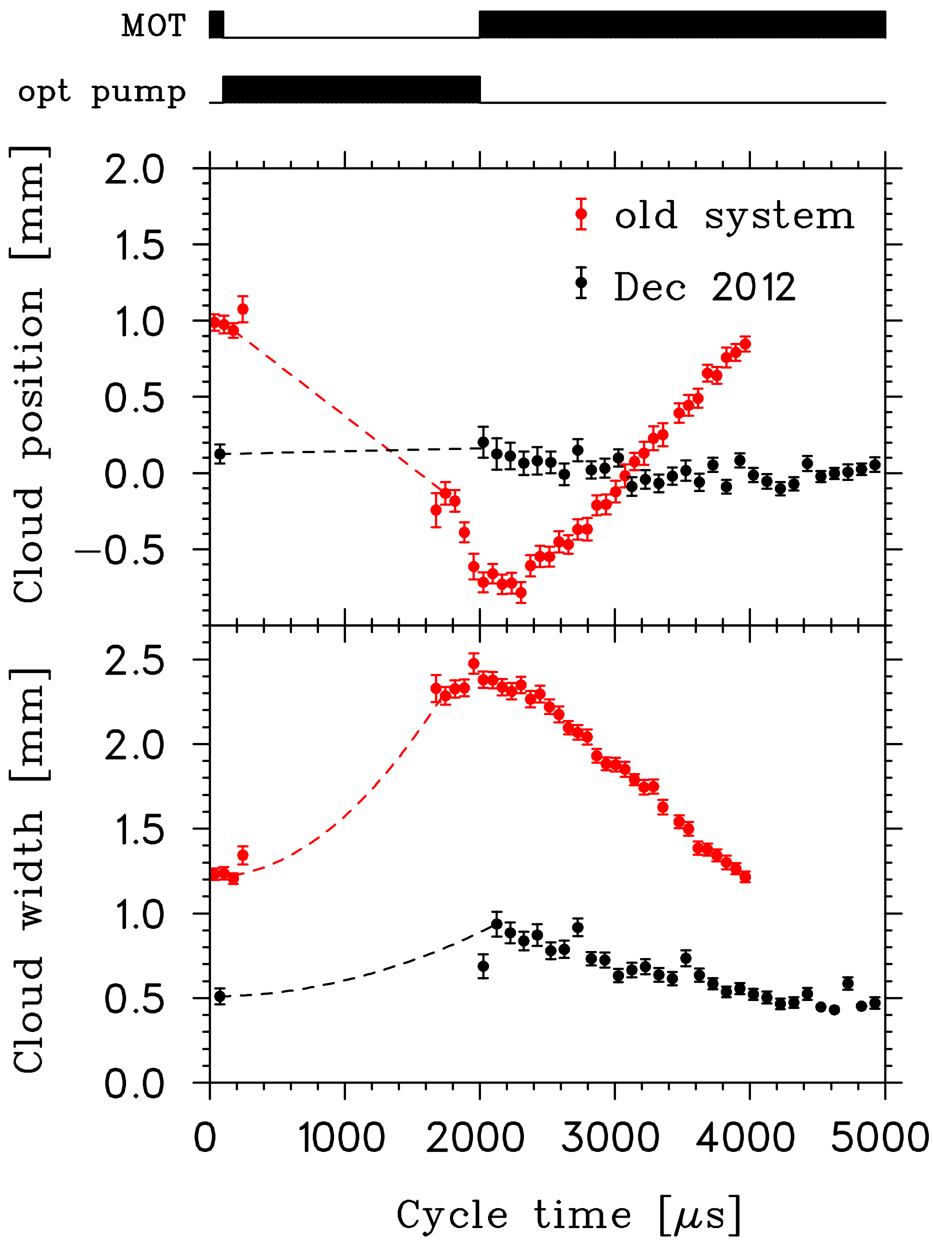
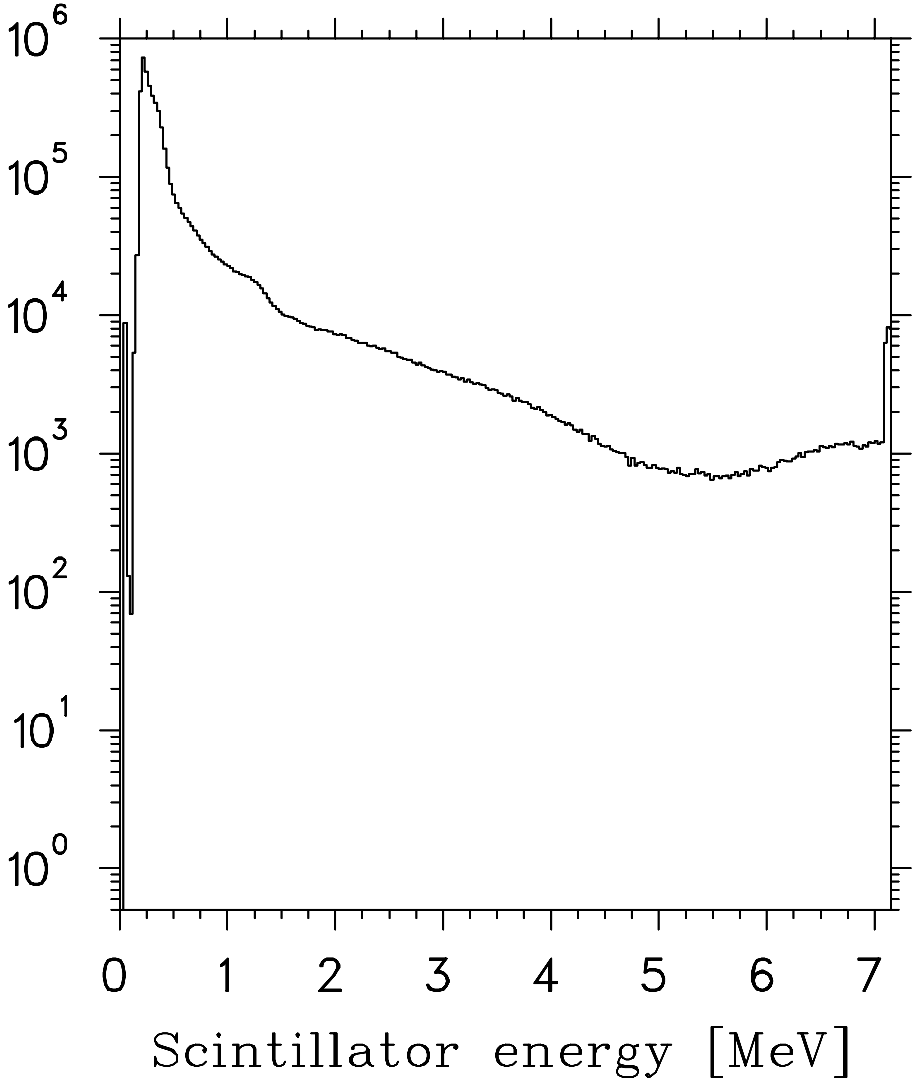


