Fundamental Interactions Group

האוניברסיטה העברית בירושלים
The Hebrew University of Jerusalem

Tricks and Traps:

Low Energy Searches for High Energy Physics

Guy Ron
Hebrew University of Jerusalem

MIT LNS
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הקרן הלאומית למדע

PAZY
EXCELLING IN SCIENCE

BSF
United States – Israel
Binational Science Foundation

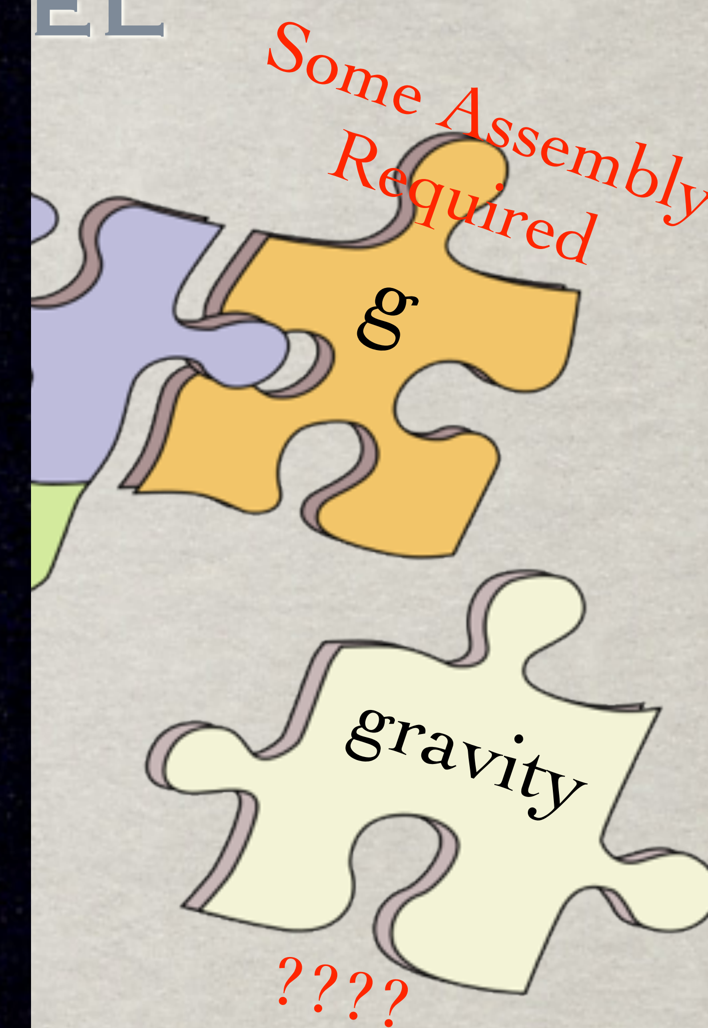
Outline

- β-decay 101 & the Standard Model
- NeAT
- WIRED
- OLiVIA

EL

- Pretty good desc
  - Electroweal
  - Strong forc
    Field Theor
  - Gravity - w
- Interactions are b
- Gauge groups de $\otimes \underbrace{U(1)_Y}_{EM}$
- Chiral symmetry
  interactions).
- Vacuum is electr sate
  breaks symmetry

$$
\begin{gathered}
-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\tfrac{1}{2} i g_s^2 (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \\
\tfrac{1}{2} m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \tfrac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\tfrac{2M^2}{g^2} + \\
\tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - i g c_w [\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)] - i g s_w [\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - \\
W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\tfrac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2 A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha [H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
\tfrac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] - \\
g M W^+_\mu W^-_\mu H - \tfrac{1}{2} g \tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \tfrac{1}{2} i g [W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\
W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \tfrac{1}{2} g [W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H \partial_\mu \phi^+ - \\
\phi^+ \partial_\mu H)] + \tfrac{1}{2} g \tfrac{1}{c_w} (Z^0_\mu (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - i g \tfrac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + \\
i g s_w M A_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) - i g \tfrac{1-2c_w^2}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
i g s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \tfrac{1}{4} g^2 W^+_\mu W^-_\mu [H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
\tfrac{1}{4} g^2 \tfrac{1}{c_w^2} Z^0_\mu Z^0_\mu [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+\phi^-] - \tfrac{1}{2} g^2 \tfrac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + \\
W^-_\mu \phi^+) - \tfrac{1}{2} i g^2 \tfrac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \tfrac{1}{2} g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + \\
W^-_\mu \phi^+) + \tfrac{1}{2} i g^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \tfrac{s_w}{c_w} (2c_w^2 - 1) Z^0_\mu A_\mu \phi^+ \phi^- - \\
g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma\partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma\partial \nu^\lambda - \bar{u}^\lambda_j (\gamma\partial + m_u^\lambda) u^\lambda_j - \bar{d}^\lambda_j (\gamma\partial + \\
m_d^\lambda) d^\lambda_j + i g s_w A_\mu [-(\bar{e}^\lambda \gamma e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j \gamma u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j \gamma d^\lambda_j)] + \tfrac{ig}{4c_w} Z^0_\mu [(\bar{\nu}^\lambda \gamma^\mu (1 + \\
\gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (\tfrac{4}{3} s_w^2 - 1 - \gamma^5) u^\lambda_j) + \\
(\bar{d}^\lambda_j \gamma^\mu (1 - \tfrac{8}{3} s_w^2 - \gamma^5) d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} W^+_\mu [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (1 + \\
\gamma^5) C_{\lambda\kappa} d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}} W^-_\mu [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa} \gamma^\mu (1 + \gamma^5) u^\lambda_j)] + \\
\tfrac{ig}{2\sqrt{2}} \tfrac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \tfrac{g}{2} \tfrac{m_e^\lambda}{M} [H (\bar{e}^\lambda e^\lambda) + \\
i \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}^\lambda_j C_{\lambda\kappa} (1 - \gamma^5) d^\kappa_j) + m_u^\lambda (\bar{u}^\lambda_j C_{\lambda\kappa} (1 + \\
\gamma^5) d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 + \gamma^5) u^\kappa_j) - m_u^\kappa (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 - \gamma^5) u^\kappa_j] - \\
\tfrac{g}{2} \tfrac{m_u^\lambda}{M} H (\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2} \tfrac{m_d^\lambda}{M} H (\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2} \tfrac{m_u^\lambda}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \tfrac{ig}{2} \tfrac{m_d^\lambda}{M} \phi^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j) + \\
\bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \tfrac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + \\
i g c_w W^+_\mu (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + i g s_w W^+_\mu (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + \\
i g c_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + i g s_w W^-_\mu (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + \\
i g c_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + i g s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \\
\tfrac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2} \bar{X}^0 X^0 H] + \tfrac{1-2c_w^2}{2c_w} i g M [\bar{X}^+ X^0 \phi^+ - \\
\bar{X}^- X^0 \phi^-] + \tfrac{1}{2c_w} i g M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + i g M s_w [\bar{X}^0 X^- \phi^+ - \\
\bar{X}^0 X^+ \phi^-] + \tfrac{1}{2} i g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
\end{gathered}
$$



But...

Higgs VEV - 1 — 2

$\alpha_{U(1)}$ - 1

$\alpha_{SU(2)}$ - 1 — 3

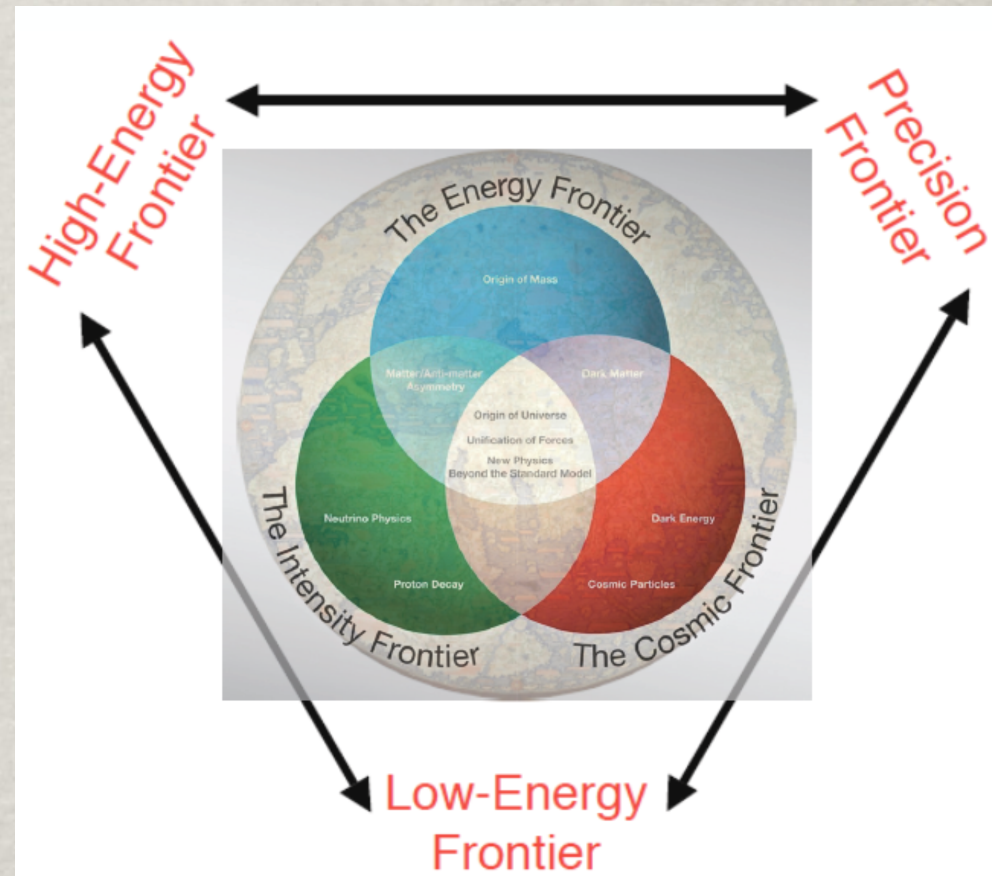
α_{Strong} - 1

Cosmological Constant - 1

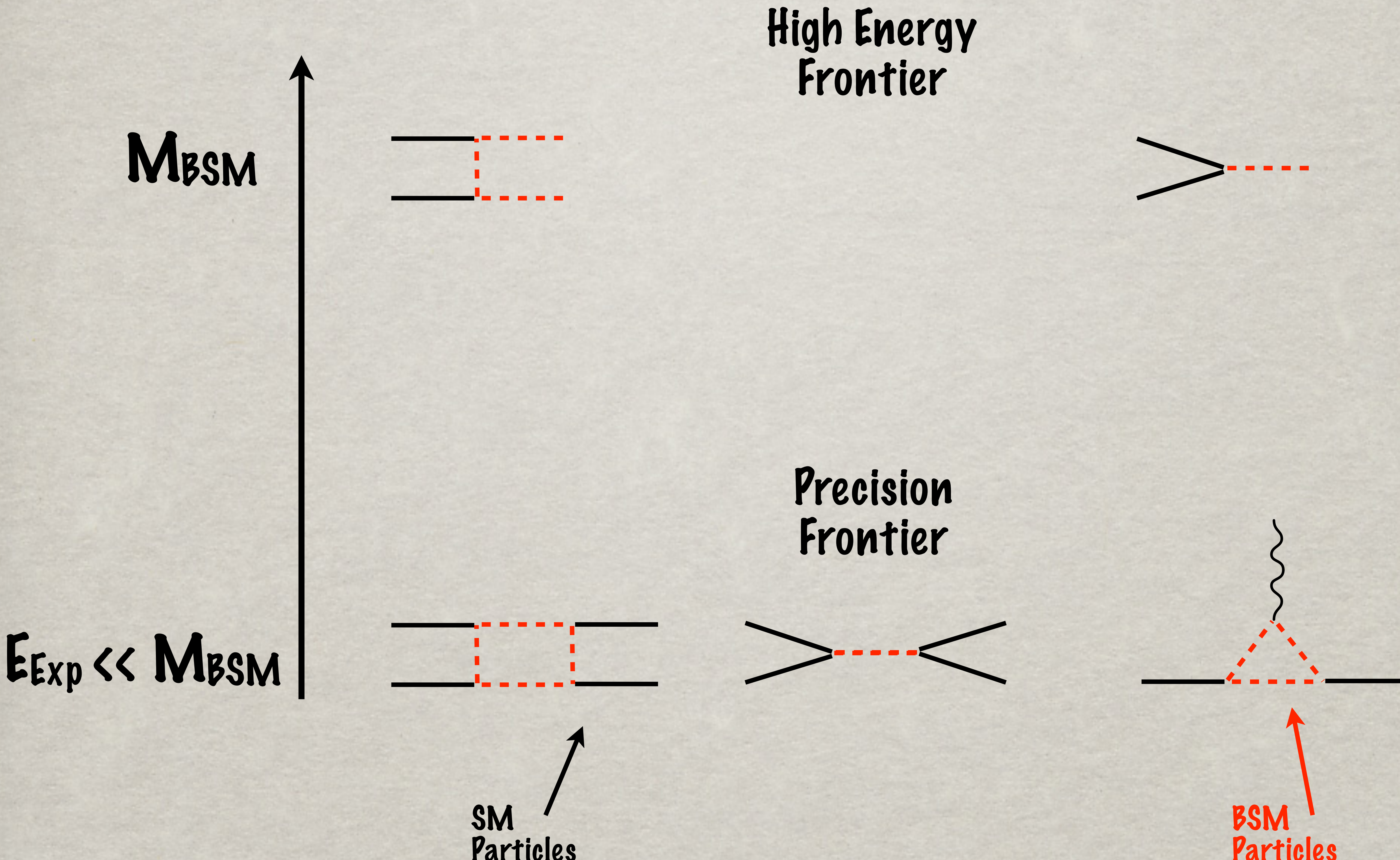
θ_{QCD} - 1 — 2

Beyond SM
ust Exist!
e should we look
for it?

Where to search for beyond SM Physics?

