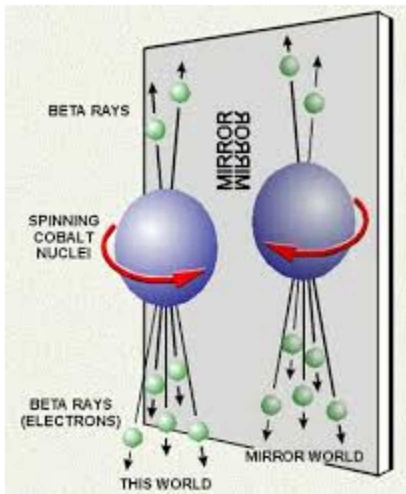
# Standard Model and ion traps: symmetries galore




**Jason Clark**

**Exotic Beam Summer School**

**July 28 – August 1, 2014**

# Overview of lectures

- Overview of the Standard Model (SM)
- Nature of the weak interaction and β decay
- Tests of the SM description of the weak interaction
    - β-ν correlations
    - unitarity of CKM matrix
    - constancy of *Ft* values
    - searches for neutrinoless double β decay
- Methods used to test SM description of weak interaction
    - Paul trap
    - Penning trap

# Lecture 1 outline

- Overview of the Standard Model (SM)
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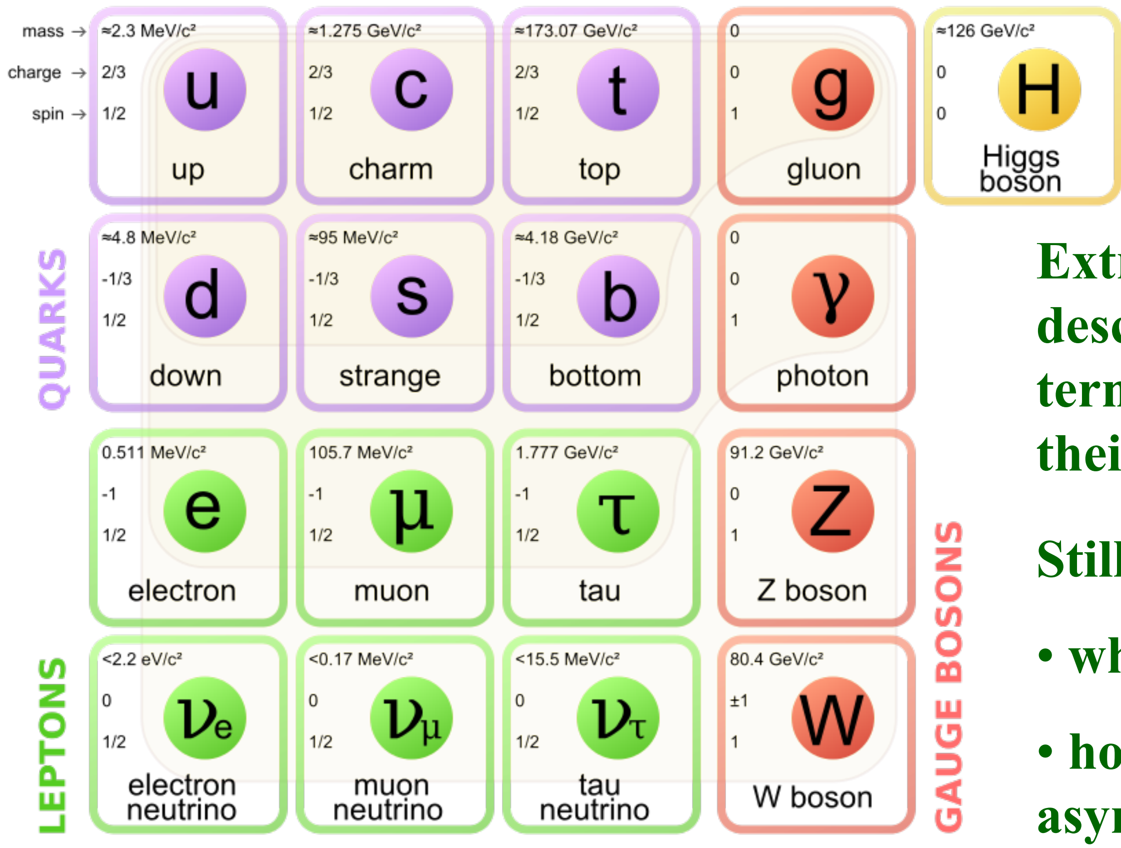
# Standard Model




**Extremely successful at describing the world around us in terms of basic constituents and their interactions.**

**Still some open questions:**

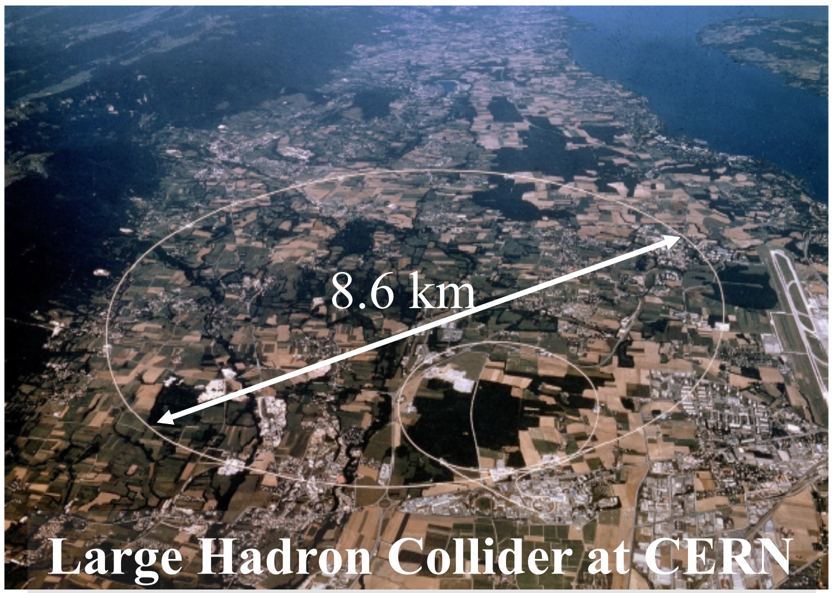
- **what is dark energy?**
- **how did the matter/antimatter asymmetry come to be?**

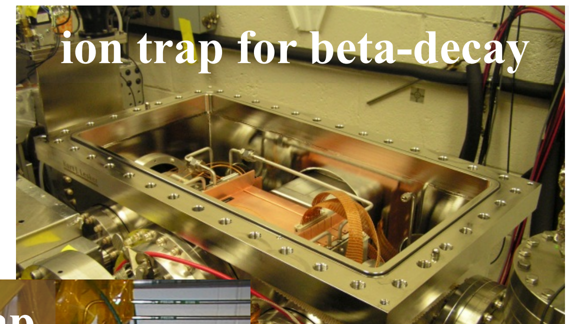
**Is there something beyond the Standard Model?**