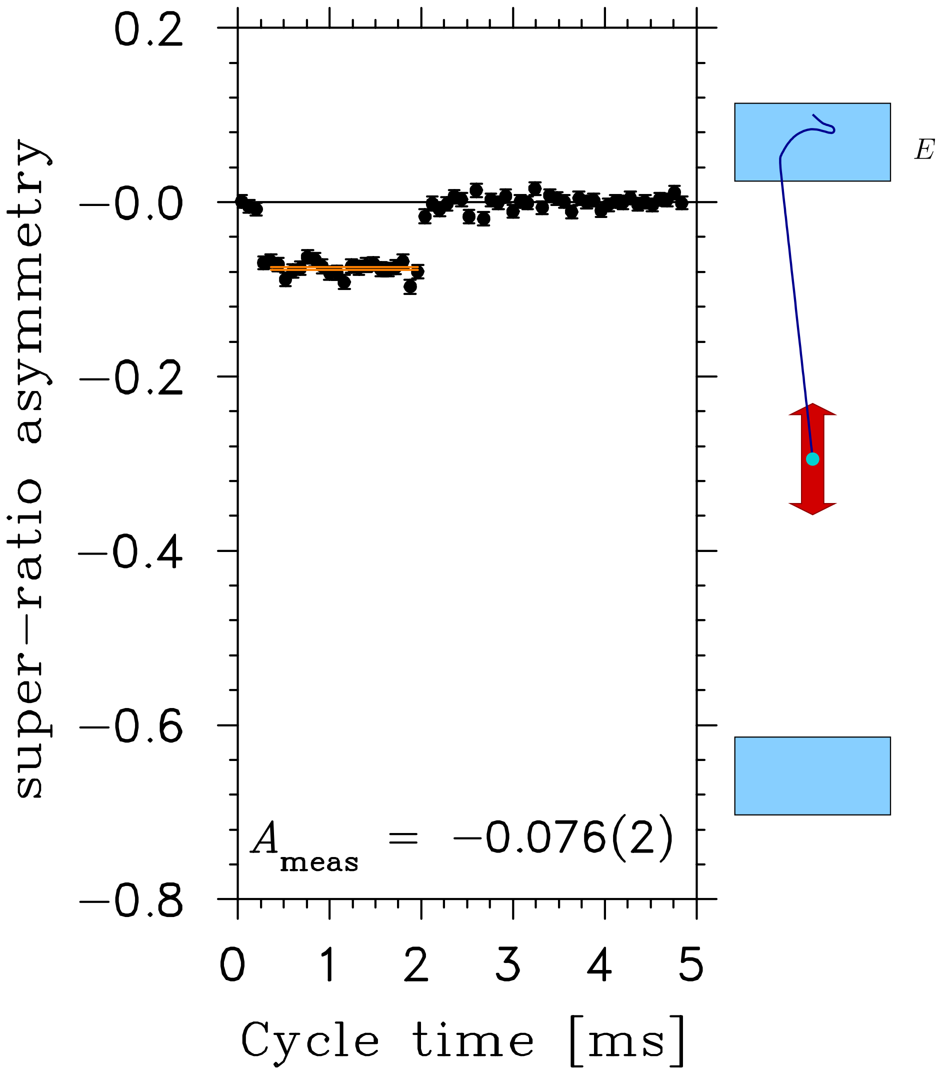
- old system:
  - retroreflected beams
  - kludged "Helmholtz" coils
  - eddy currents
- Dec 2012:
  - beams balanced
  - anti-Helmholtz → Helmholtz well-defined fields
  - ac-MOT ⇒ fast switching and low eddy currents

much more stable!
lower cloud temperature!