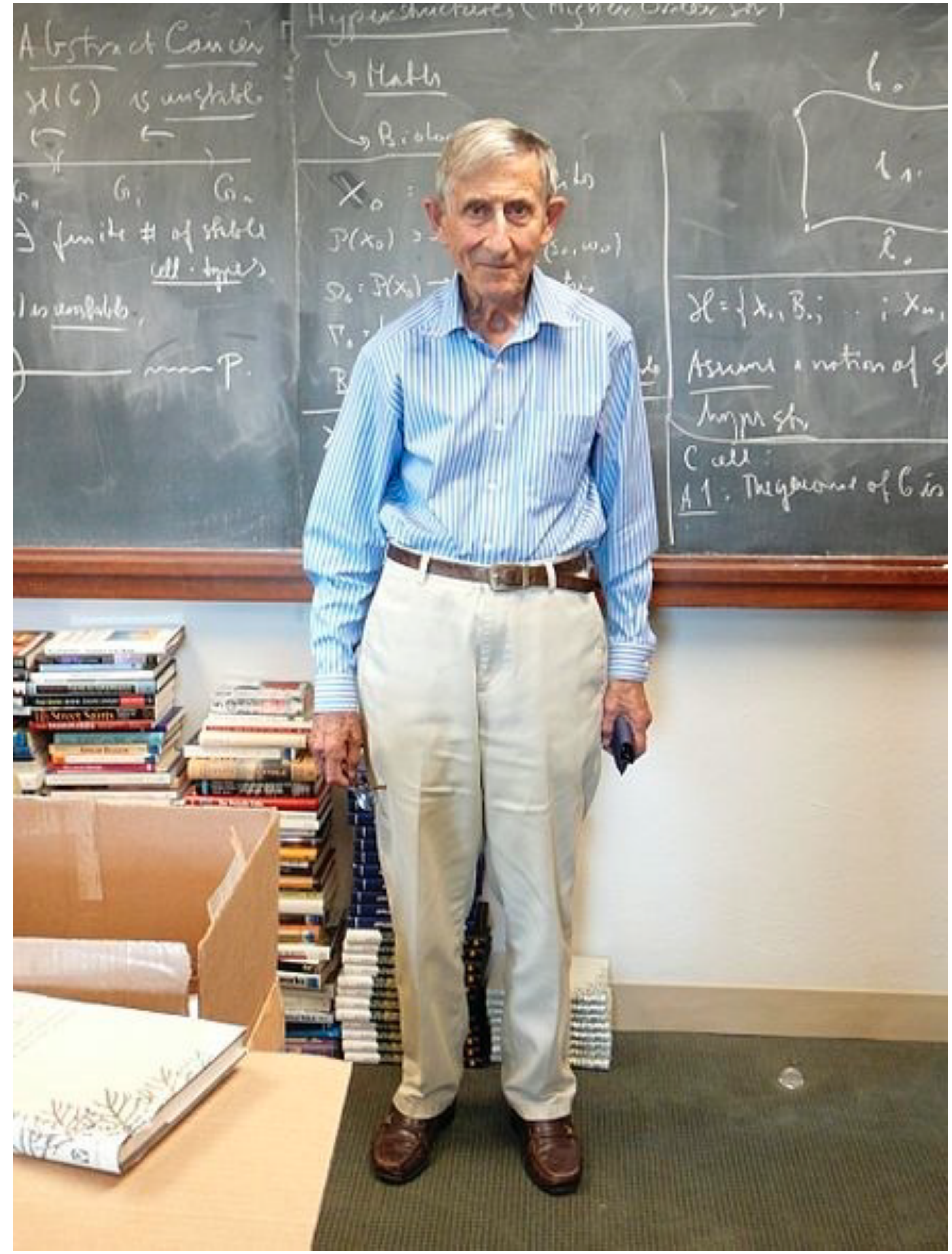


- High Energy Frontier
  - Go higher in energy/luminosity.
  - LHC/Tevatron/ILC.
- Precision Frontier
  - High precision experiments.
  - Detect the effect of beyond SM on low energy observables.
  - "Table top" experiments: $0\nu\beta\beta$, atomic PNC, EDM, $\nu\beta$ correlation.
  - Accelerator based: Proton/Neutron weak charge (Q_{weak}, PRex, ...).


High Energy Frontier
M_{BSM}
Precision Frontier
$E_{Exp} << M_{BSM}$
SM Particles
BSM Particles

Freeman Dyson on 16 discoveries awarded the Nobel Prize between 1945 and 2008:

The results of my survey are then as follows: four discoveries on the energy frontier, four on the rarity frontier, eight on the accuracy frontier. Only a quarter of the discoveries were made on the energy frontier, while half of them were made on the accuracy frontier. For making important discoveries, high accuracy was more useful than high energy.



The weak interaction
(at low energy)

- Proceeds (as far as we know) via the V-A (vector - axial vector) interaction:

$$\mathcal{L}_{\text{Leptonic}} \propto G_F \left[u_e \gamma_\mu \left(1 - \gamma^5\right) v_{\bar{\nu}} + h.c \right]$$

- Renormalized by the strong force for the hadronic case:

$$\mathcal{L}_{\text{Hadronic}} \propto G_F \left[N \gamma_\mu \left(C_V - C_A \gamma^5\right) P + h.c \right]$$

$$C_V = 1,\ C_A \sim 1.26$$

- Interaction mediated by vector bosons ($W^\pm$, Z^0) - since intermediate bosons are heavy (M ~ 90 GeV) interaction approximated by 4-point contact interaction (for low energy).

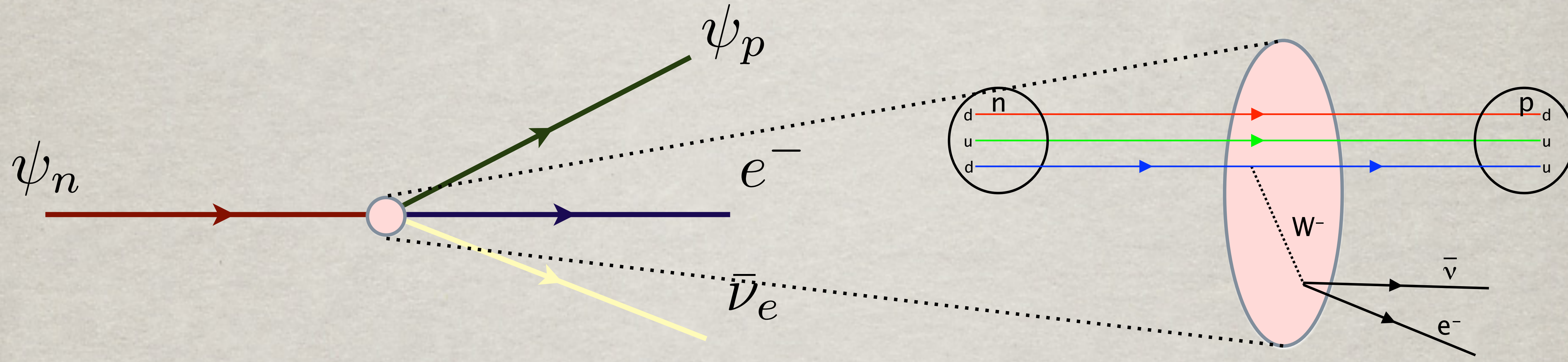
- But no apriori reason for this.

- Most general form for β-decay amplitude:

$$A \propto \sum_i \int d^3x \left[\bar{\psi}_p \mathcal{O}_i \psi_n\right] \left[\bar{\psi}_e \mathcal{O}_i \left(C_i - C_i' \gamma_5\right) \psi_\nu\right]$$

$$i = S, V, T, A, P$$

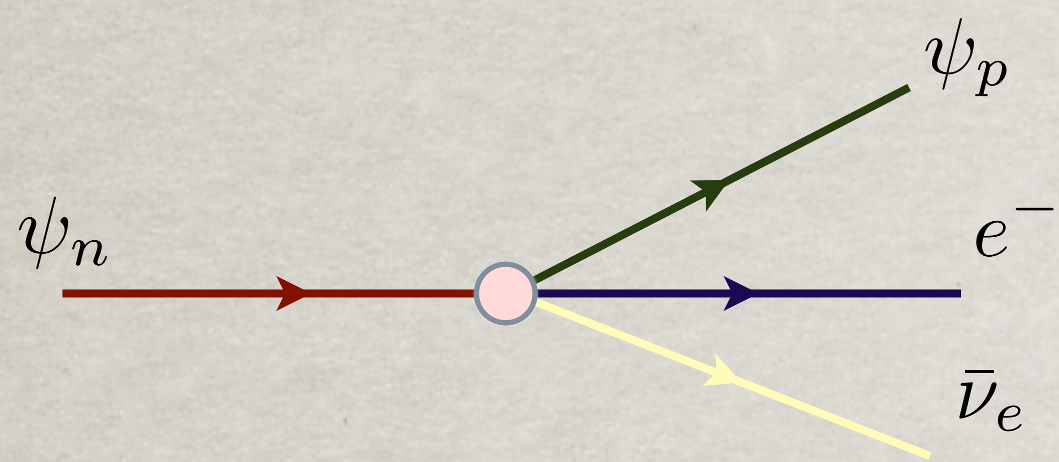
Nuclear β decay



$$
\begin{aligned}
H_\beta = \quad & (\bar{\psi}_n \psi_p)(C_s \bar{\psi}_e \psi_\nu + C'_s \bar{\psi}_e \psi_\nu \gamma_5 \psi_\nu) \\
& +(\bar{\psi}_n \gamma_\mu \psi_p)(C_V \bar{\psi}_e \gamma^\mu \psi_\nu + C'_V \bar{\psi}_e \gamma^\mu \gamma_5 \psi_\nu) \\
& +\frac{1}{2}(\bar{\psi}_n \sigma_{\lambda\nu} \psi_p)(C_T \bar{\psi}_e \sigma^{\lambda\nu} \psi_\nu + C'_T \bar{\psi}_e \sigma^{\lambda\nu} \gamma_5 \psi_\nu) \\
& -(\bar{\psi}_n \gamma_\mu \gamma_5 \psi_p)(C_A \bar{\psi}_e \gamma^\mu \gamma_5 \psi_\nu + C'_A \bar{\psi}_e \gamma^\mu \psi_\nu) \\
& +(\bar{\psi}_n \gamma_5 \psi_p)(C_P \bar{\psi}_e \gamma_5 \psi_\nu + C'_P \bar{\psi}_e \psi_\nu)
\end{aligned}
$$

19 free parameters
(10 complex couplings
- arbitrary phase)

This is Standard Model



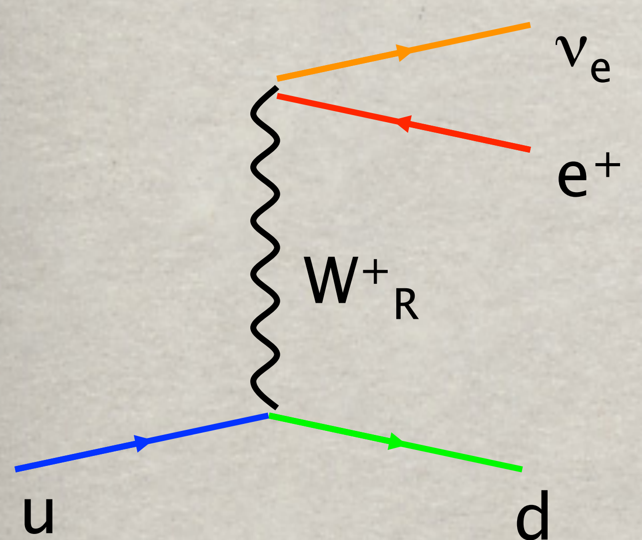
$$H_\beta = (\bar{\psi}_n\gamma_\mu\psi_p)(C_V\bar{\psi}_e\gamma^\mu\psi_\nu + C'_V\bar{\psi}_e\gamma^\mu\gamma_5\psi_\nu) - (\bar{\psi}_n\gamma_\mu\gamma_5\psi_p)(C_A\bar{\psi}_e\gamma^\mu\gamma_5\psi_\nu + C'_A\bar{\psi}_e\gamma^\mu\psi_\nu)$$

$$C_V = C'_V = 1$$

$$C_A = C'_A = 1.26$$

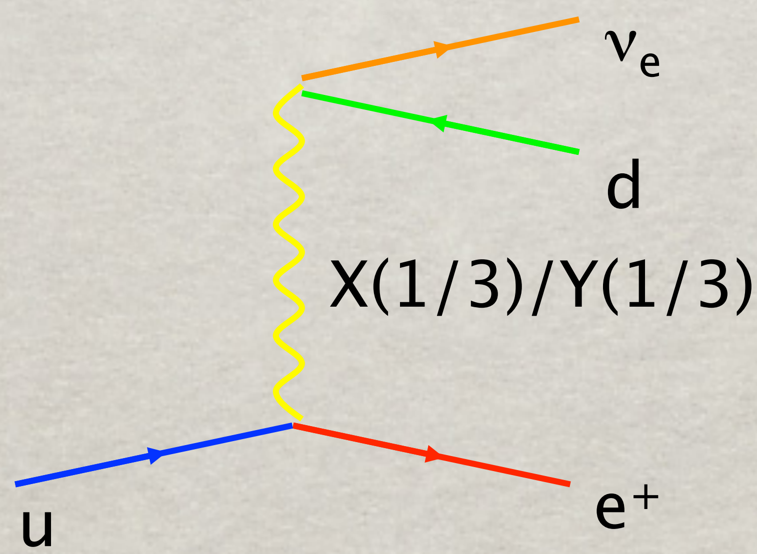
BSM mechanisms: **MANY**

This is Not....