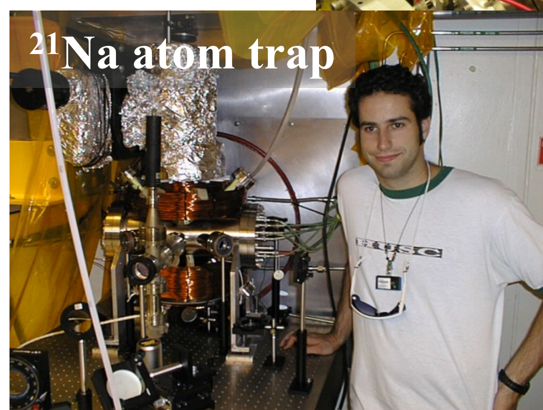
# Beyond the Standard Model

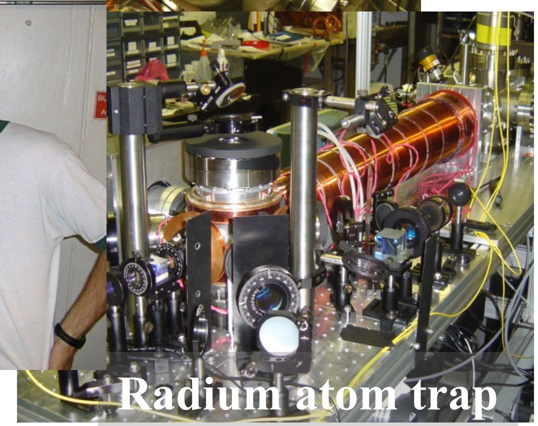
*High energy* → *Low energy*

*nuclear and atomic physics*



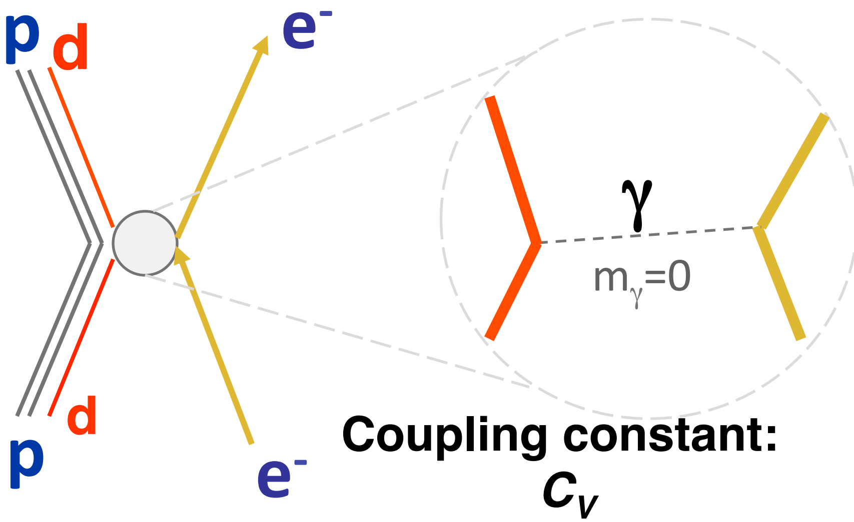




*Direct searches for new phenomena and particles at colliders*

*Indirect searches with high precision for subtle deviations from SM predictions*

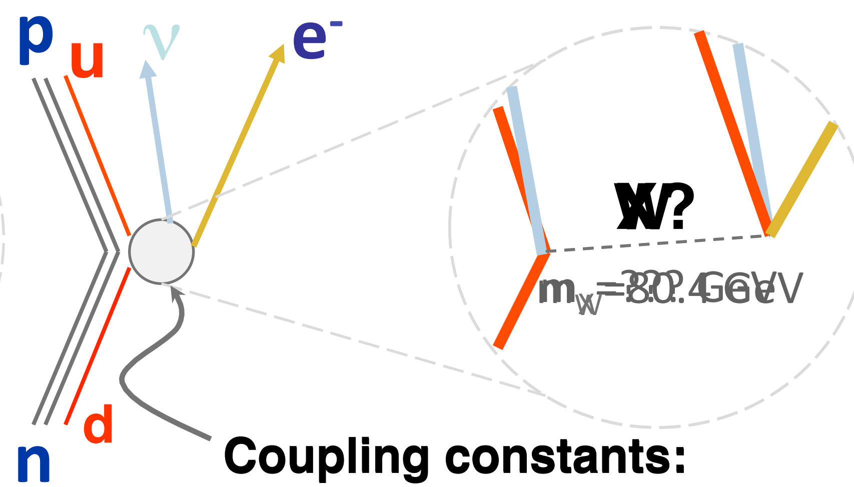
# Electroweak theory predicts a symmetry between EM and weak interaction

## Electromagnetism




**Coupling constant:**
$C_V$

## Weak Interaction




**Coupling constants:**
$C_S$?, $C_T$?

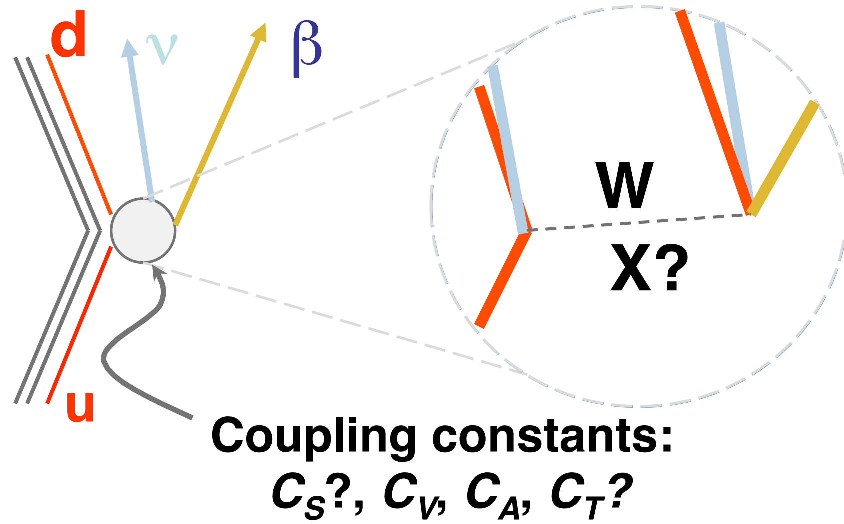
1979 Nobel Prize in Physics for electroweak theory

1984 Nobel Prize in Physics for discovery of the weak bosons

$$
\begin{aligned}
\mathcal{H}_\beta = & (\bar{p}n)[\bar{e}(C_S + C'_S\gamma_5)\nu] \\
& + (\bar{p}\gamma_\mu n)[\bar{e}\gamma_\mu(C_V + C'_V\gamma_5)\nu] \\
& + \tfrac{1}{2}(\bar{p}\sigma_{\lambda\mu}n)[\bar{e}\sigma_{\lambda\mu}(C_T + C'_T\gamma_5)\nu] \\
& - (\bar{p}\gamma_\mu\gamma_5 n)[\bar{e}\gamma_\mu\gamma_5(C_A + C'_A\gamma_5)\nu] \\
& + (\bar{p}\gamma_5 n)[\bar{e}\gamma_5(C_P + C'_P\gamma_5)\nu] + \text{H.c.}
\end{aligned}
$$

# Nuclear β decay correlations

**The form of the interaction results in certain correlations between the emitted β and ν and the spins…**




$$dW = dW_o \varepsilon \left[ 1 + \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} a + \frac{\Gamma m_e}{E_e} b \right] + \ldots$$

$$dW_0 = F(Z, E_e) p_e E_e (E_0 - E_e)^2 dE_e d\Omega_e d\Omega_\nu$$

- Compare experimental values to SM predictions
- Put limits on terms "forbidden" by SM

# Tests of the Standard Model: accurate physics in an inaccurate system

$$dW = dW_o \varepsilon \left[ 1 + \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} a + \frac{\Gamma m_e}{E_e} b \right]$$