Scintillator spectra — Fall 2012

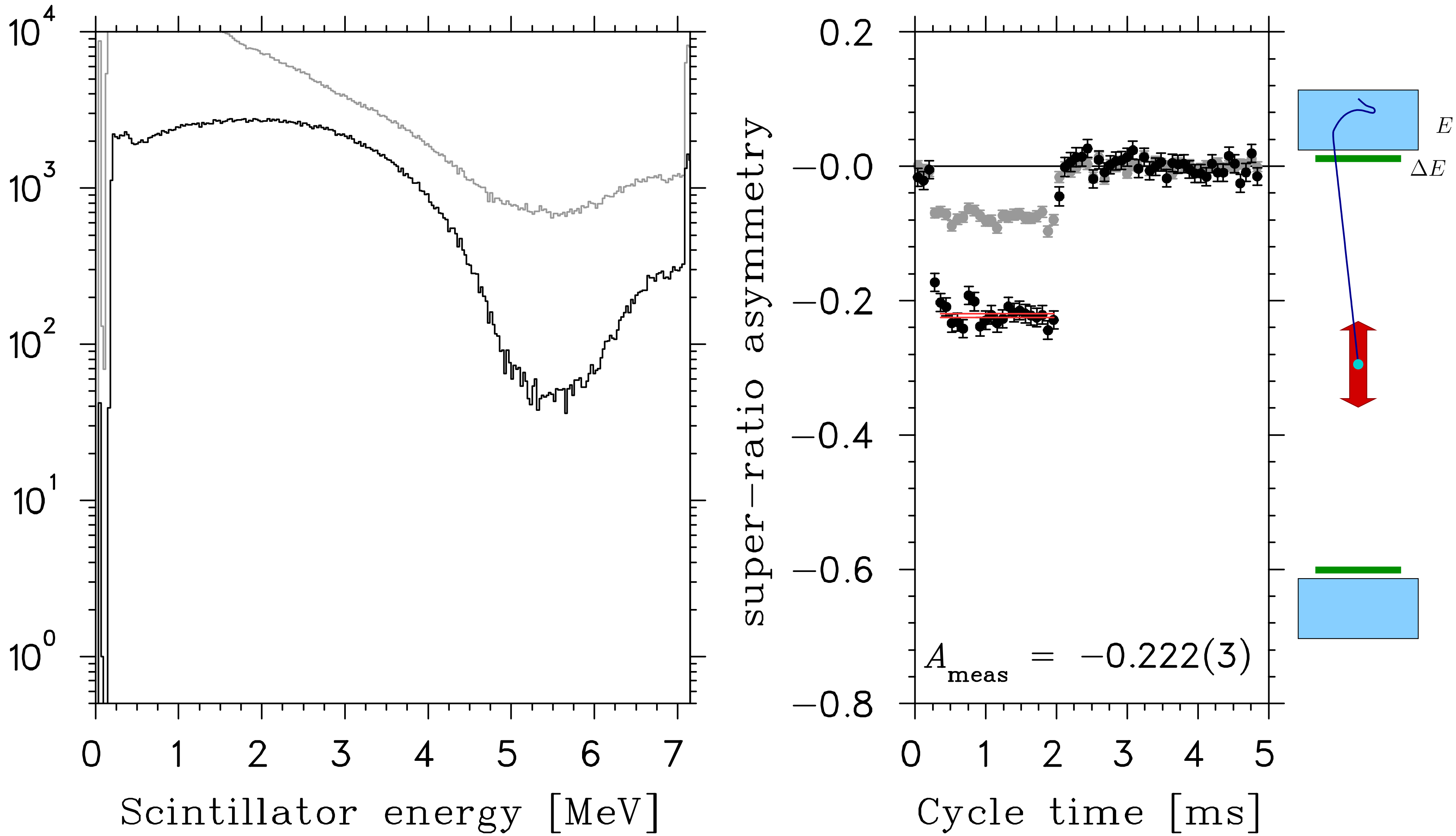
Just the raw data; a slight lower-energy cut to get rid of 511s