Right handed bosons

$$C \neq C'$$



Scalar or Tensor Leptoquarks

$$C_T \neq 0$$

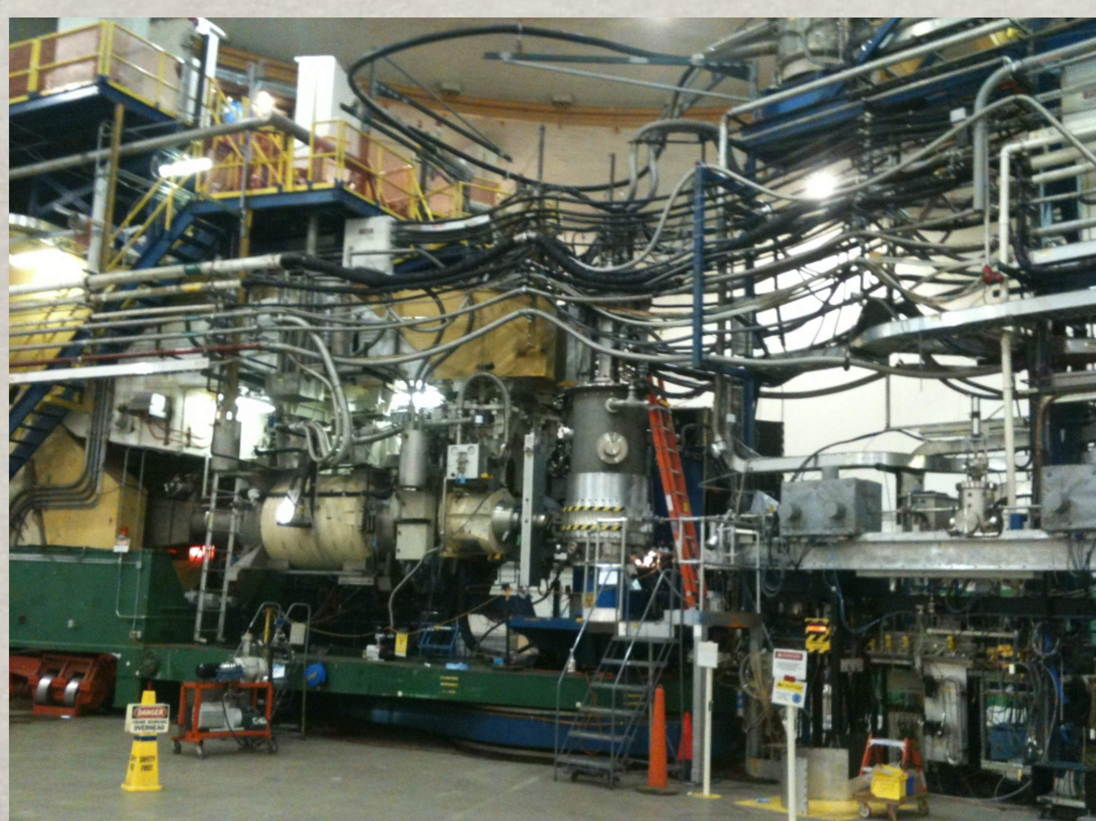
$$C_S \neq 0$$

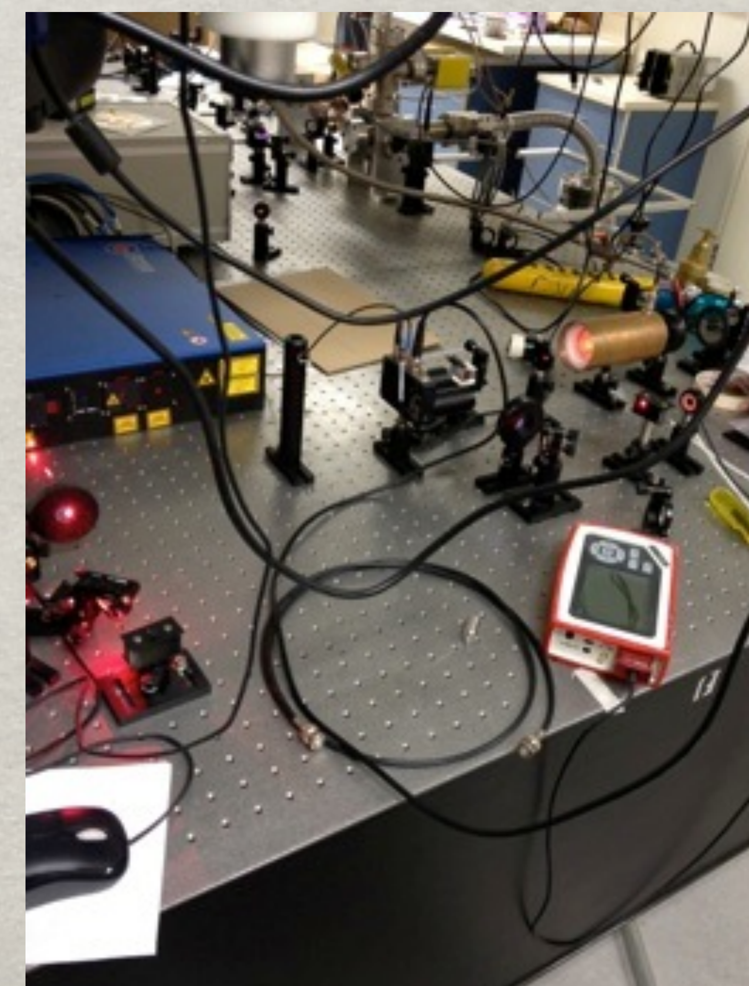
- SUSY slepton flavor mixing.
- SUSY LR mixing.
- many more (with different C's)...

In The Lab

$$
\begin{aligned}
H_\beta \quad = \quad & (\bar{\psi}_n \psi_p)(C_s \bar{\psi}_e \psi_\nu + C'_s \bar{\psi}_e \psi_\nu \gamma_5 \psi_\nu) \\
& +(\bar{\psi}_n \gamma_\mu \psi_p)(C_V \bar{\psi}_e \gamma^\mu \psi_\nu + C'_V \bar{\psi}_e \gamma^\mu \gamma_5 \psi_\nu) \\
& +\frac{1}{2}(\bar{\psi}_n \sigma_{\lambda\nu} \psi_p)(C_T \bar{\psi}_e \sigma^{\lambda\nu} \psi_\nu + C'_T \bar{\psi}_e \sigma^{\lambda\nu} \gamma_5 \psi_\nu) \\
& -(\bar{\psi}_n \gamma_\mu \gamma_5 \psi_p)(C_A \bar{\psi}_e \gamma^\mu \gamma_5 \psi_\nu + C'_A \bar{\psi}_e \gamma^\mu \psi_\nu) \\
& +(\bar{\psi}_n \gamma_5 \psi_p)(C_P \bar{\psi}_e \gamma_5 \psi_\nu + C'_P \bar{\psi}_e \psi_\nu)
\end{aligned}
$$

?





β DECAY 101

Total decay … on polarization not detected)

$$\frac{d\Gamma}{dE_\beta d\Omega_\beta d\Omega_\nu} \propto \xi \left\{ \ldots a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} + c\left[\frac{1}{3}\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} - \frac{(\vec{p}_e\cdot\vec{j})(\vec{p}_\nu\cdot\vec{j})}{E_eE_\nu}\right]\right.$$

$$\left.\left[\frac{J(J+\ldots \vec{j})^2>}{J(2J-1)}\right] + \frac{<\vec{J}>}{J}\cdot\left[A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e\times\vec{p}_\nu}{E_eE_\nu}\right]\right\}$$

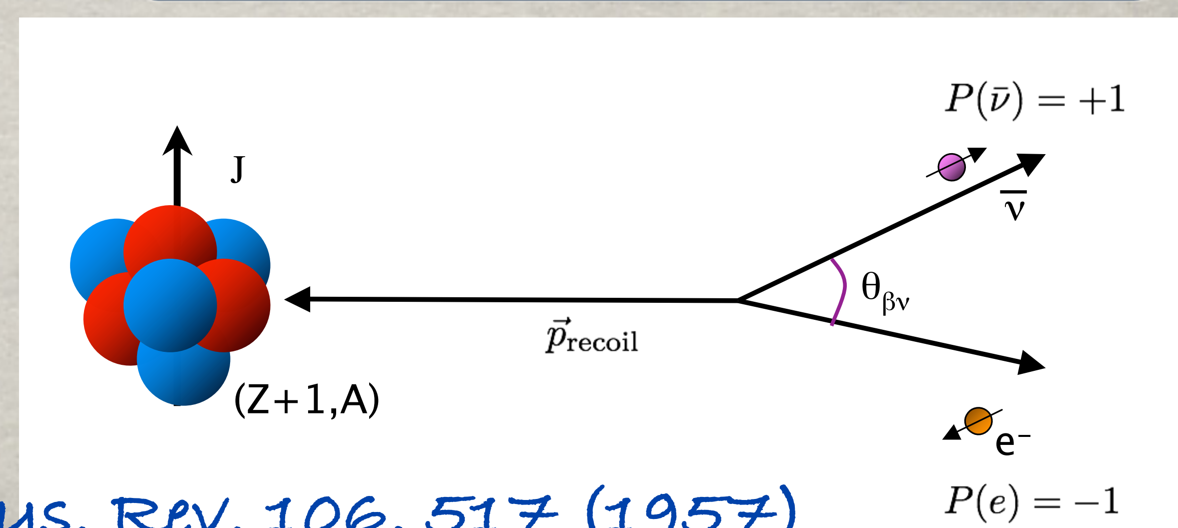
Electron-neutrino correlation

$$\xi a = |M_F|^2\left(-|C_S|^2 + |C_V|^2 - |C'_S|^2 + |C'_V|^2\right) + \frac{|M_{GT}|^2}{3}\left(|C_T|^2 - |C_A|^2 + |C'_T|^2 - |C'_A|^2\right)$$

$$\xi = |M_F|^2\left(|C_S|^2 + |C_V|^2 + |C'_S|^2 + |C'_V|^2\right) + |M_{GT}|^2\left(|C_T|^2 + |C_A|^2 + |C'_T|^2 + |C'_A|^2\right)$$

β + ν carry no AM → emitted in same direction (opposite helicities)

Pure Fermi: a = 1

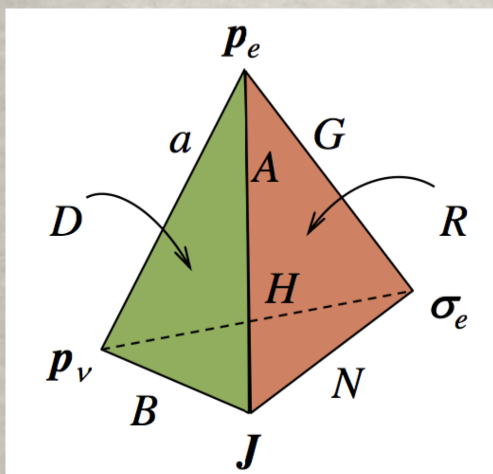


J.D. Jackson, S.B. Treiman, & H.W. Wyld, Phys. Rev. 106, 517 (1957)

β DECAY 101

Possible observables in nuclei

$$\frac{d\Gamma}{dE_\beta d\Omega_\beta d\Omega_\nu} \propto \xi \left\{ 1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} + b\frac{m}{E_e} + c\left[\frac{1}{3}\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} - \frac{(\vec{p}_e\cdot\vec{j})(\vec{p}_\nu\cdot\vec{j})}{E_eE_\nu}\right] \left[\frac{J(J+1)-3<(\vec{J}\cdot\vec{j})^2>}{J(2J-1)}\right] + \frac{<\vec{J}>}{J}\cdot\left[A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e\times\vec{p}_\nu}{E_eE_\nu}\right]\right\}$$

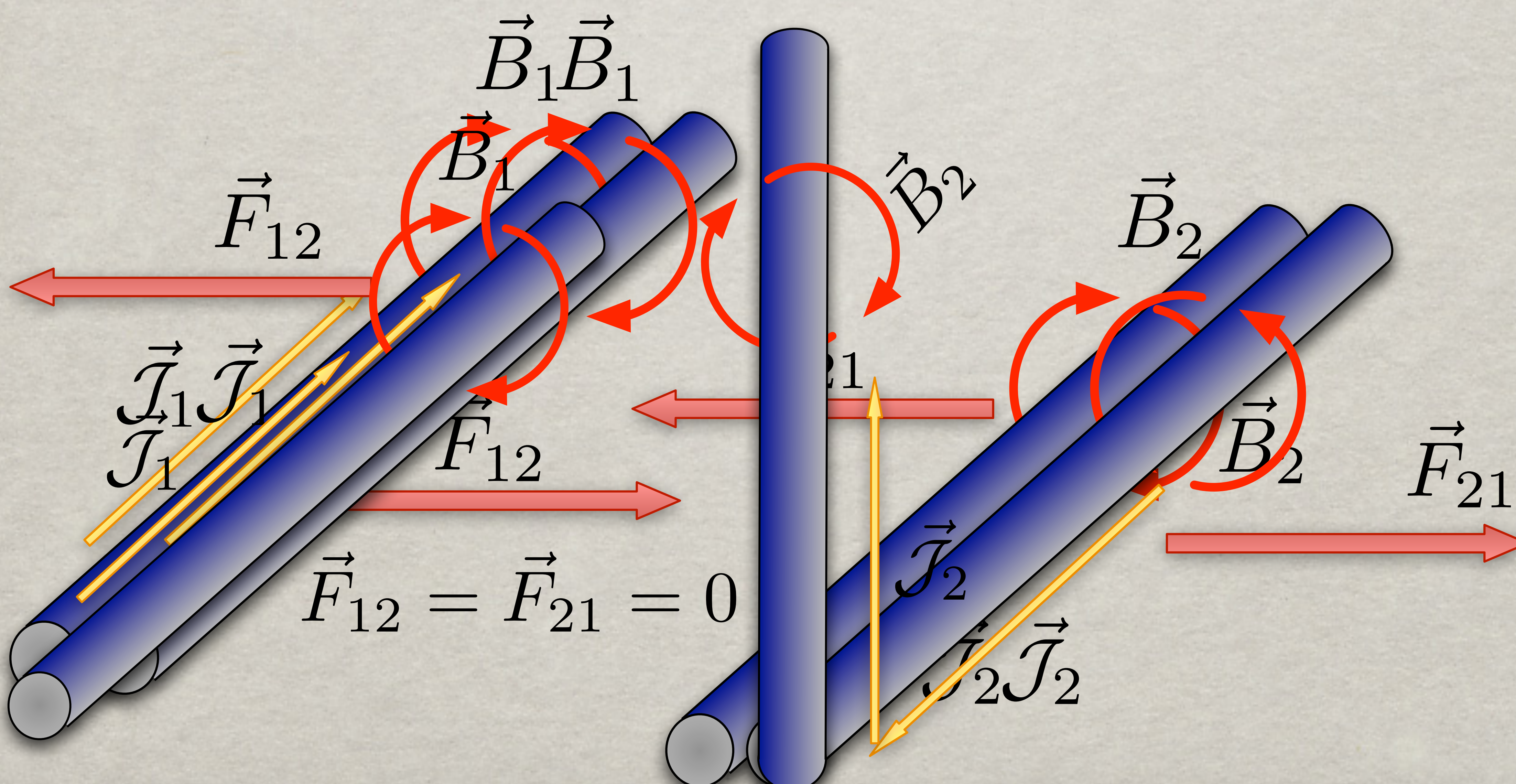


	Observable	Sensitivity	SM Prediction
a	β-ν (recoil) correlation	Tensor & Scalar terms	1 for pure Fermi -1/3 for pure GT or combination
b (Fierz term)	Comparison of β^+ to EC rate	SV/T/A interference	0
A	β asymmetry for polarized nuclei	Tensor, ST/VA Parity	Nucleus dependent
B	ν asymmetry (recoil) for polarized nuclei	Tensor,TA/ST/VA/SA/VT Parity	Nucleus dependent
D	Triple product	ST/VA Interference TRI	0