**The nucleus is a complex quantum system not generally amenable to an exact description. However, by a proper choice of nuclear system, specific physical processes can be isolated and determined to high precision.**

**For measurements of angular correlations in nuclear beta-decay, only certain types of decays can be interpreted:**

- **Fermi allowed decay**
- **Gamow-Teller allowed decay**
- **mirror allowed decay**

**For pure Fermi:**

$$a = \frac{|C_V|^2 - |C_S|^2}{|C_V|^2 + |C_S|^2}$$

**SM prediction (only V-A terms):**

**= +1**

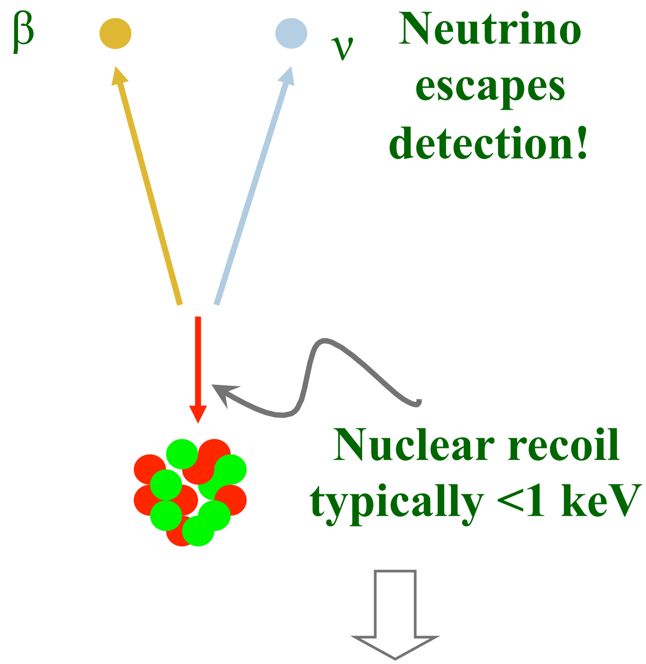
**For pure Gamov-Teller:**

$$a = -\frac{1}{3} \frac{|C_A|^2 - |C_T|^2}{|C_A|^2 + |C_T|^2}$$

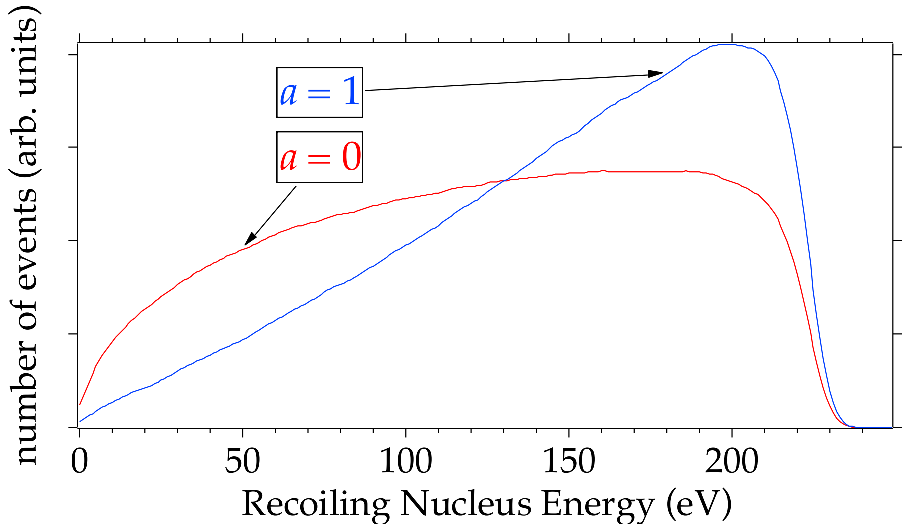
**= -1/3**

# The Beta-Neutrino Angular Correlation

**Neutrino too difficult to detect – correlation must be inferred from nuclear recoil**




**Example Recoil Energy Spectrum ($^{21}Na$)**



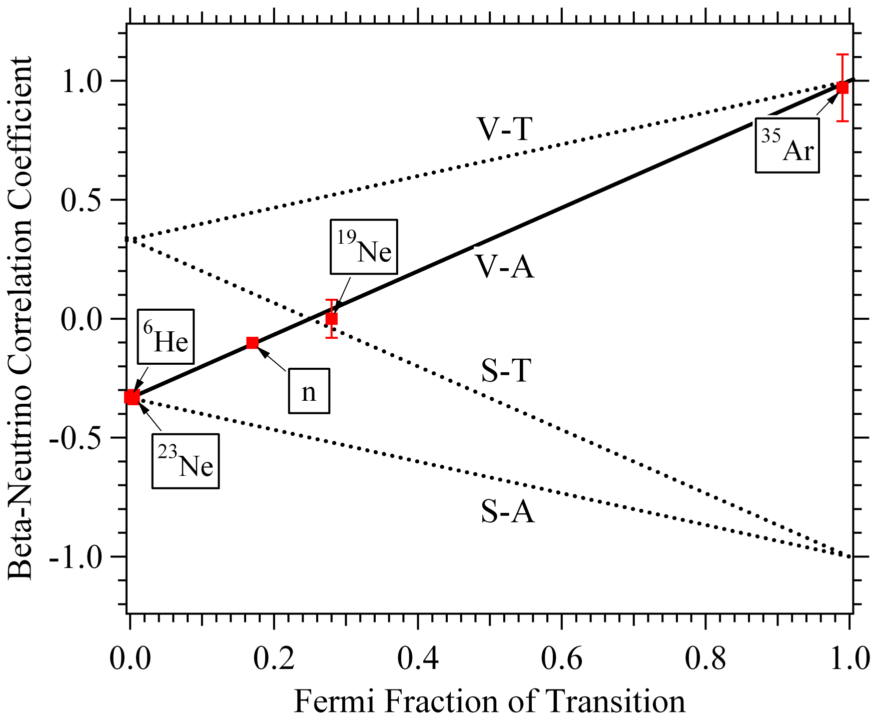

***a* > 0 leads to larger average recoil energy**

- **Direct detection -- acceleration of daughters**
- **Energy shift in subsequent particle emission**

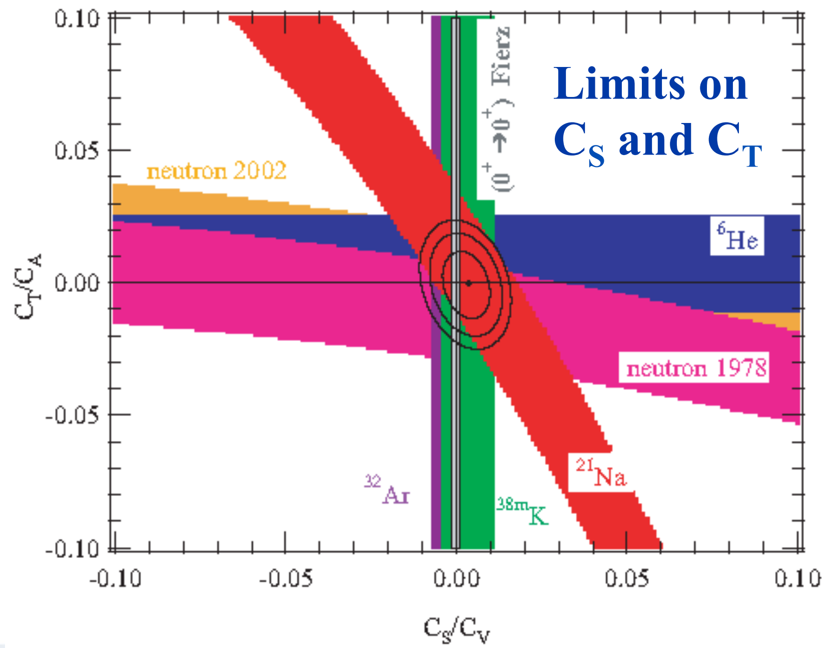
- **Sensitive to detector thresholds and resolution**
- **Correlation easily perturbed by scattering**