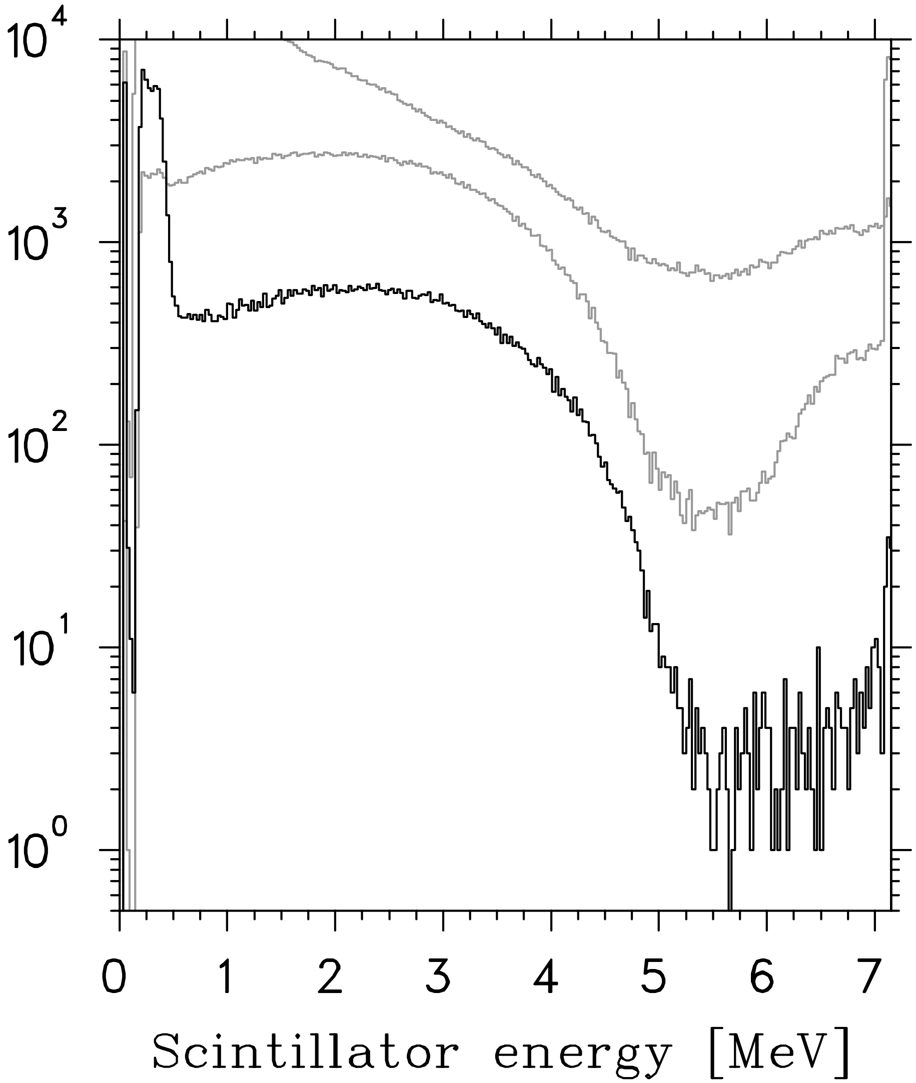
Scintillator spectra — Fall 2012

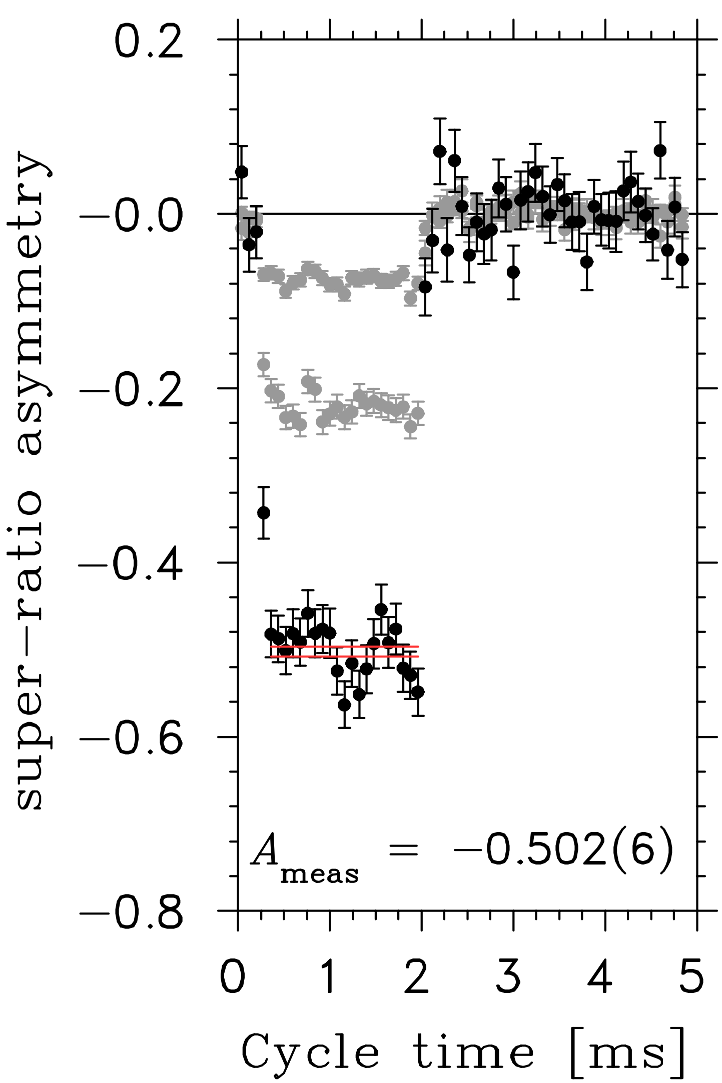
Requiring a ΔE coincidence $\Rightarrow$ remove γs