Probing the Nature of Currents Using Correlations - A Classical Analogy

The EM Force Between Currents

$$d\vec{F} = \frac{q}{c}\vec{v} \times \vec{B}$$



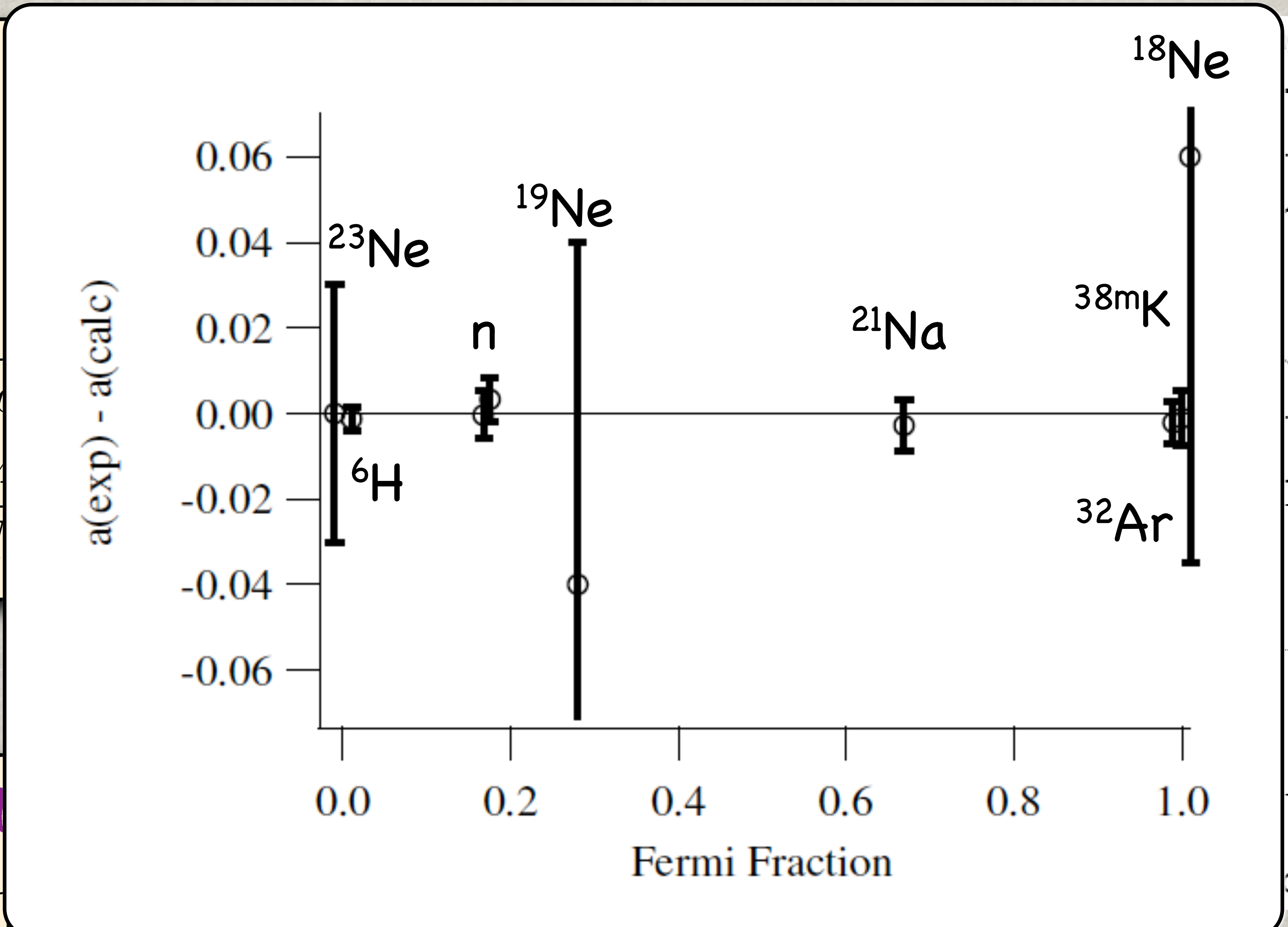
So... is β decay V-A?

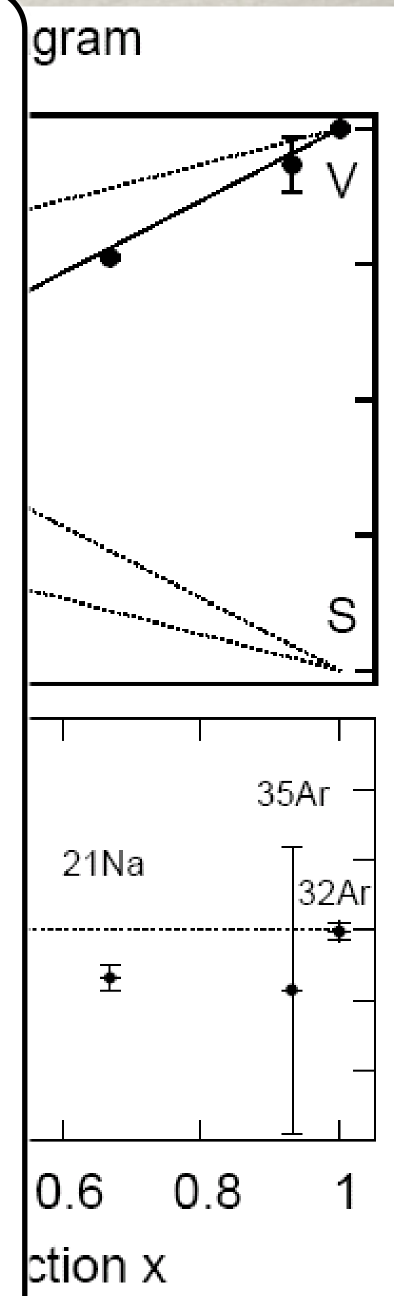
In SM

$a_0 = \frac{1}{3}\Big($

$x = \frac{1}{1+\rho}$

$\rho = \frac{C_A M}{C_V M}$





Beyond

$a \approx a_0(1$

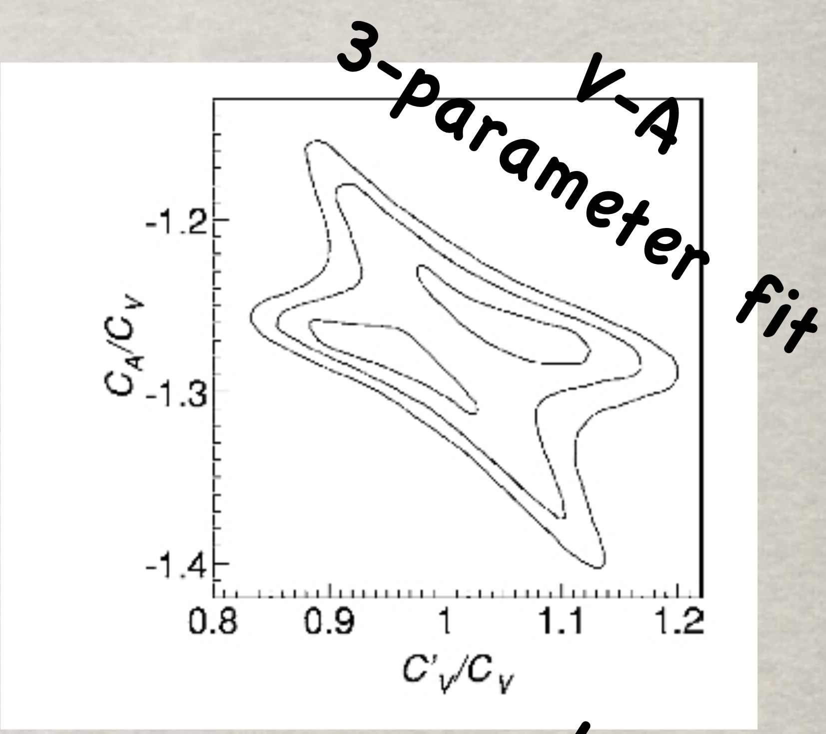
F: $a_0 = 1$ $\alpha = (|C_s|^2 + |C_s'|^2)/C_V^2$

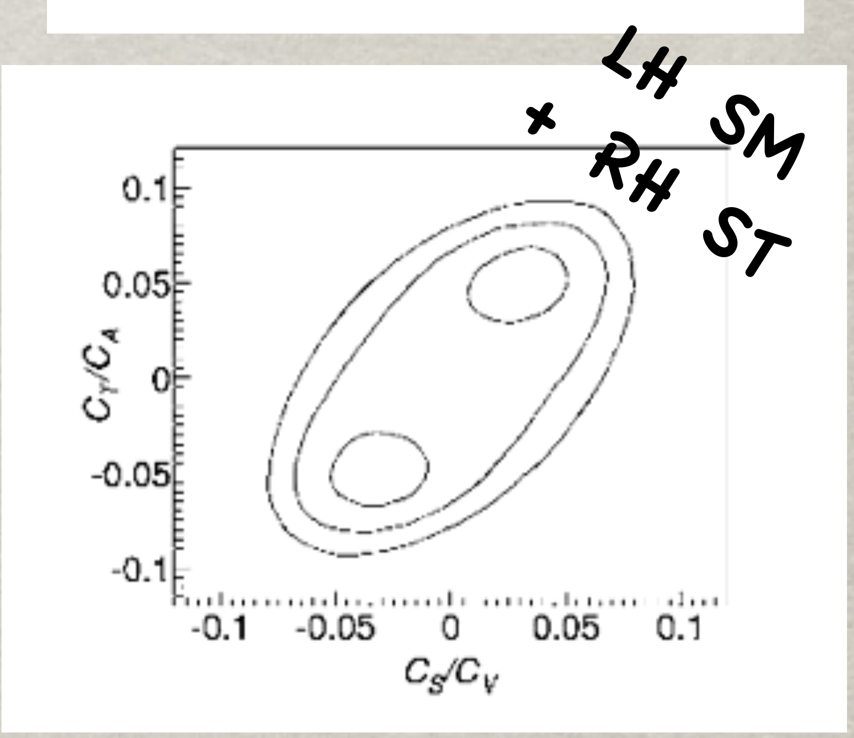
GT $a_0 = -1/3$ $\alpha = (|C_T|^2 + |C_T'|^2)/C_A^2$

Limits on non-SM coupling

- Very large model space.
- Not spanned by collider experiments.
- Current best limits not very stringent.
- Naively $\frac{C_T}{C_A}, \frac{C_S}{C_V} \propto \left(\frac{M_W}{M_{NewPhys}}\right)^2$

  so uncertainty to 0.01 probes new physics at ~ 1TeV!

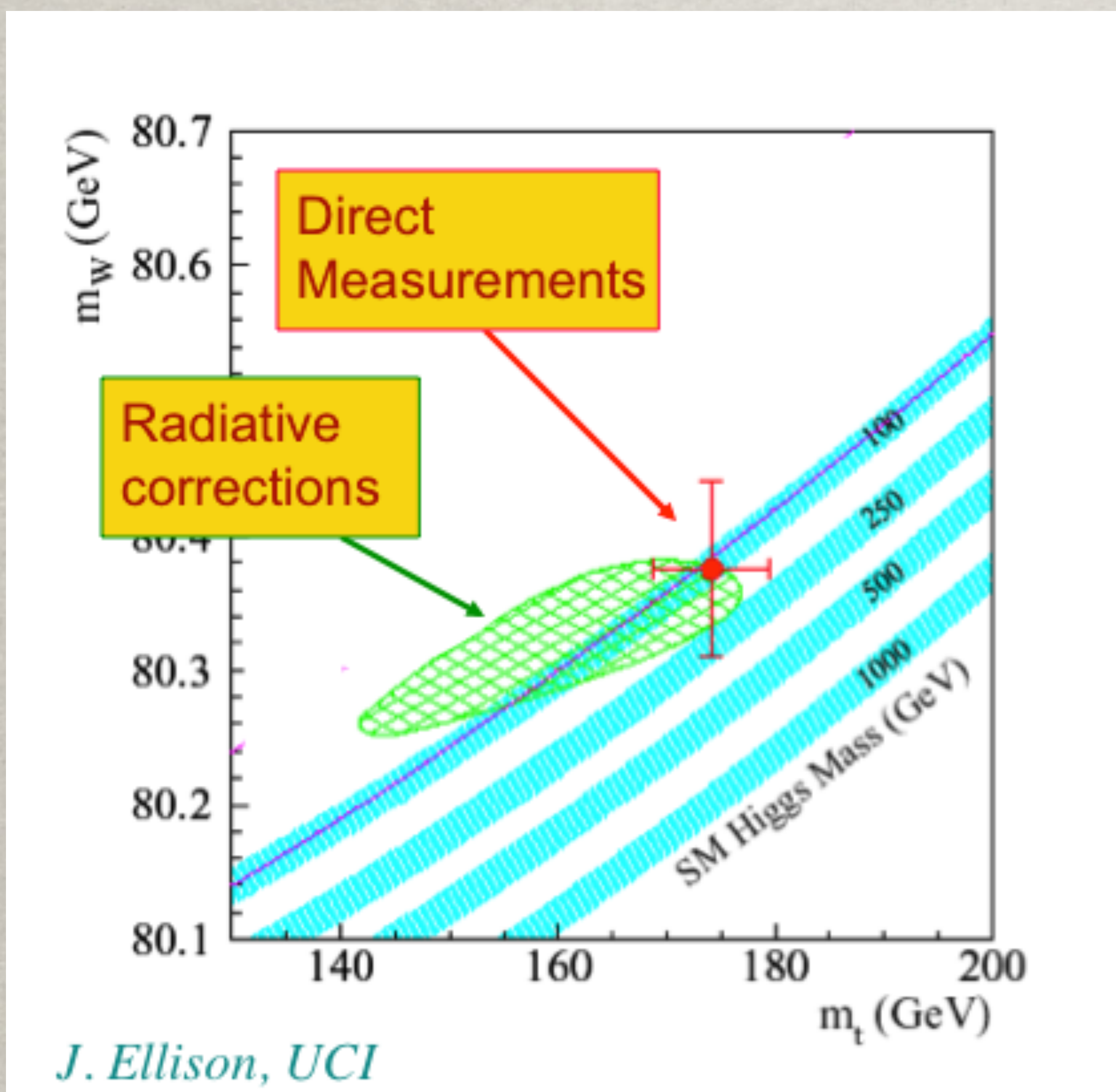




N. Severijns, M. Beck, and O. Naviliat-Cuncic, Rev. Mod. Phys. 78, 991 (2006)
J. Sromki, AIP Conf Proc 338 (1995)

Low Energy in the Age of LHC....