# Weak Interactions in Nuclei

**Historically the V-A structure of the weak interaction was determined by measurements of the beta-neutrino correlation in noble gas nuclei in the 1960's**



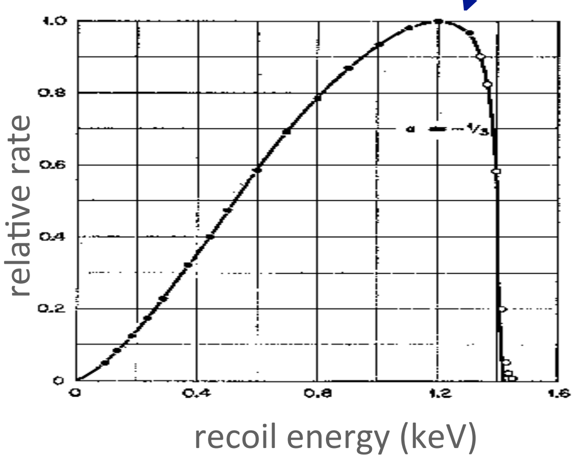

**Today, precise measurements of the beta-neutrino correlation are conducted to search for scalar or tensor contributions from exotic weak bosons**

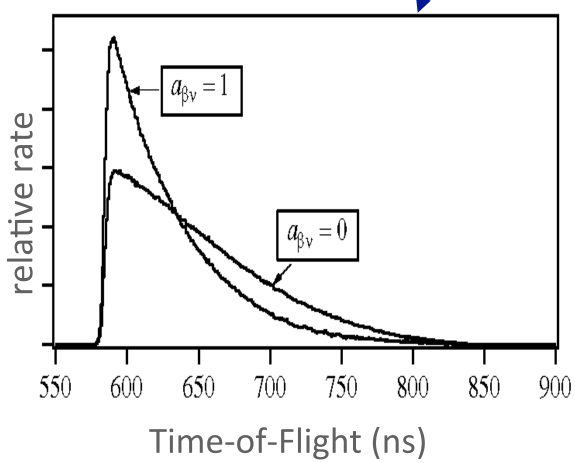


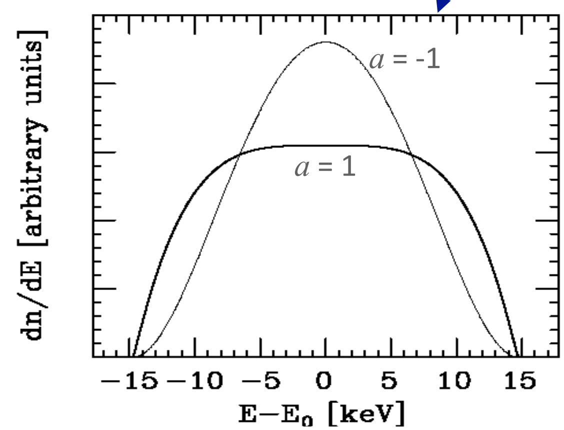

**P.A. Vetter *et al.*, PRC 77, 035502 (2008)**

# Experimental approaches

| Measure decay product energy directly | Measure TOF of recoil nucleus | Measure delayed particle emission |
| --- | --- | --- |
| n, $^{19}$Ne, $^{23}$Ne, $^{35}$Ar, $^{6}$He | n, $^{6}$He, $^{38m}$K, $^{21}$Na, $^{37}$K, $^{19}$Ne | **$^{8}$Li($\alpha$)**, $^{11}$Be($\gamma$), $^{14}$O($\gamma$) $^{18}$Ne($\gamma$), $^{20}$Na($\alpha$), $^{32}$Ar(p) $^{8}$He($\gamma$) |




0+ → 0+ delayed proton for *a*=1 & *a*=-1

C.H. Johnson *et al*. Phys. Rev. **132**, 1149

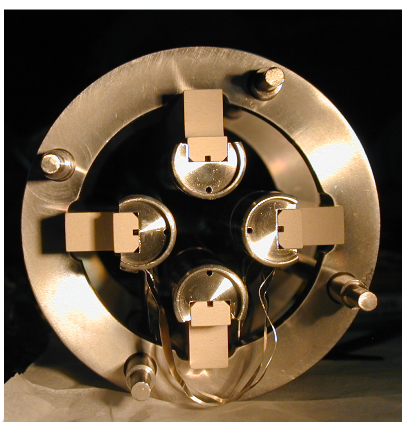
N. D. Scielzo *et al.* PRL.**93**,102501, 2004

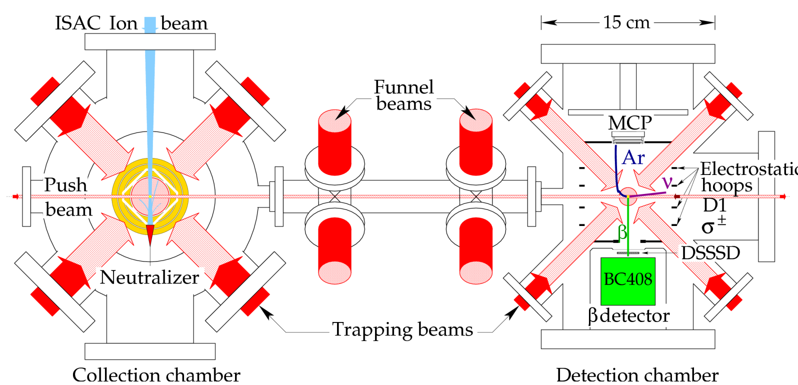
E.G. Adelberger *et al.* PRL.**83**, 1299 (1999).

# Traps provide access to nuclear recoil

**Traps provide a "massless" sample of radioactive nuclei suspended in vacuum**

- **Negligible scattering in source volume → nuclear recoil available for study**
- **Collect sample in ~1-mm$^3$ volume → excellent geometry for radiation detection**
- **Make efficient use of rare nuclei → high statistics needed for precision measurements**