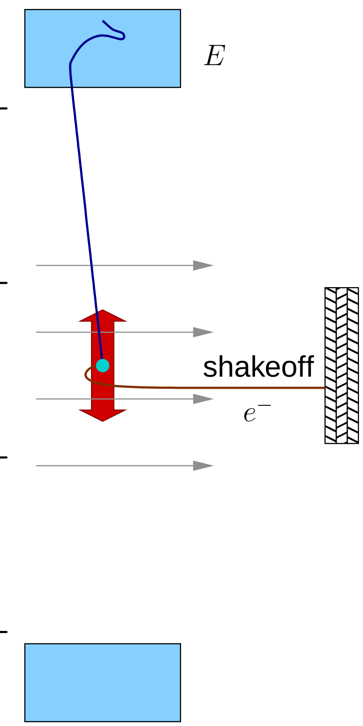


Scintillator spectra — Fall 2012

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

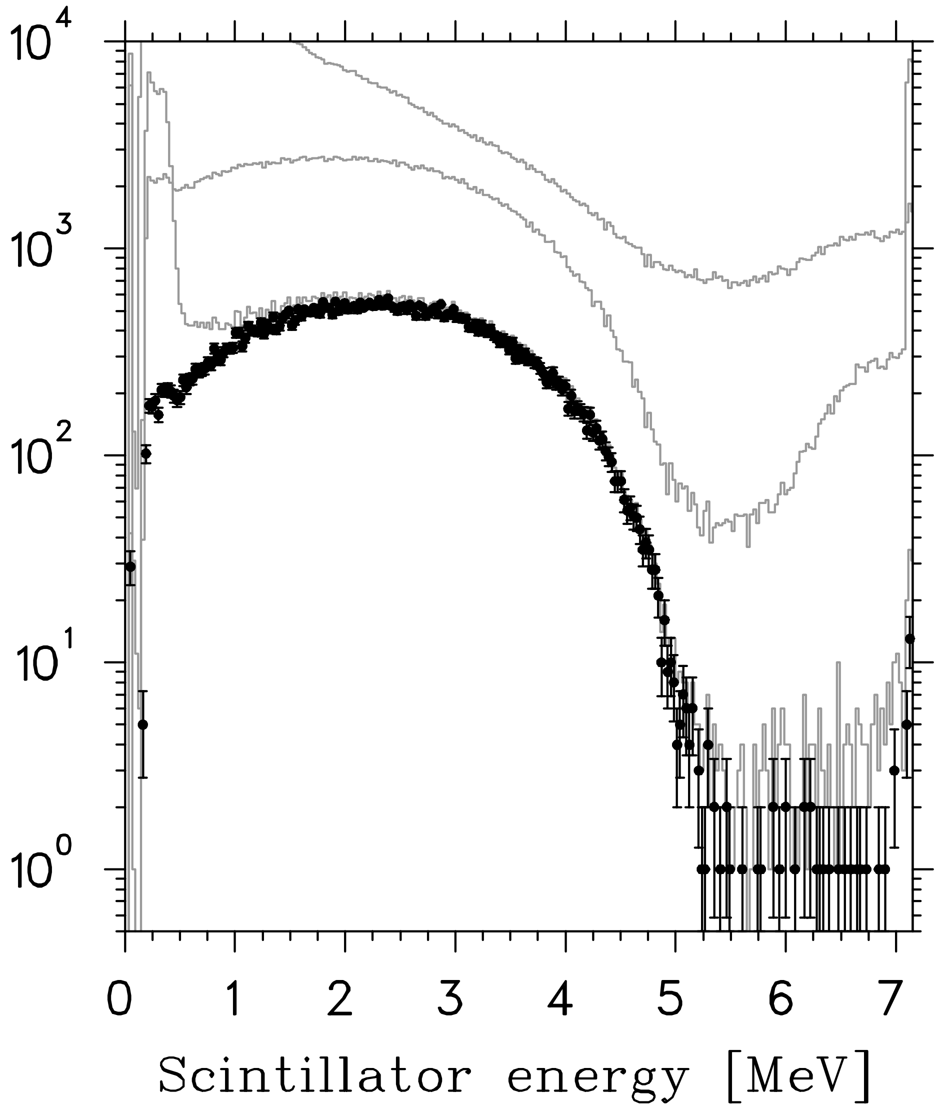


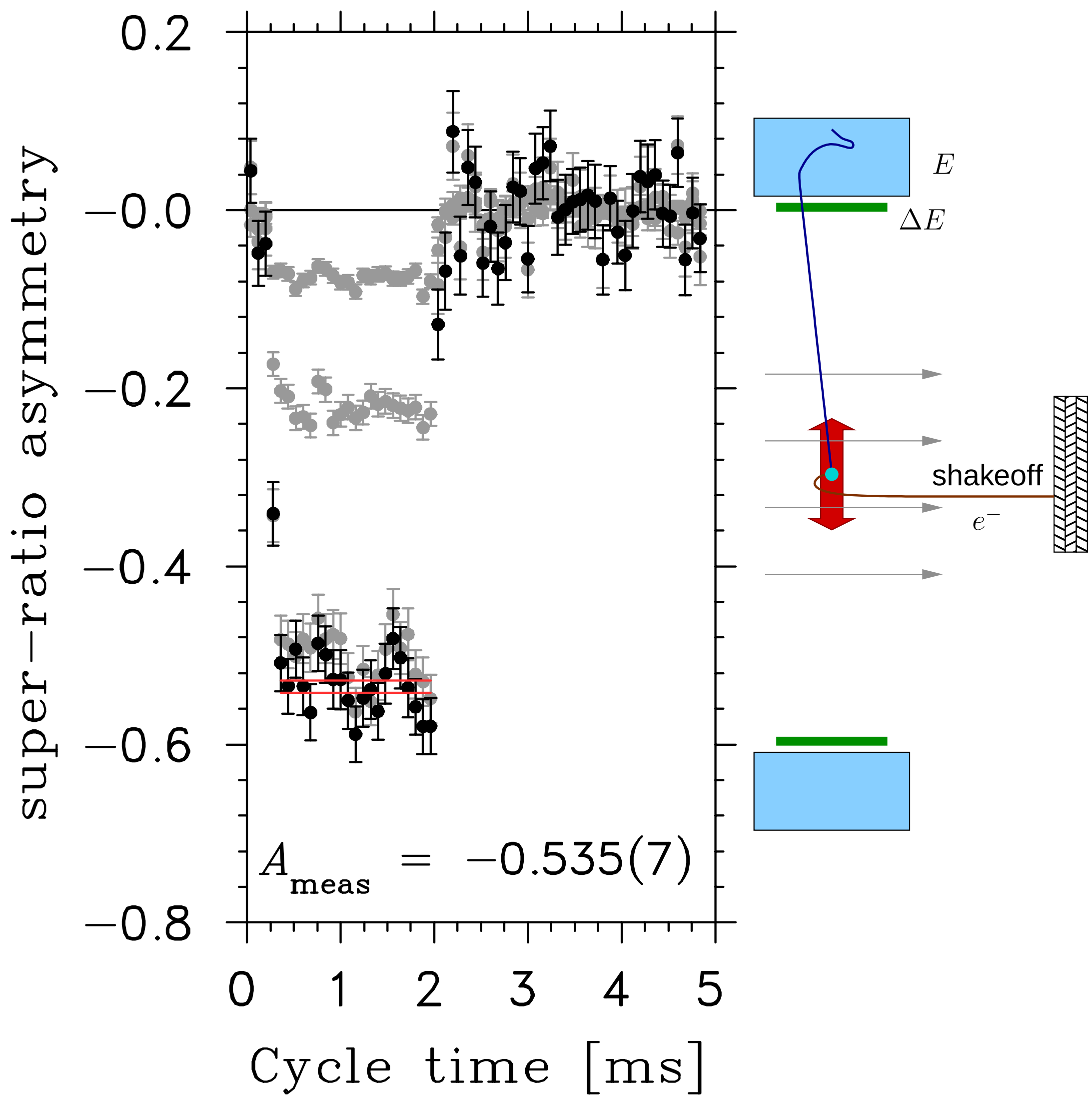




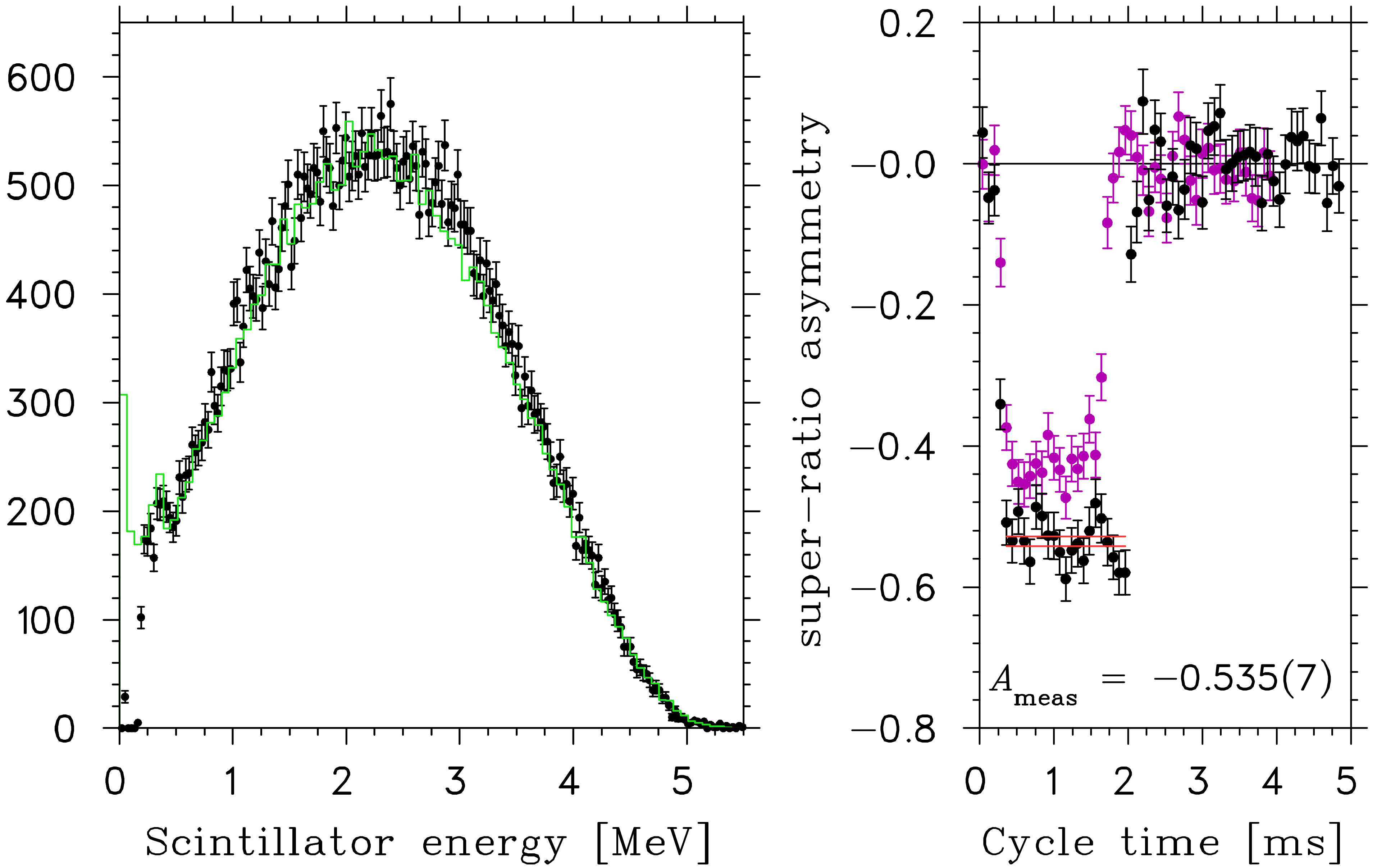
Scintillator spectra — Fall 2012

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

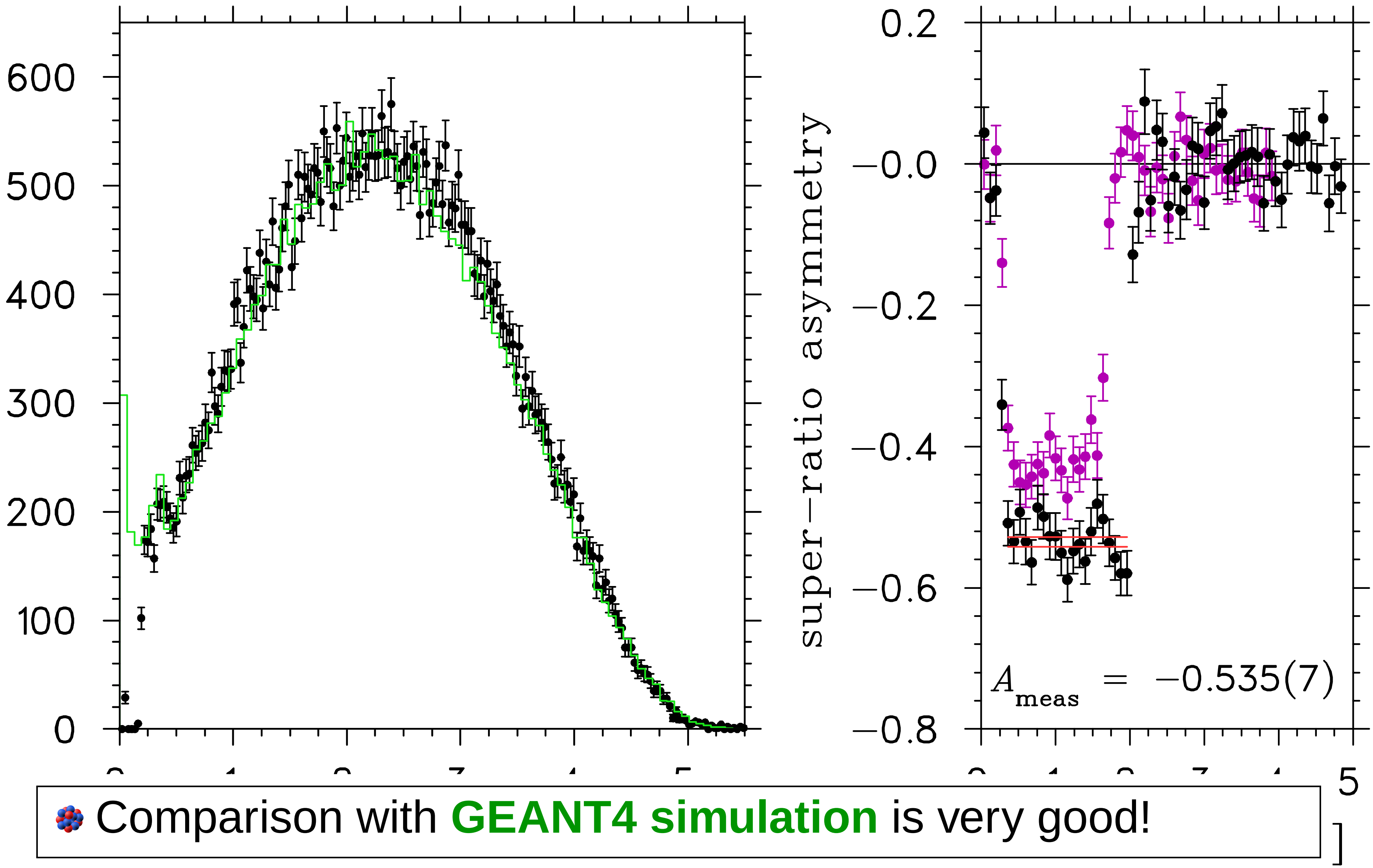