Historically, this works



Low Energy in the Age of LHC....

$$
\begin{aligned}
\mathcal{L}_{\rm eff} \;=\; & -\frac{G_F V_{ud}}{\sqrt{2}} \, [\, (1+\epsilon_L) \;\; \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\
& + \;\; \tilde{\epsilon}_L \;\; \bar{e}\gamma_\mu(1+\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\
& + \;\; \epsilon_R \;\; \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1+\gamma_5)d \\
& + \;\; \tilde{\epsilon}_R \;\; \bar{e}\gamma_\mu(1+\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1+\gamma_5)d \\
& + \;\; \epsilon_S \;\; \bar{e}(1-\gamma_5)\nu_e \cdot \bar{u}d \; + \; \tilde{\epsilon}_S \;\; \bar{e}(1+\gamma_5)\nu_e \cdot \bar{u}d \\
& - \;\; \epsilon_P \;\; \bar{e}(1-\gamma_5)\nu_e \cdot \bar{u}\gamma_5 d \; - \; \tilde{\epsilon}_P \;\; \bar{e}(1+\gamma_5)\nu_e \cdot \bar{u}\gamma_5 d \\
& + \;\; \epsilon_T \; \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_e \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \\
& + \;\; \tilde{\epsilon}_T \; \bar{e}\sigma_{\mu\nu}(1+\gamma_5)\nu_e \cdot \bar{u}\sigma^{\mu\nu}(1+\gamma_5)d] + \text{h.c.} \; .
\end{aligned}
$$

	$\varepsilon_L+\varepsilon_R$	ε_S	ε_T	$\tilde{\varepsilon}_S$	$\tilde{\varepsilon}_T$	$\tilde{\varepsilon}_{L,R}$
β decays	5×10^{-4}	8.0×10^{-3}	1.3×10^{-3}	7.5×10^{-2}	2.5×10^{-2}	7.5×10^{-2}
LHC	--	1.7×10^{-2}	3.4×10^{-3}	1.7×10^{-2}	3.4×10^{-3}	6.3×10^{-3}

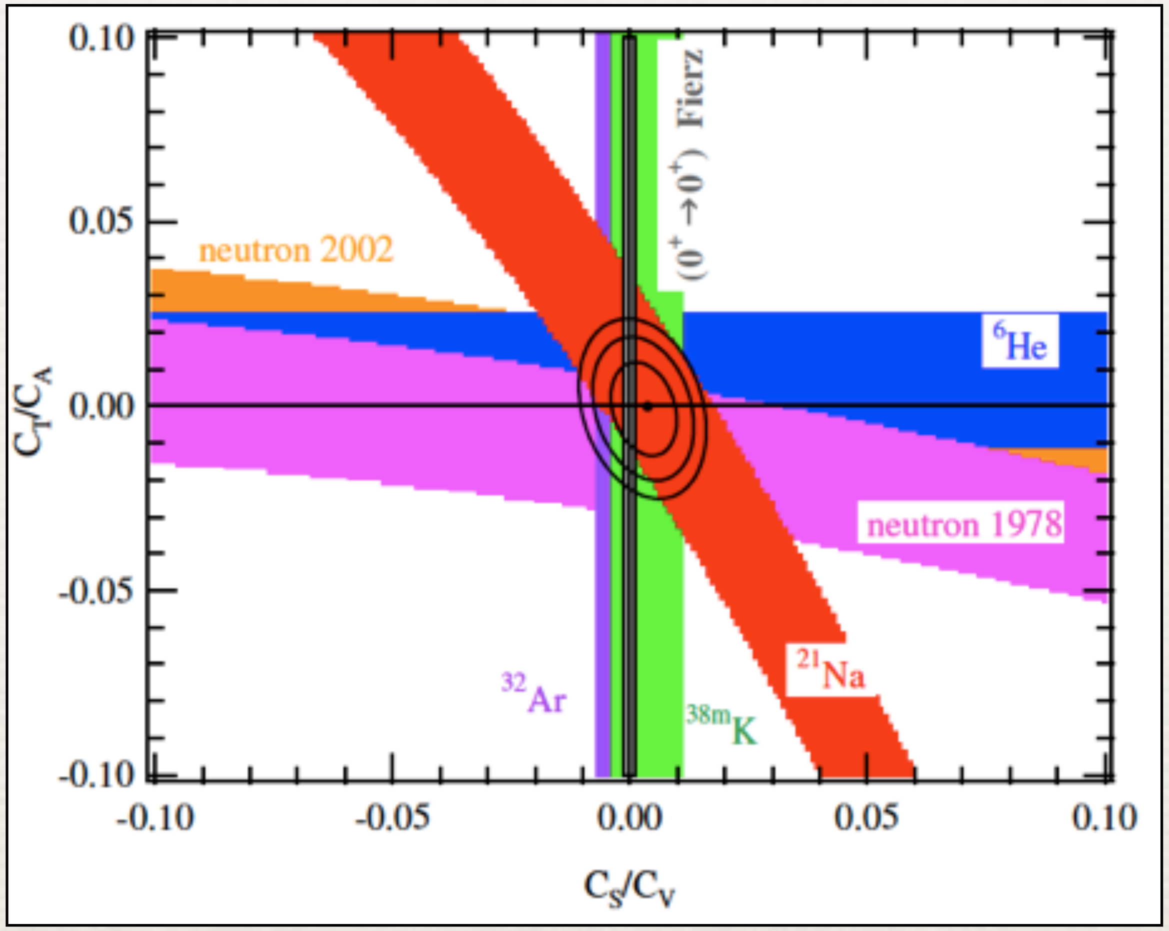
Unmatched low-energy sensitivity

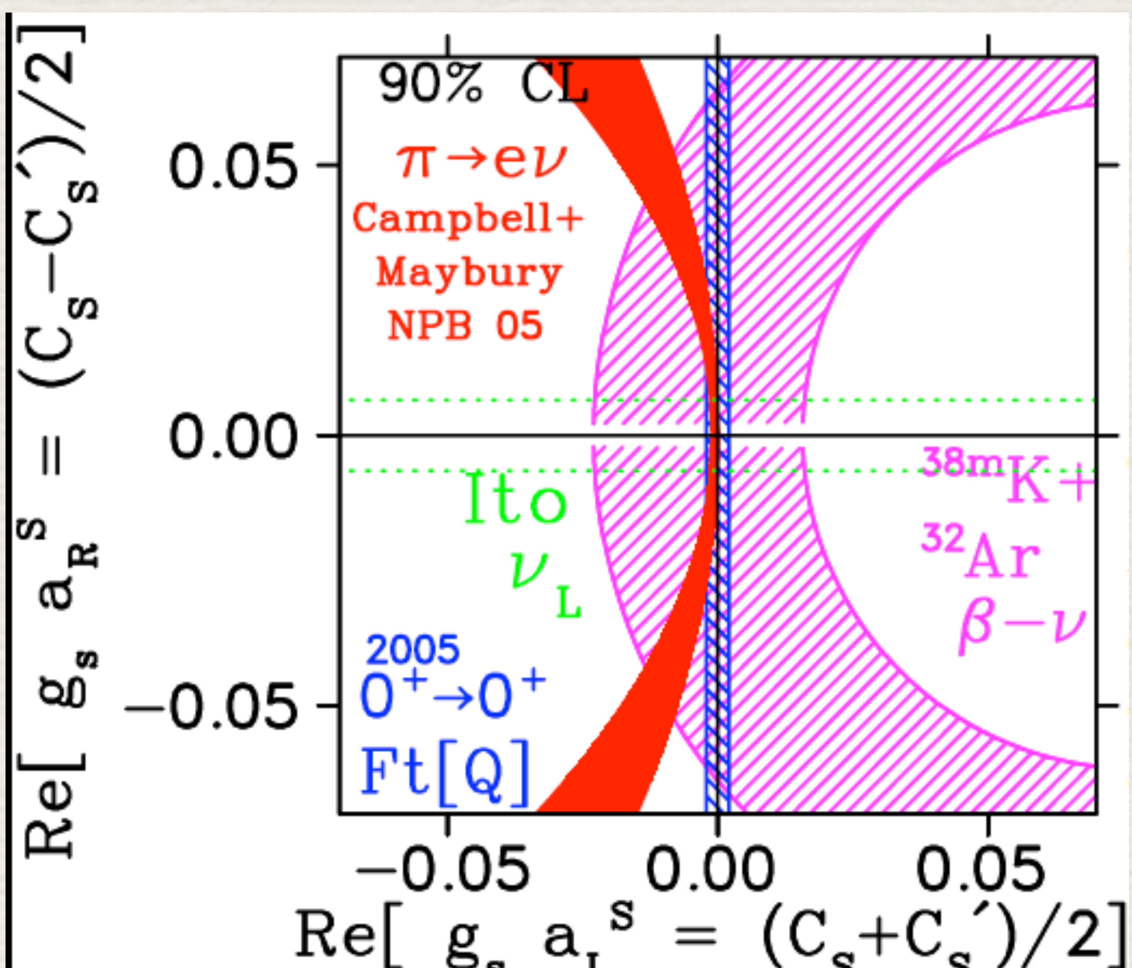
LHC limits close to low-energy.
Interesting interplay in the future

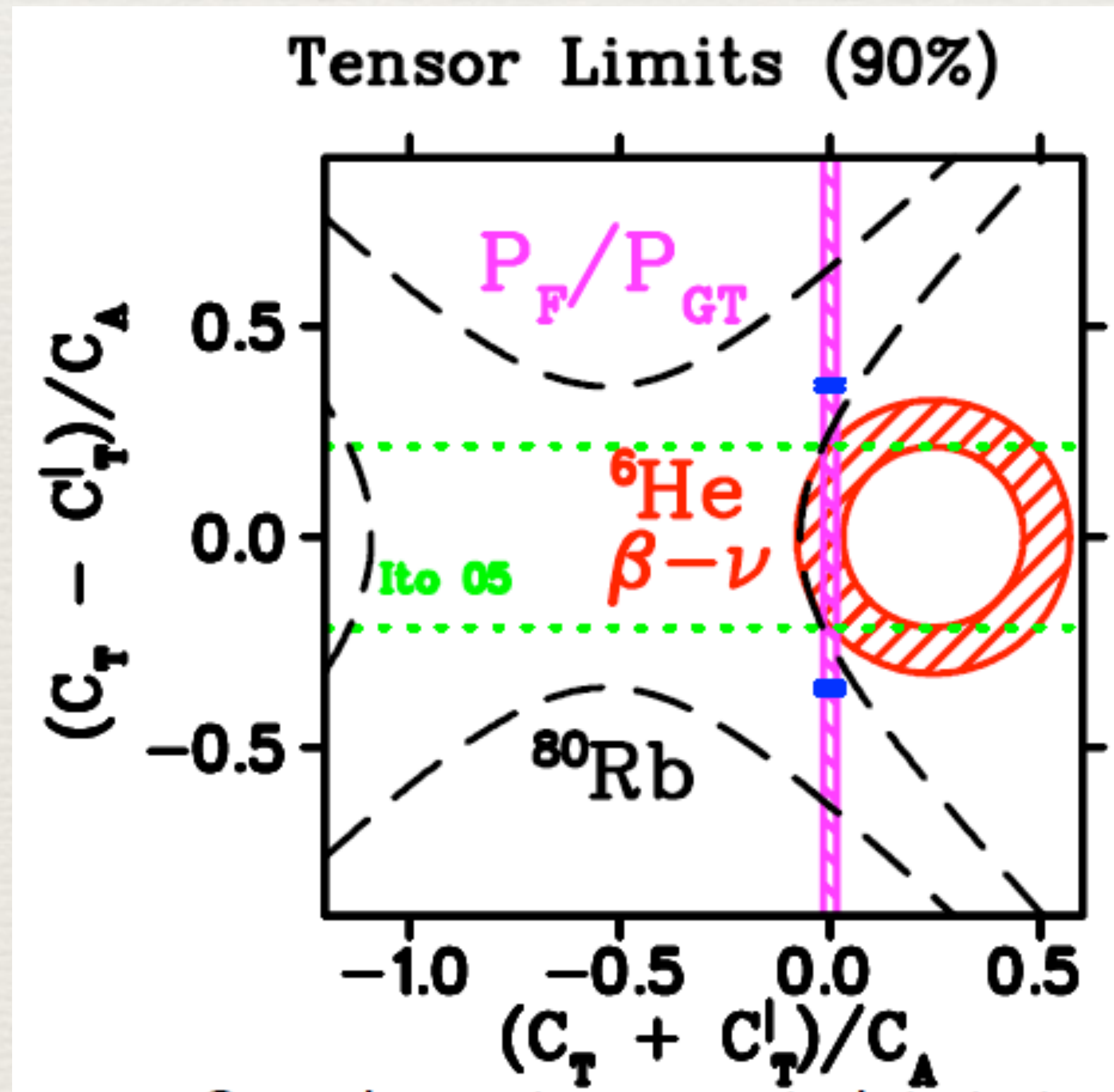
LHC superior to low-energy!

V. Cirigliano, Fundamental Symmetries and Neutrino, Chicago 2012

State of the Art....

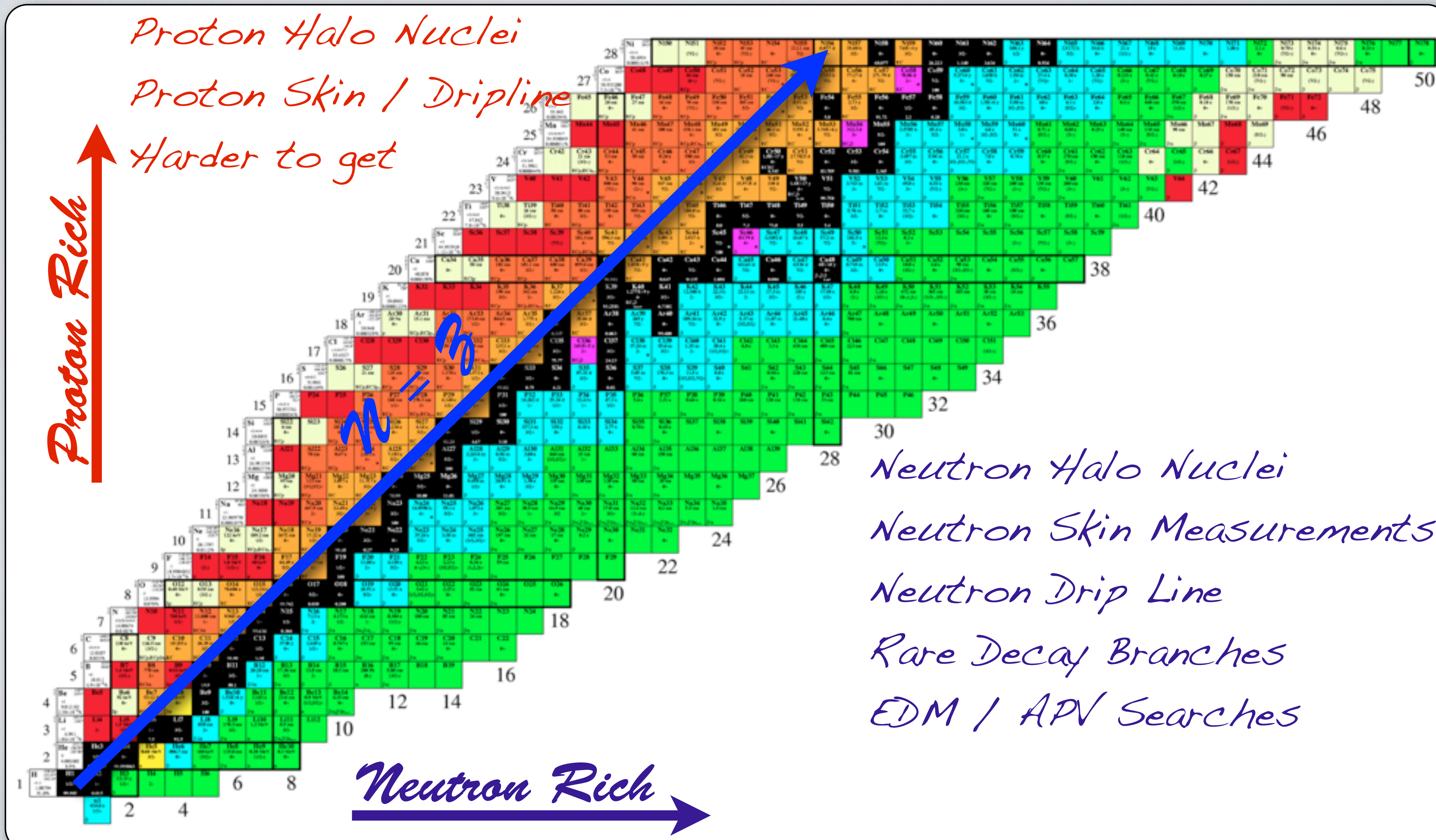






Looking Ahead

Where should we look?