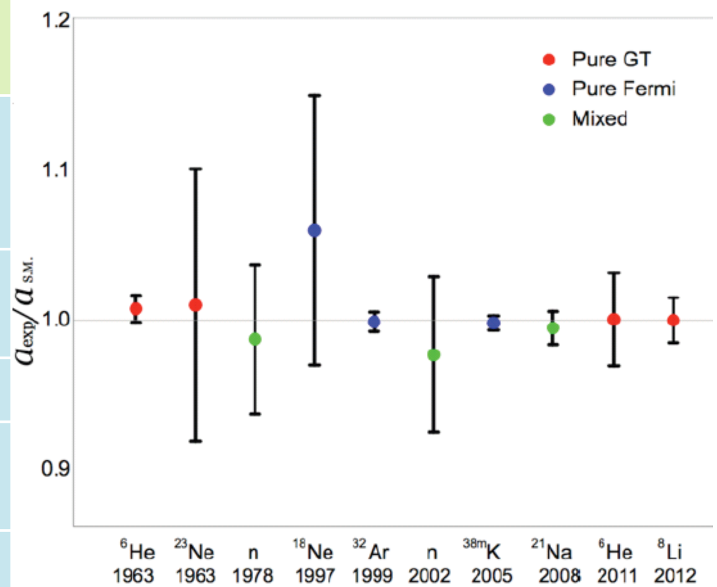
# β−ν correlation measurements using nuclei

| *Parent* | *Technique* | *Group, Lab* | *Results & Status* |
|---|---|---|---|
| $^{35}$Ar | Penning trap | Leuven+/ISOLDE | on going |
| $^{35}$Ar | Paul trap | LPC+/GANIL | on going |
| $^{38m}$K | Laser trap | SFU+/TRIUMF | Gorelov *et al.* PRL 94 (2005) 142501; Upgrade in progress |
| $^{21}$Na | Laser trap | Berkeley | Scielzo *et al.* PRL 93 (2004) 102501 ; Vetter *et al.* PRC 77 (2008) 035502 |
| $^{6}$He | Paul trap | LPC+/GANIL | Flechard *et al.* JPG 38 (2011) 055101; Upgrade in progress |
| $^{8}$Li | Paul trap | ANL+/Northwestern/LLNL | Li et al. PRL 110 (2013) 092502; Upgrade in progress |
| $^{6}$He | Laser trap | ANL+/CENPA | on going |
| $^{6}$He | Electrostatic trap | WIS (SOREQ) | in preparation |
| $^{32}$Ar | Penning trap | Texas A&M | In preparation |

**Fermi (*)** (*) pure or dominant

**Mixed**

**Gamow-Teller (*)**



# Confining ions with electric fields ...

# the Paul trap

W. Paul

# How to confine an ion in 1D with electric fields

To confine in 1D, need a restoring force:

$$F_z = -k_z(z - z_o)$$

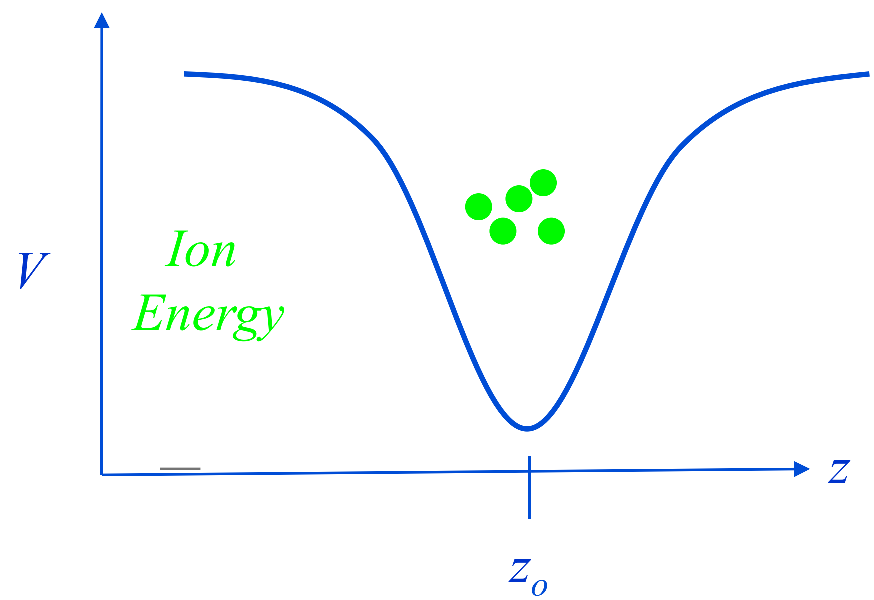
This force can be provided with an electric field: $F_z = qE_z$

Since: $\vec{E} = -\vec{\nabla} V$

then the potential required is:

$$V = \frac{k_z}{2q}(z - z_o)^2$$

or in a more general form: $V = \lambda_Z z^2$



# How to confine an ion in 2D with electric fields

Taking the general form of 1D confinement and extending it to 2D:

$$V = \lambda_x x^2 + \lambda_y y^2$$

In a source free region:

$$\vec{\nabla} \cdot \vec{E} = 0$$

$$\therefore \nabla^2 V = 0$$

Result is that:

$$\lambda_x + \lambda_y = 0$$

$$\therefore \lambda_x = -\lambda_y \equiv \lambda$$

$$\Rightarrow V = \lambda(x^2 - y^2)$$

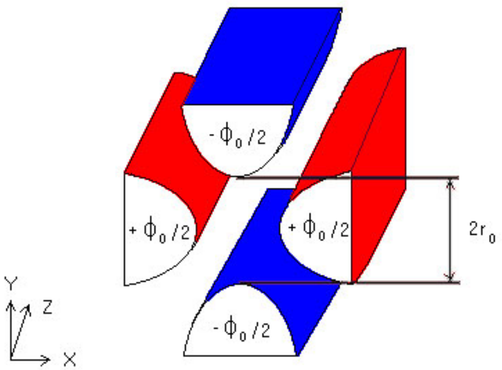
(Trivial solution of $\lambda_x = \lambda_y = 0$ does not provide a restoring force.)

# Equipotential surfaces required for 2D confinement

If we define: $V = \frac{\varphi_o}{2}$ at $(x,y) = (r_o,0)$

then: $\lambda = \frac{\varphi_o}{2r_o^2}$

Potential describes rods of hyperbolic cross section.




Result is equipotential surfaces:

$$\frac{x^2}{r_o^2} - \frac{y^2}{r_o^2} = 1 \quad \text{with} \quad V = \frac{\varphi_o}{2}$$

$$\frac{x^2}{r_o^2} - \frac{y^2}{r_o^2} = -1 \quad \text{with} \quad V = -\frac{\varphi_o}{2}$$

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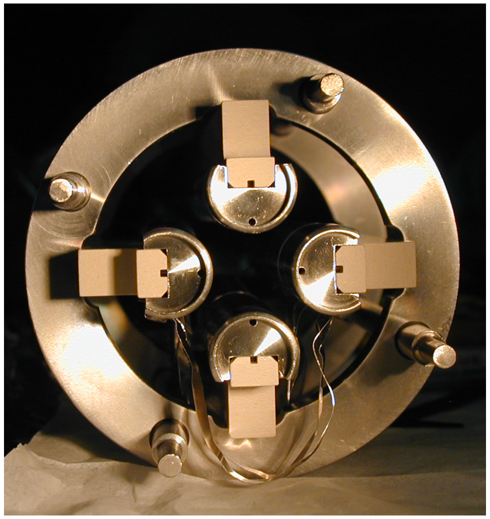
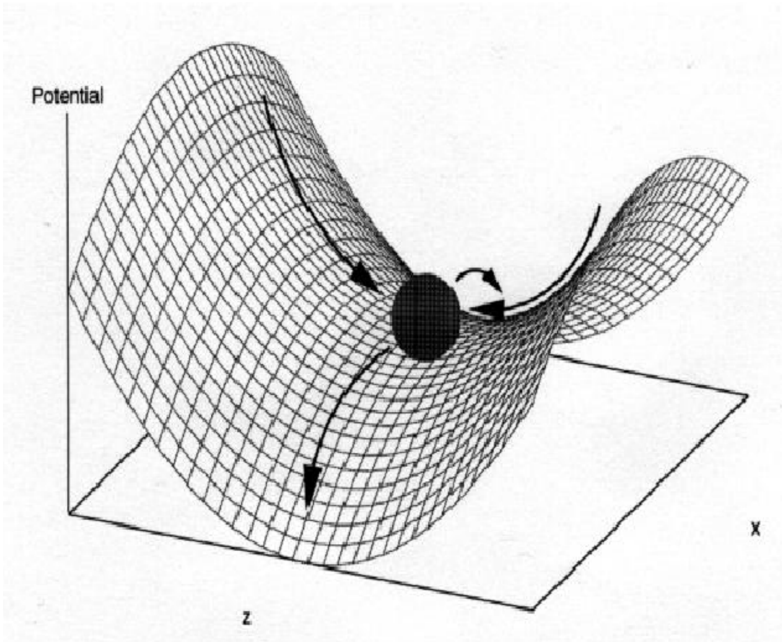