Scintillator spectra — Fall 2012

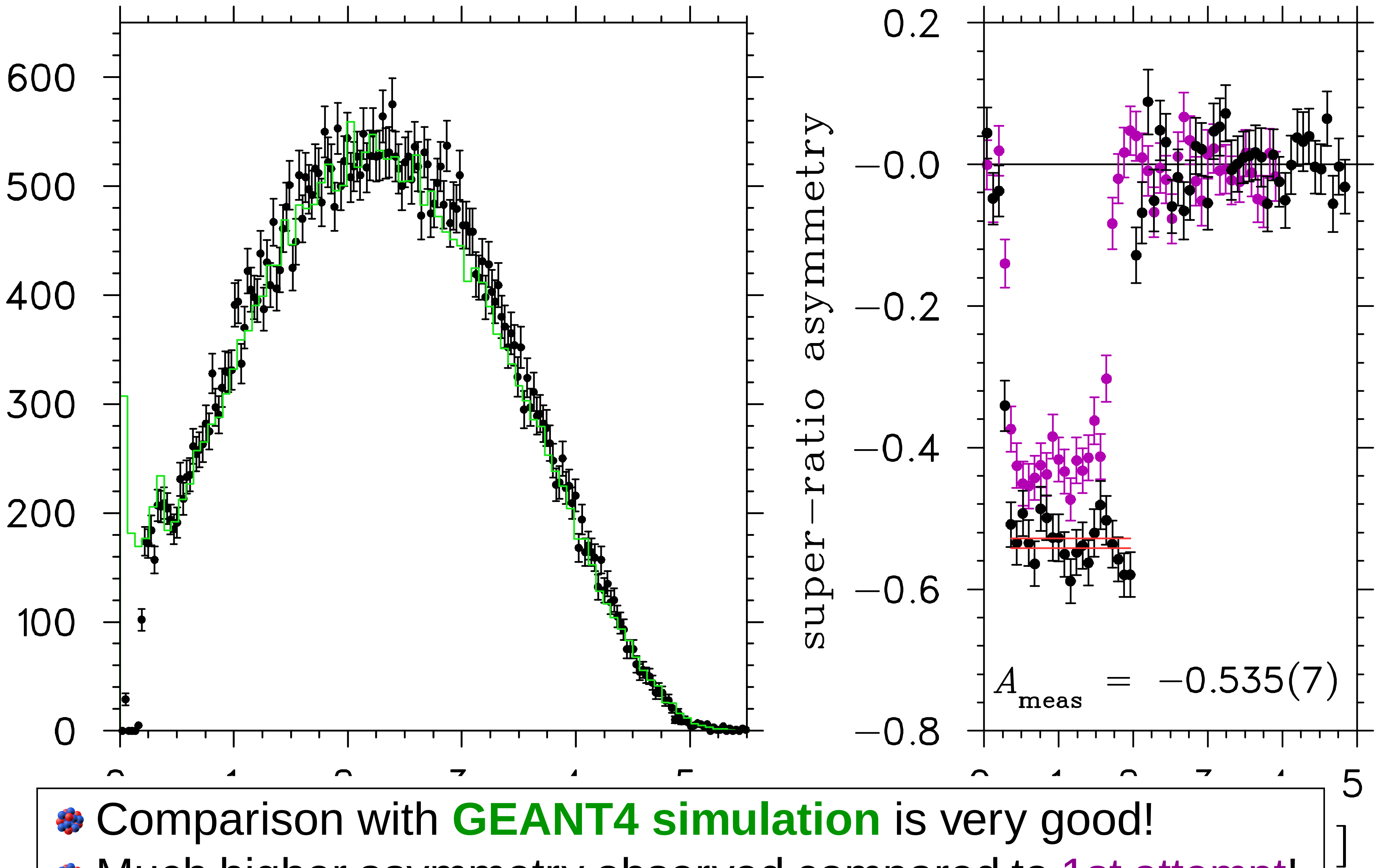


Scintillator spectra — Fall 2012



Comparison with **GEANT4 simulation** is very good!

Scintillator spectra — Fall 2012



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

Summary

- SM is fantastic, but **not** our "ultimate" theory
- many exciting avenues to find more a complete model