Anatomy of an Experiment

Produce Radioactive Atoms

(Produce, Transport, Neutralize)

↓

Trap/Contain

(MOT, Dipole, Ion, Electrostatic)

↓

Wait...

↓

Detect decay products (β, Ion)

(Scintillators, MCPs,...)

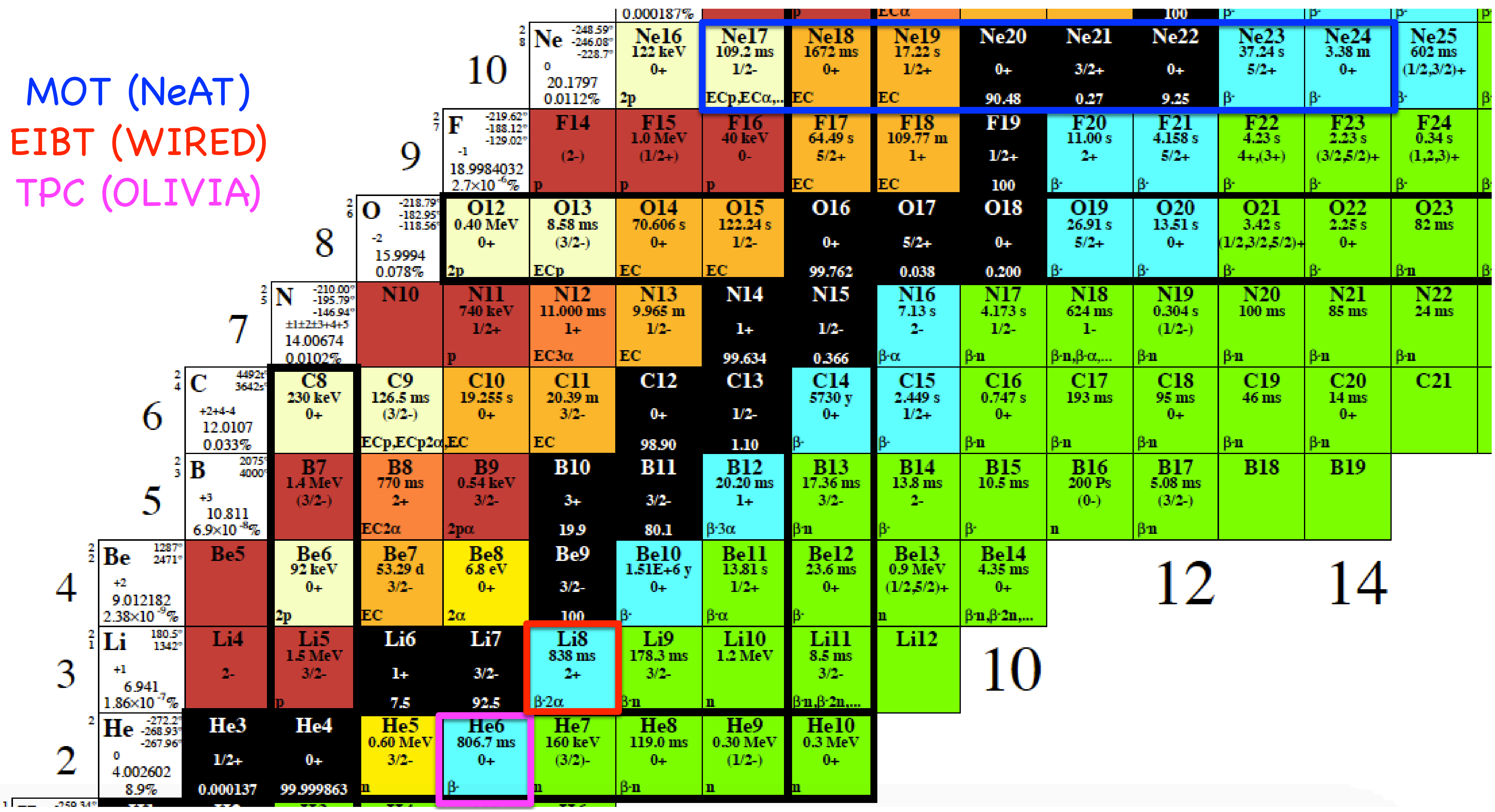
↓

Analyze and compare to SM

Looking Ahead

New Measurements and New Ideas

MOT (NeAT)
EIBT (WIRED)
TPC (OLIVIA)



NeAT

WIRED

Why Traps?

- Cold (~200uK), dilute (~30e6 Atoms/mm^3 - 9 O.O.M lower than ideal gas), sample:
  - Low velocity, no smearing (3 O.O.M reduction compared to RT, negligible compared to recoil velocity).
  - Less interactions.
- Well localized (~200um) sample:
  - Well known emission location.
- Highly isotope selective:
  - Low background.

“Getting the right stuff” (or, selecting a target)

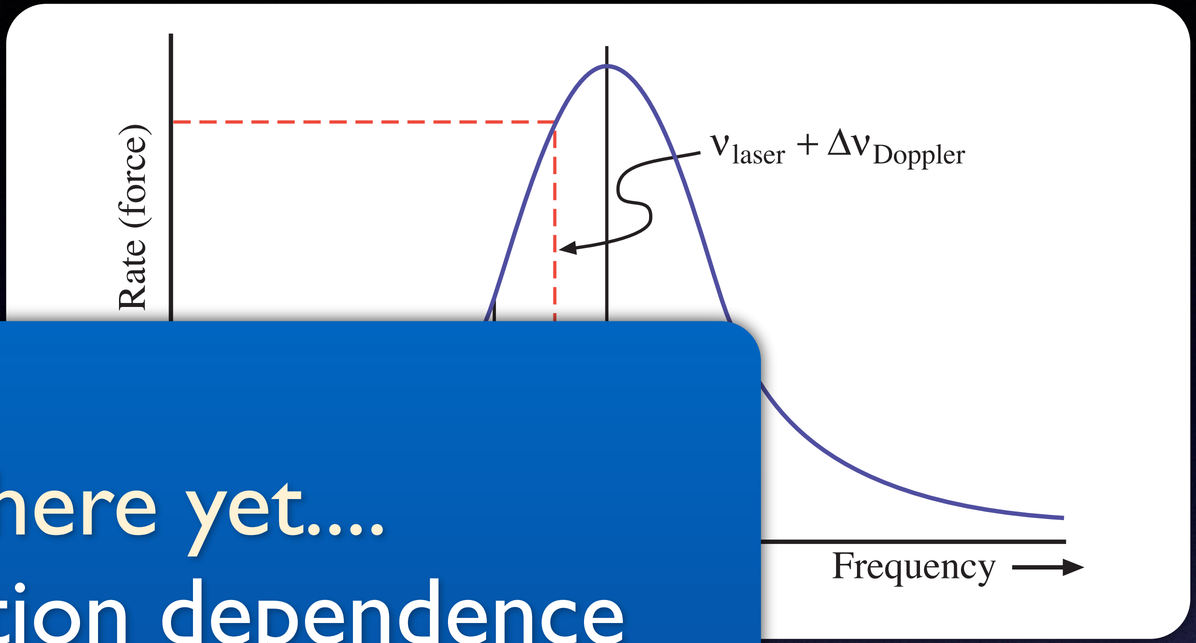
- First and foremost - must be trappable.

That was the easy part

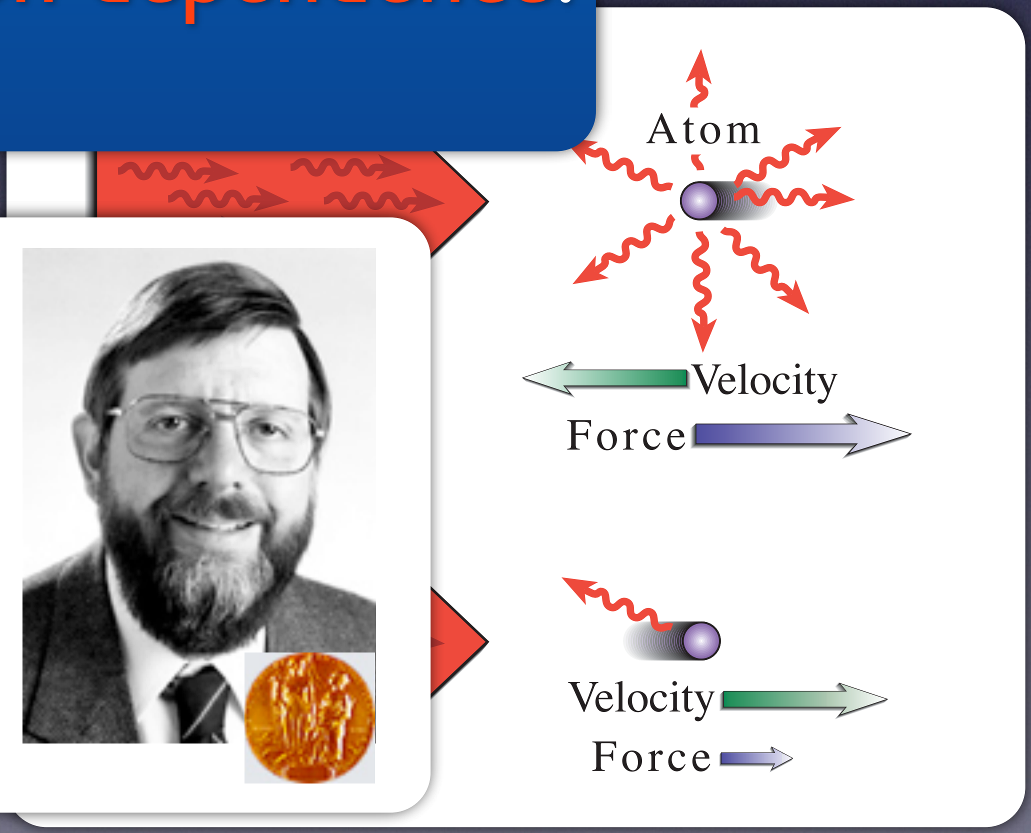
- Lifetime in proper range:
  - Too long ➛ No statistics.
  - Too short ➛ No trap.
  - O(100ms) - O(10s) is good.
- Calculable matrix elements:
  - N~Z or other special case (pure GT or pure F is good).
- Produceable: Usually means accelerator or n-generator.

Cooling with Laser Light

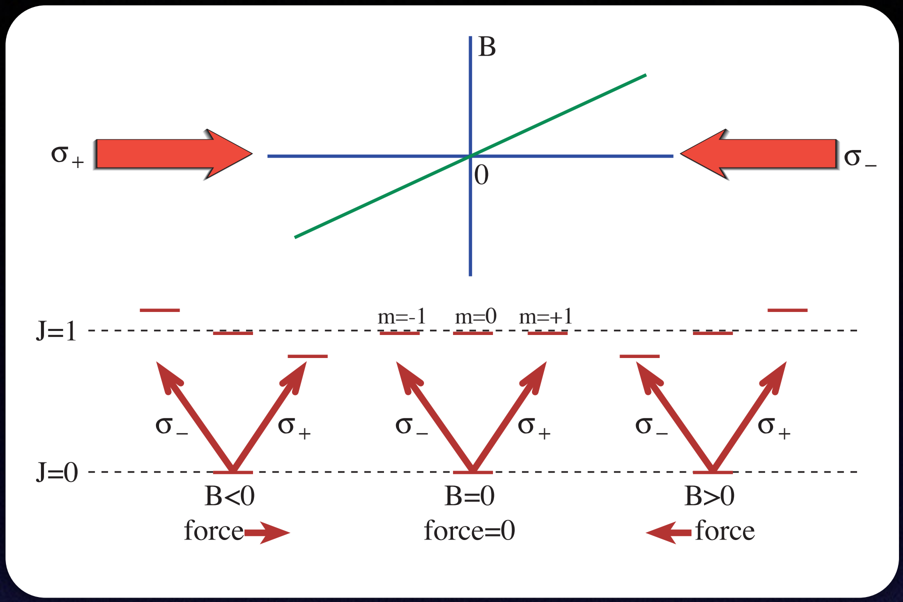
- Atoms absorb laser light and then remit it isotropically.
- Moving ato… shifted due… effect by $\vec{k}$ ·
- Velocity de… …g. Temperatur…
- Now hit the atoms from all sides ➛ preferential abs… motion ➛ coolin… molasses")



We're not there yet....
If there is no position dependence
atoms diffuse out of the molasses ➛
need to introduce position dependence.