For practical reasons, circular rods are often used:

- easier to machine
- not much difference in confinement

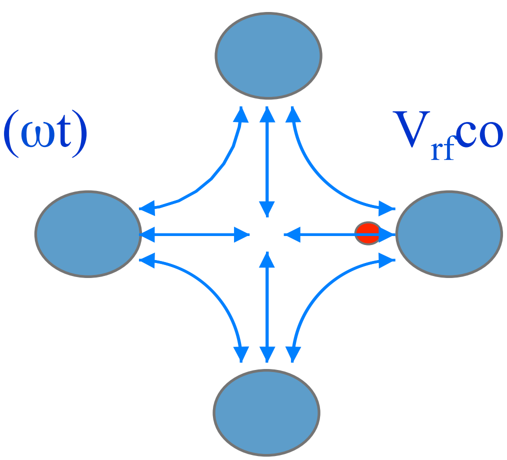
# Equipotential surface




Potential provides confinement along one direction, but ions can escape along the other direction.

Therefore need oscillating potential described by:

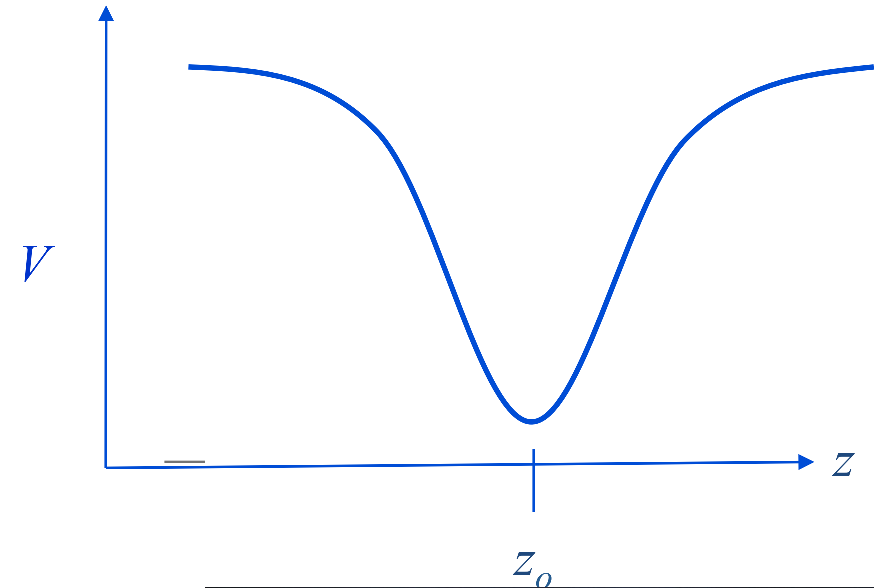
$$V = \frac{U_{DC} - V_{rf}\cos(\omega t)}{2r_o^{\ 2}}\left(x^2 - y^2\right)$$



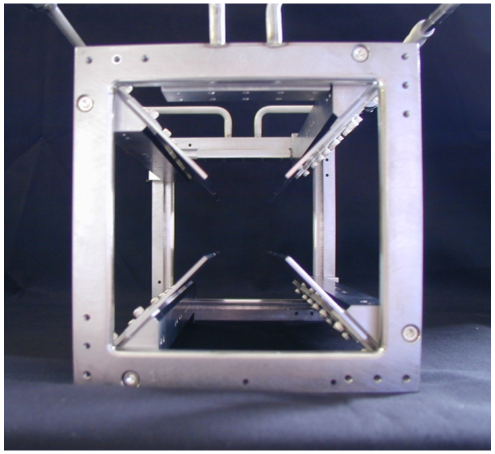

Trap in this manner called RFQ ion trap or Paul trap.

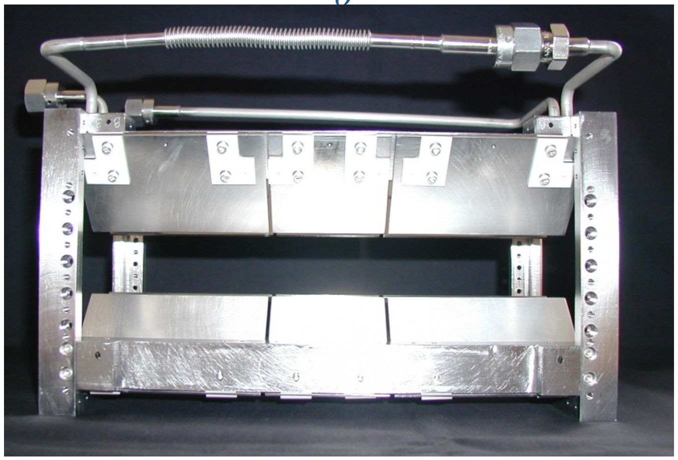
# How to confine ions in 3D … the simple approach (linear RFQ trap)

**Add a harmonic potential along the 'non-filter' axis:**



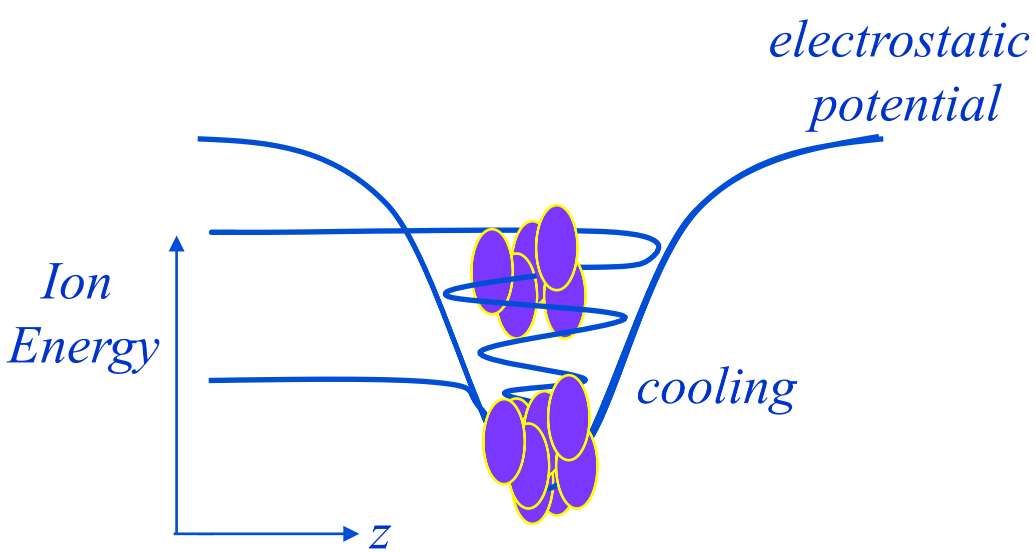

**The RF applied to the rod structure confines the ions along the 'x' and 'y' (radial) directions; the harmonic potential confines the ions along the 'z' direction.**