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Summary

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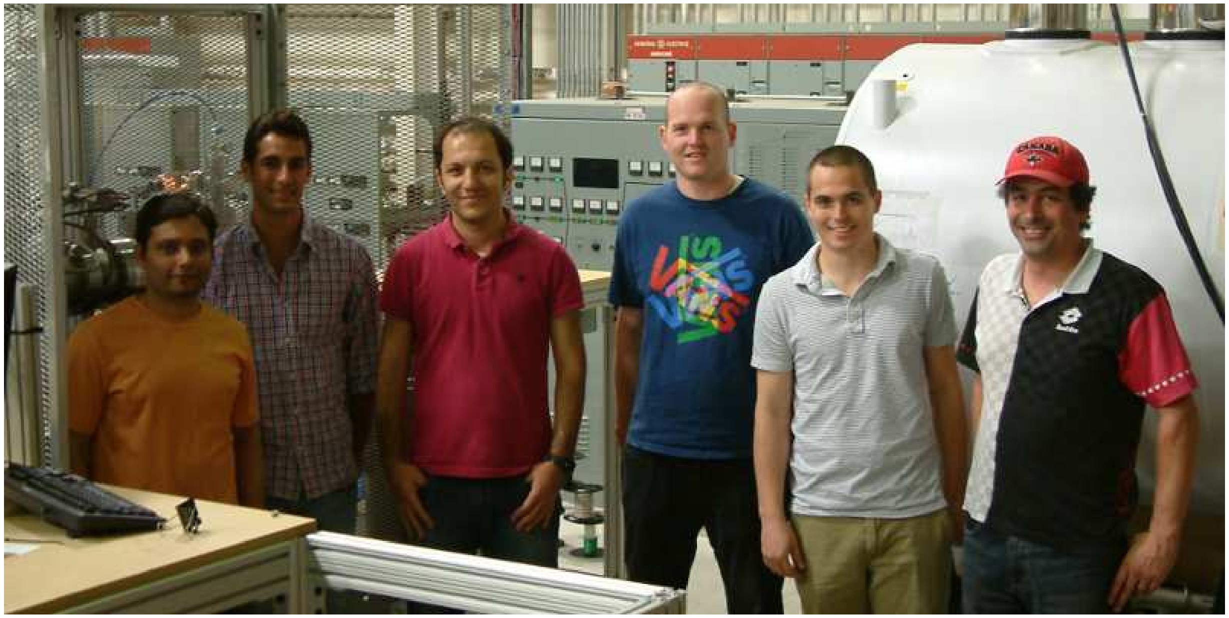
- **nuclear approach:** precision measurement of correlation parameters

Summary

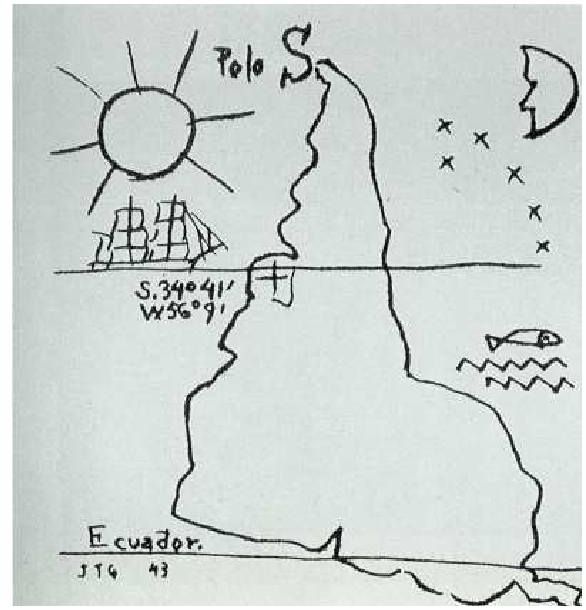
- SM is fantastic, but **not** our “ultimate” theory
- many exciting avenues to find more a complete model
- **nuclear approach:** precision measurement of correlation parameters
- Penning trap + RIB CI = ***cool*** physics
- (AC-)MOT + opt. pumping = ***cool*** physics

The Mad Trappers/Thanks

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



LASNPA organizers



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G. Gwinner

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