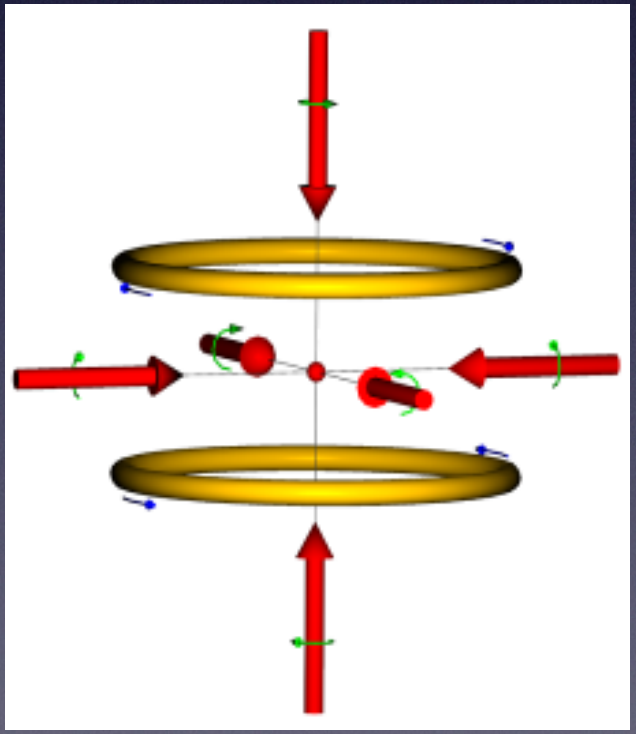


MOTs

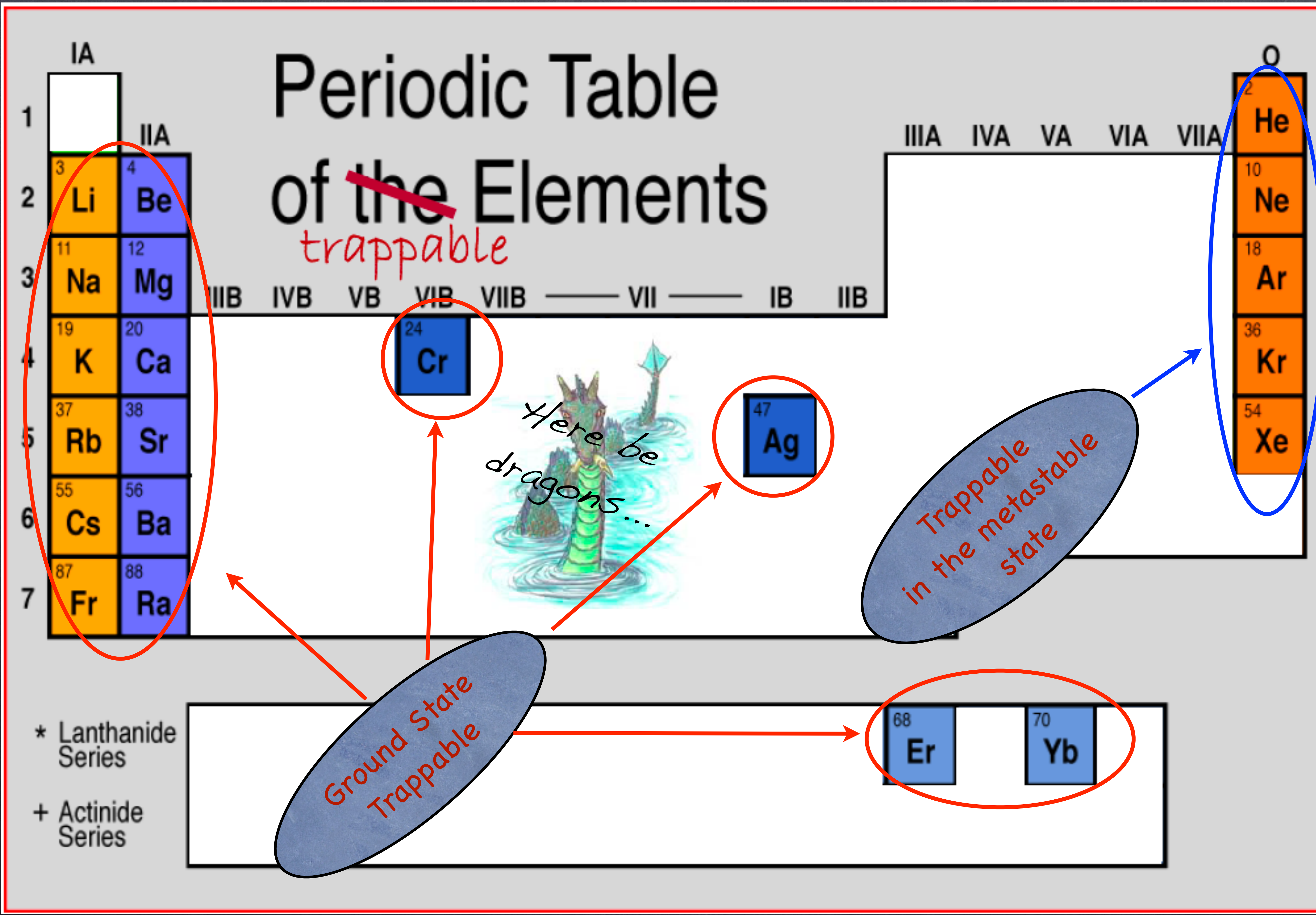


- Magnetic field used to introduce spatial dependance via Zeeman splitting.
- Linear gradient produced using anti-Helmholtz coils.
- So is this all there is to it?

Almost...



- Real atoms are not two level systems - more complicated level scheme requires additional lasers.
- Different isotopes have different wavelengths and level structure (due to different nuclear spin).



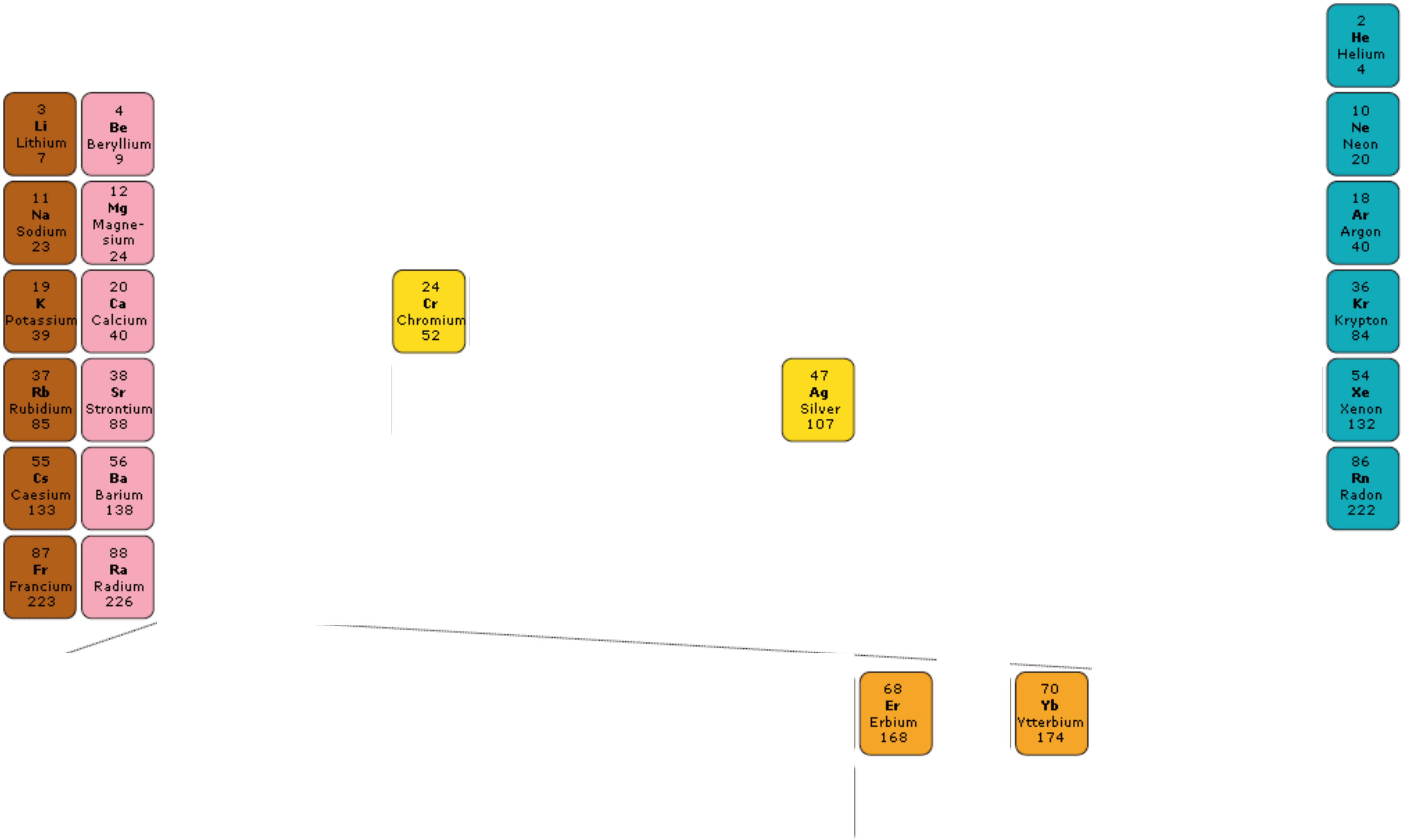
Periodic Table of the Elements
trappable
IA
IIA
IIIB IVB VB VIB VIIB VII IB IIB
IIIA IVA VA VIA VIIA
O
1 2 3 4 5 6 7
3 Li
4 Be
11 Na
12 Mg
19 K
20 Ca
37 Rb
38 Sr
55 Cs
56 Ba
87 Fr
88 Ra
24 Cr
47 Ag
2 He
10 Ne
18 Ar
36 Kr
54 Xe
68 Er
70 Yb
* Lanthanide Series
+ Actinide Series
Here be dragons...
Ground State Trappable
Trappable in the metastable state

Why Neon? - (I) The Periodic Table

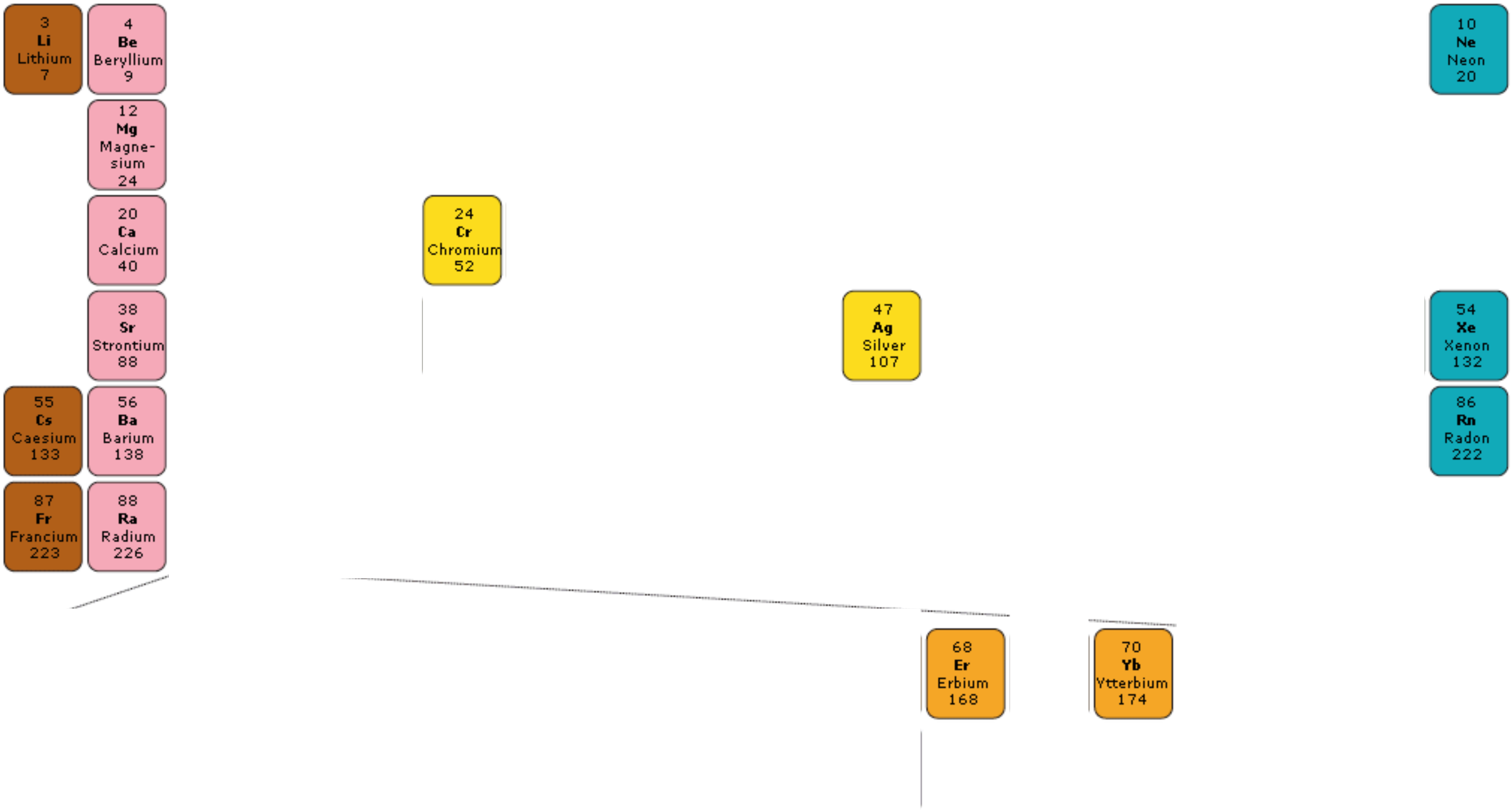
1 H Hydrogen 1																	2 He Helium 4
3 Li Lithium 7	4 Be Beryllium 9											5 B Boron 11	6 C Carbon 12	7 N Nitrogen 14	8 O Oxygen 16	9 F Fluorine 19	10 Ne Neon 20
11 Na Sodium 23	12 Mg Magnesium 24											13 Al Aluminum 27	14 Si Silicon 28	15 P Phosphorus 31	16 S Sulphur 32	17 Cl Chlorine 35	18 Ar Argon 40
19 K Potassium 39	20 Ca Calcium 40	21 Sc Scandium 45	22 Ti Titanium 48	23 V Vanadium 51	24 Cr Chromium 52	25 Mn Manganese 55	26 Fe Iron 56	27 Co Cobalt 59	28 Ni Nickel 58	29 Cu Copper 63	30 Zn Zinc 64	31 Ga Gallium 69	32 Ge Germanium 74	33 As Arsenic 75	34 Se Selenium 80	35 Br Bromine 79	36 Kr Krypton 84
37 Rb Rubidium 85	38 Sr Strontium 88	39 Y Yttrium 89	40 Zr Zirconium 90	41 Nb Niobium 93	42 Mo Molybdenum 98	43 Tc Technetium 97	44 Ru Ruthenium 102	45 Rh Rhodium 103	46 Pd Palladium 106	47 Ag Silver 107	48 Cd Cadmium 114	49 In Indium 115	50 Sn Tin 120	51 Sb Antimony 121	52 Te Tellurium 130	53 I Iodine 127	54 Xe Xenon 132
55 Cs Caesium 133	56 Ba Barium 138	57-71	72 Hf Hafnium 180	73 Ta Tantalum 181	74 W Tungsten 184	75 Re Rhenium 187	76 Os Osmium 192	77 Ir Iridium 193	78 Pt Platinum 195	79 Au Gold 197	80 Hg Mercury 202	81 Ti Thallium 205	82 Pb Lead 208	83 Bi Bismuth 209	84 Po Polonium 209	85 At Astatine 210	86 Rn Radon 222
87 Fr Francium 223	88 Ra Radium 226	89-103	104 Unq Unnilquadium 260	105 Unp Unnilpentium 262	106 Unh Unnilhexium 263	107 Uns Unnilseptium 262	108 Uno Unniloctium 265	109 Une Unnilennium 266									

57 La Lanthanum 139	58 Ce Cerium 140	59 Pr Praseodymium 141	60 Nd Neodymium 142	61 Pm Promethium 145	62 Sm Samarium 152	63 Eu Europium 153	64 Gd Gadolinium 158	65 Tb Terbium 159	66 Dy Dysprosium 164	67 Ho Holmium 165	68 Er Erbium 168	69 Tm Thulium 169	70 Yb Ytterbium 174	71 Lu Lutetium 175
89 Ac Actinium 227	90 Th Thorium 232	91 Pa Protactinium 231	92 U Uranium 238	93 Np Neptunium 237	94 Pu Plutonium 244	95 Am Americium 243	96 Cm Curium 247	97 Bk Berkelium 247	98 Cf Californium 251	99 Es Einsteinium 254	100 Fm Fermium 257	101 Md Mendelevium 258	102 No Nobelium 255	103 Lr Lawrencium 256