# How to trap, cool, and accumulate ions

**Often a buffer gas, like He, is used in the RFQ trap to cool the ions through collisional cooling. The equations of motion, then, include a 'drag force' and the solutions become complex versions of the regular Mathieu equations. This situation is analogous to the complex solutions which describe damped simple harmonic motion.**




**Bunched beam enters trap region**

**Trap closes**

**Ions cooled in 10-1000 ms to <1 eV using helium buffer gas**

**Hold cold ions for measurement**

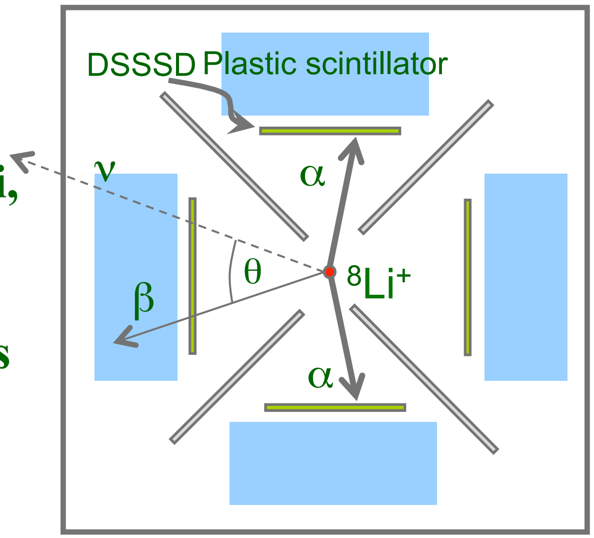
**Trap opens for next bunch while retaining trapped ions**

**Repeat to accumulate ions**

# RFQ trap composed of square plates allows open geometry

**Surround trapped radioactive ions with radiation detectors to reconstruct decay kinematics to determine energy/momenta of neutrinos or neutrons, particles that are normally hard to detect:**

**For β-ν correlation studies of $^{8}$Li, surround trapped ions with DSSSDs and plastic scintillators**



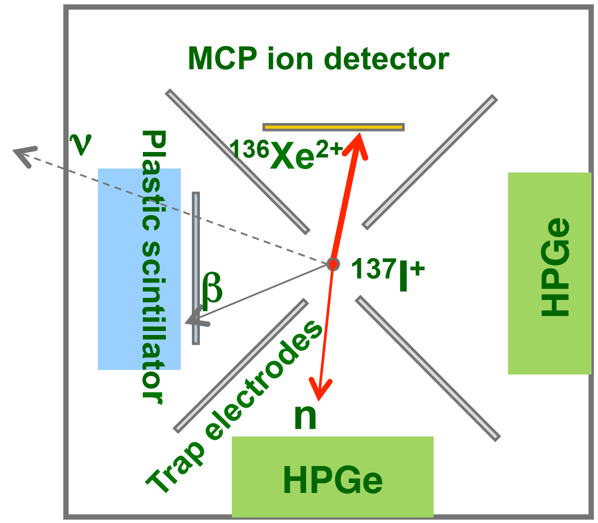

$^{8}Li \rightarrow {}^{8}Be^{*} + \beta^{-} + \nu$

$\quad \hookrightarrow \alpha + \alpha$

At rest in center of trap

Measure

Determine




**For β-delayed neutron studies, surround trap with plastic scintillators and MCPs**

$^{137}I \rightarrow {}^{137}Xe^{*} + \beta^{-} + \nu$

$\quad \hookrightarrow {}^{136}Xe + n$

At rest in center of trap

Measure

Determine

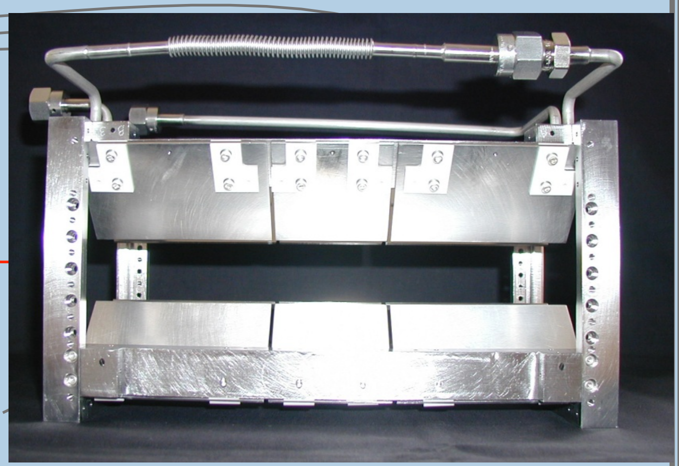
# Advantages of RFQ traps for decay studies

RFQ electrodes

SIDE VIEW:

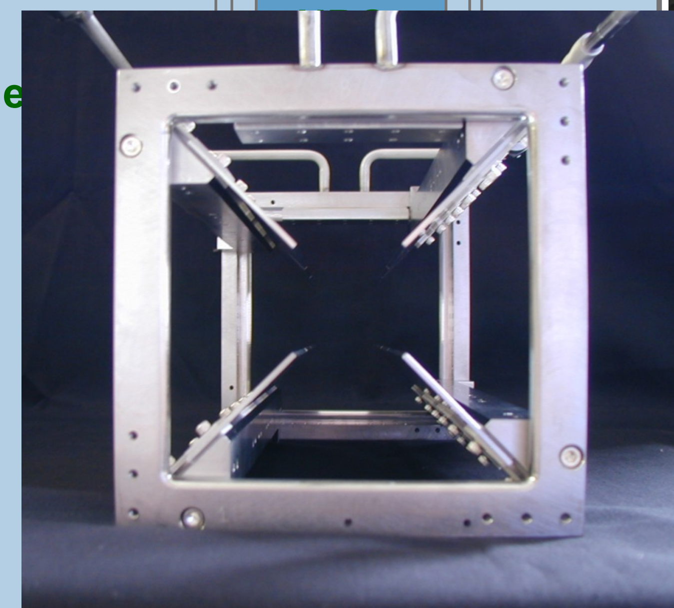
inject ions

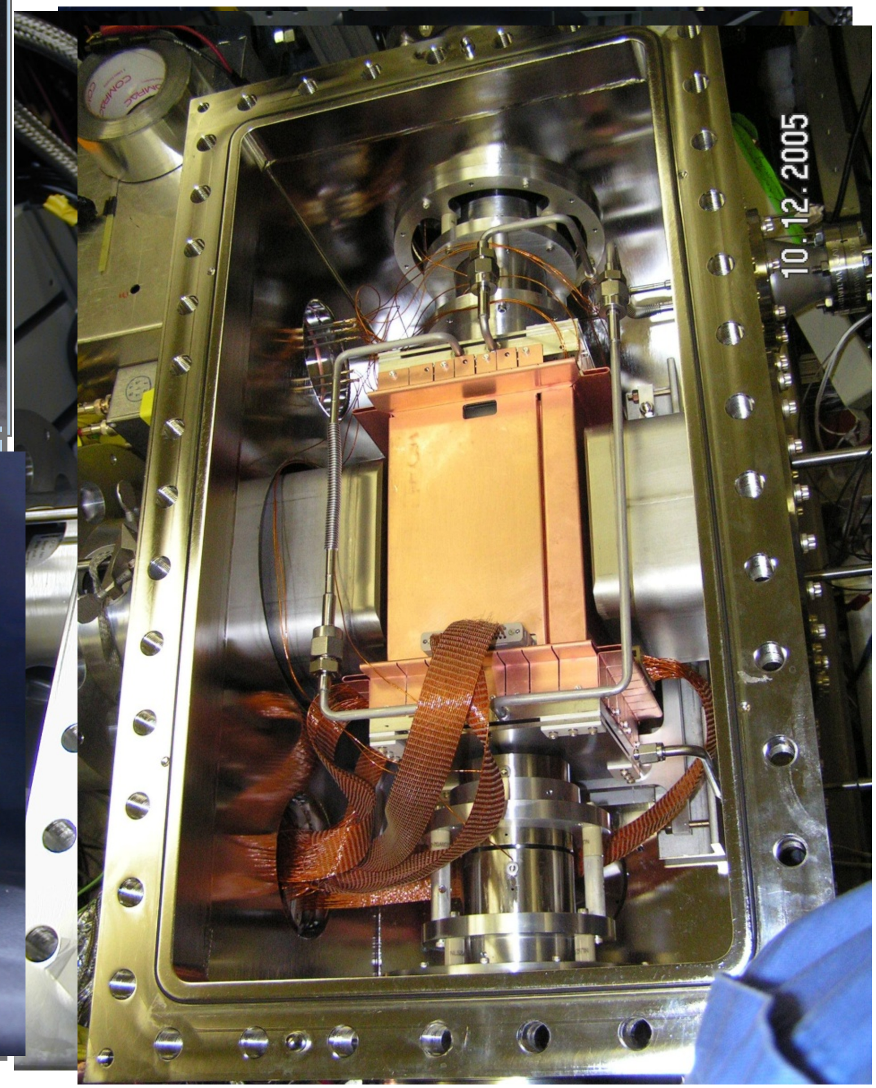
trapped ions



tele

END VIEW:





# Why is $^8$Li a promising candidate for improvement?

$^8$Li decay has many advantages:

$^8\text{Li} \rightarrow {}^8\text{Be}^* + \beta^- + \nu$
$\quad\quad\quad\quad \hookrightarrow \alpha + \alpha$

**$Q \approx$ 13 MeV** (broad $^8$Be* state at 3 MeV)

**$t_{1/2}$ = 0.808 sec**

- ➢ Large $Q$ value and small nuclear mass → 12-keV nuclear recoils and large shifts in a break up
  - energy difference ±400 keV
  - angle deviation from 180$^0$ by up to 7$^0$

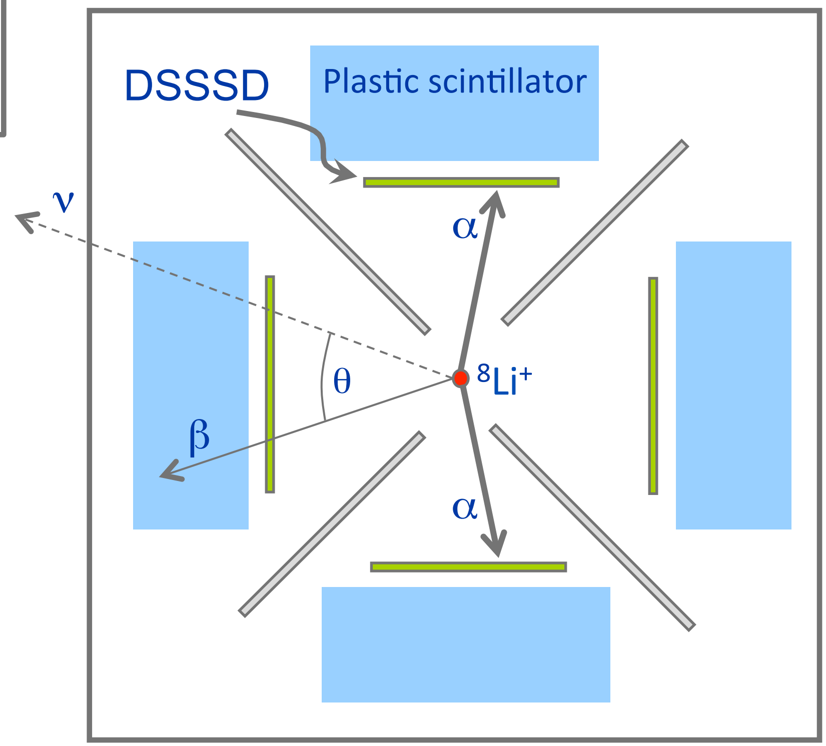
- ➢ Additional correlation between $\alpha$ and leptons enhances A/T difference

  $\beta-\nu$: ±1/3

  $\beta-\nu-\alpha$: ±1

- ➢ Symmetry of decay and detector array provides reduction of systematic effects

Surround trapped ions with DSSDs and plastic scintillators



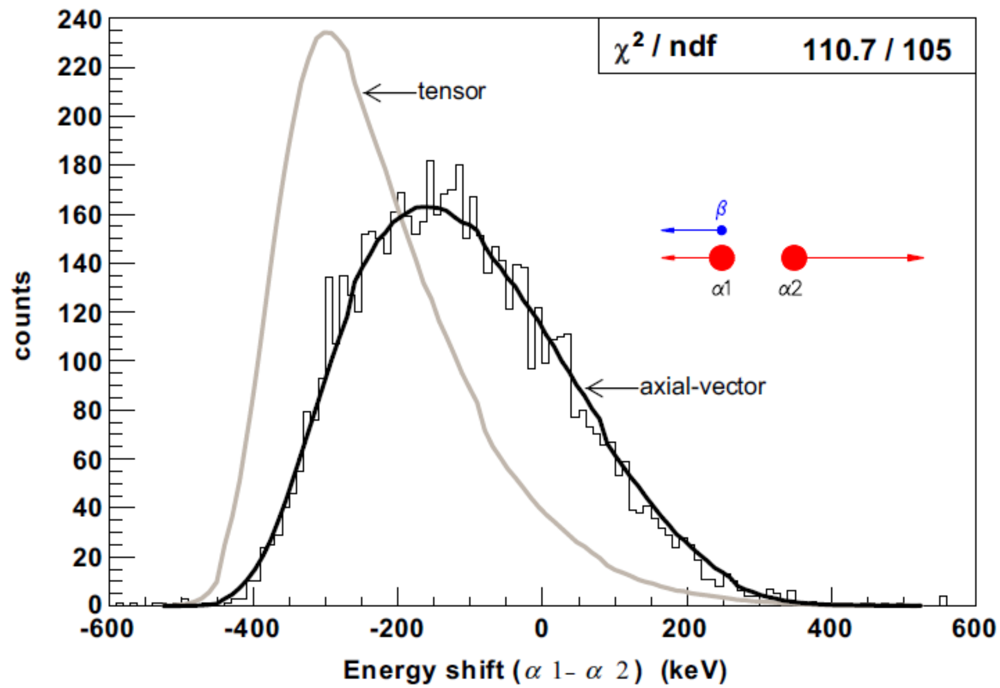
# $1^{st}$ results: β−α−α coincidences from $^{8}Li$ held in an RFQ ion trap

G. Li *et al.*, PRL **110**, 092502 (2013)
N.D. Scielzo *et al.*, NIM A **681**, 94 (2012)

**Axial vector vs. tensor difference enhanced by β-ν-α correlation**

**Symmetry of apparatus and of decay suppresses systematic effects**

**<1% statistical and systematic uncertainties in test of Standard Model**




**"Pure" Gamow-Teller decay**

$a_{SM}$ = -1/3

$a$ = -0.3307±0.0090 → data for further reduction by ×3 under analysis

# Questions?