Why Neon? - (II) The Periodic Table of Trappable Elements

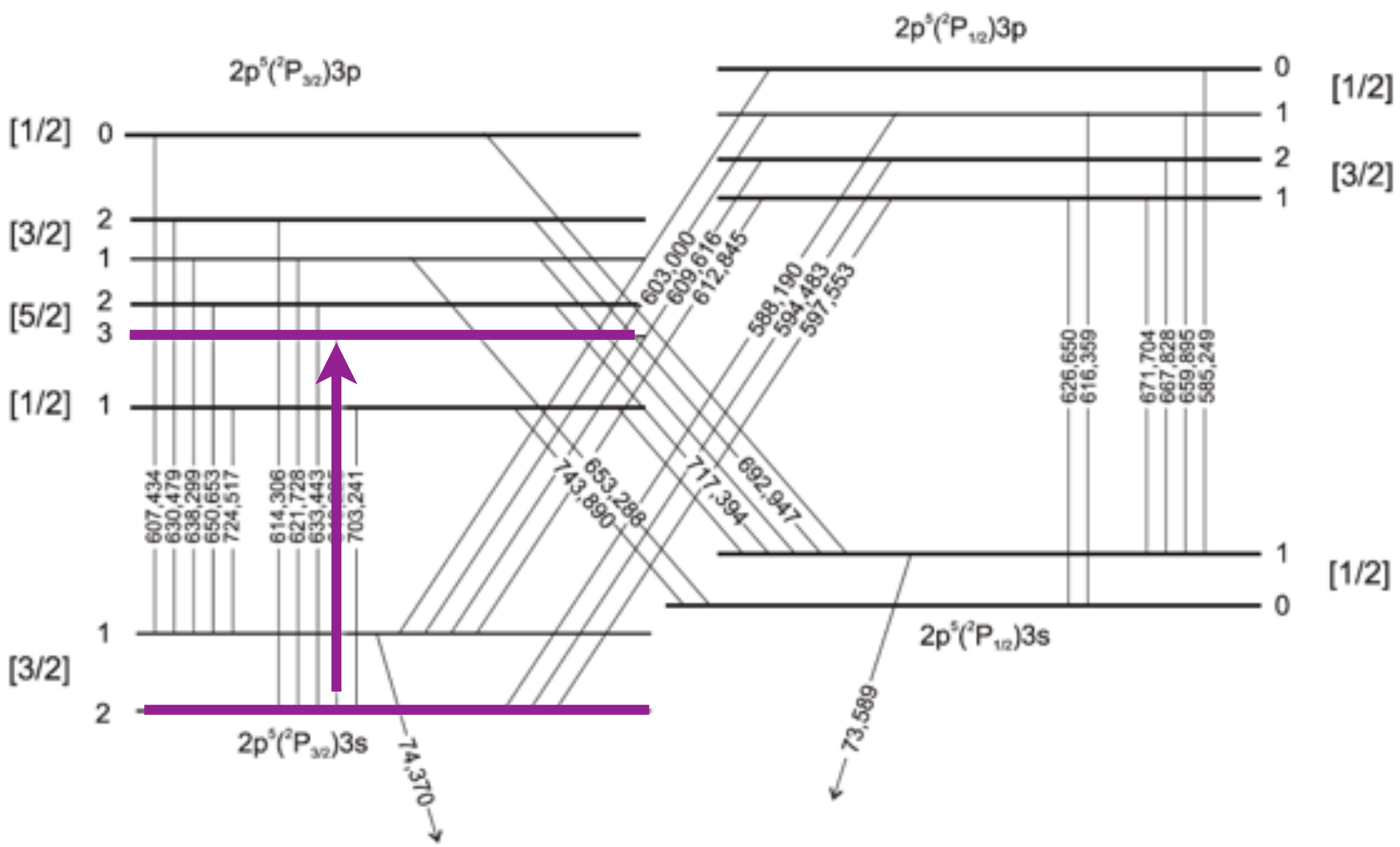


Why Neon? - (III) The Period Table of Trappable Elements Not already used for MOT β Decay



Why Neon? - (III) The Period Table of Trappable Elements Not already used for MOT β Decay & Decent to Calculate/ Implement

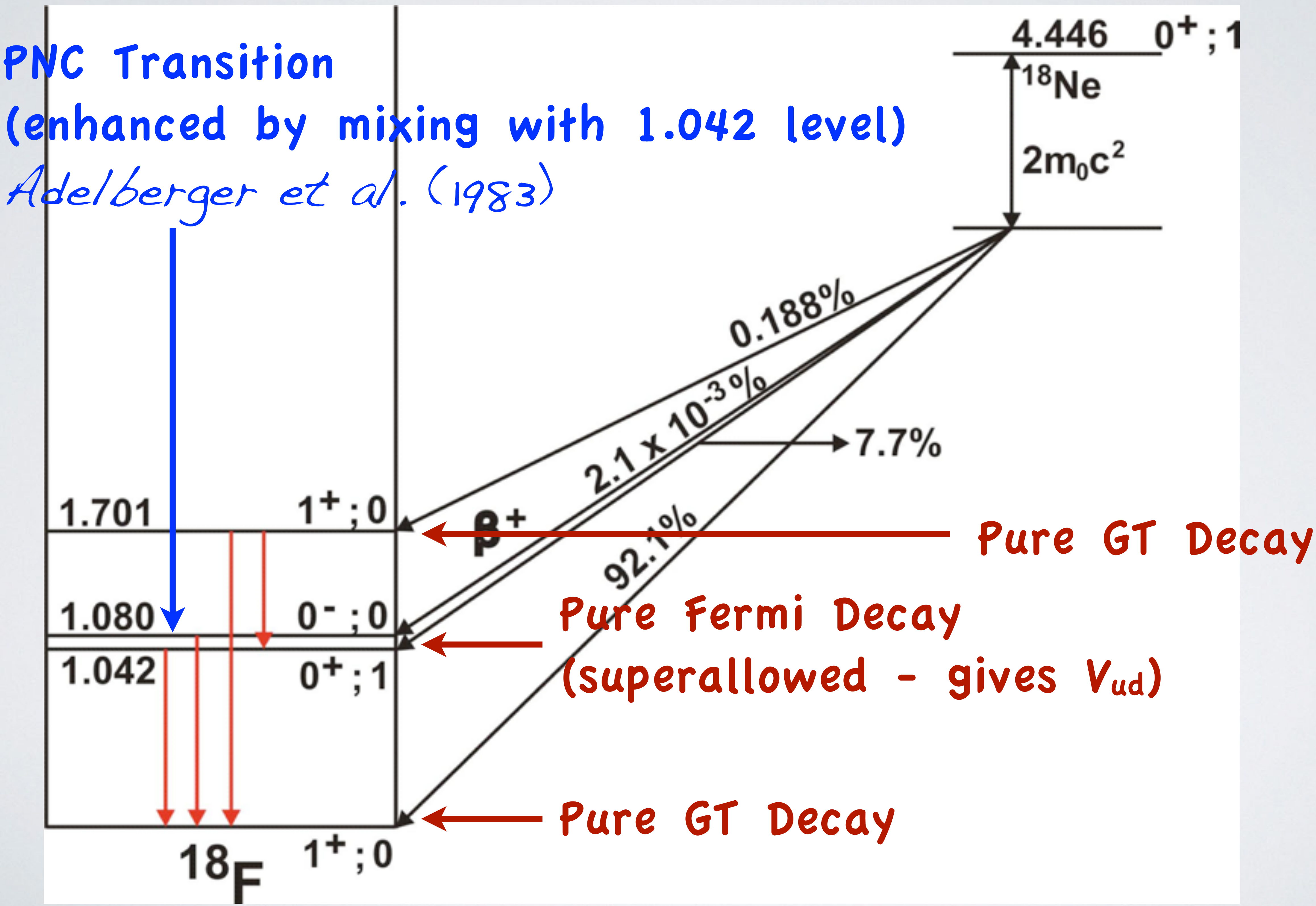
10 



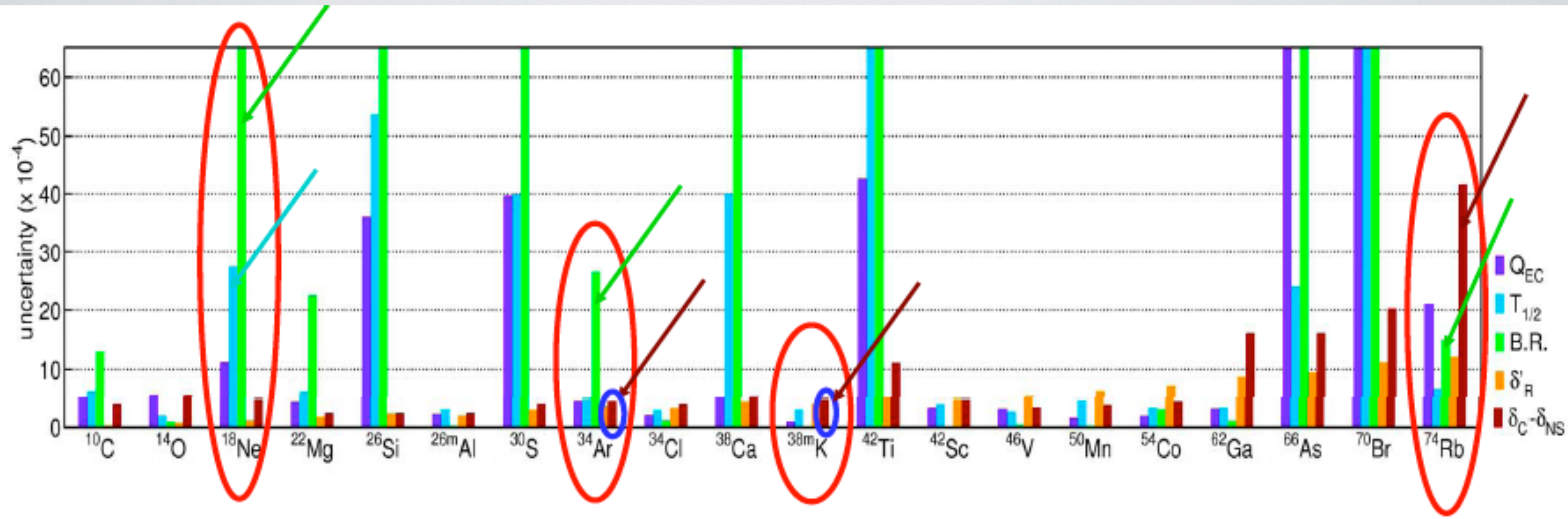
Fully closed transition for even neon isotopes (single frequency for trapping).

- **Easy to trap**
- **Interesting physics other the beta decay**
- **Needs to be in metastable state**
- **Problematic WL for lasers**
- **Harder to produce**

Why ^{18}Ne?


PNC Transition
(enhanced by mixing with 1.042 level)
Adelberger et al. (1983)
4.446 0+ ; 1
18Ne
2m0c2
0.188%
2.1 x 10-3 %
7.7%
92.1%
β+
1.701 1+ ; 0
1.080 0- ; 0
1.042 0+ ; 1
18F 1+ ; 0
Pure GT Decay
Pure Fermi Decay
(superallowed - gives Vud)
Pure GT Decay

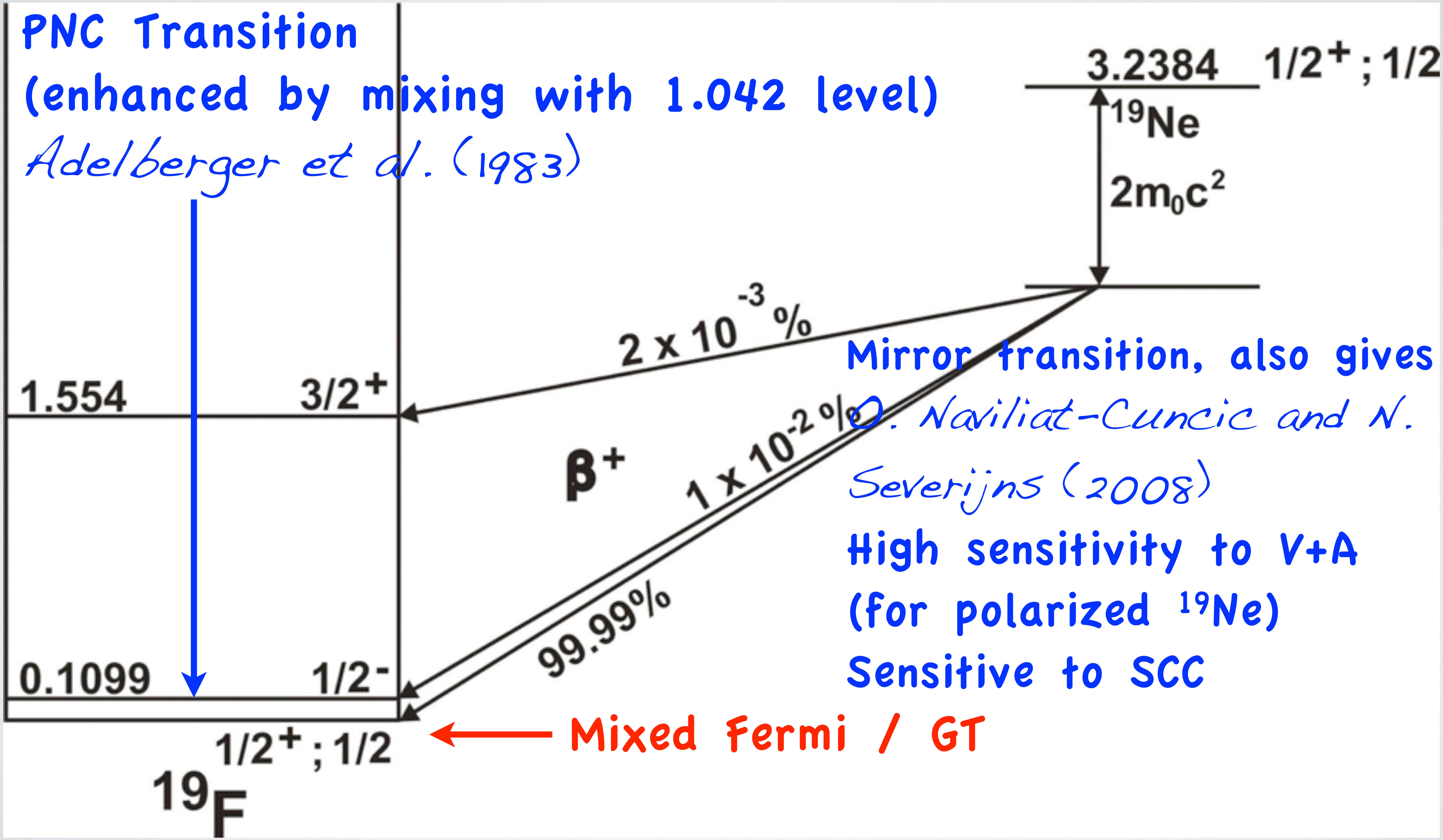
V_{ud} Uncertainties for superallowed decays



Options:
- improve quantities indicated by green & blue arrows
- if CVC accepted → Ft-measurements test δ_c - δ_{NS} from theoretical models
- go for factor ~10 higher precision in Ft than available now for the 4 isotopes indicated

N. Severijns, presentation BriX workshop 2008, SCK-CEN, Mol, Belgium, 2008.

Why ^{19}Ne?



PNC Transition
(enhanced by mixing with 1.042 level)
Adelberger et al. (1983)

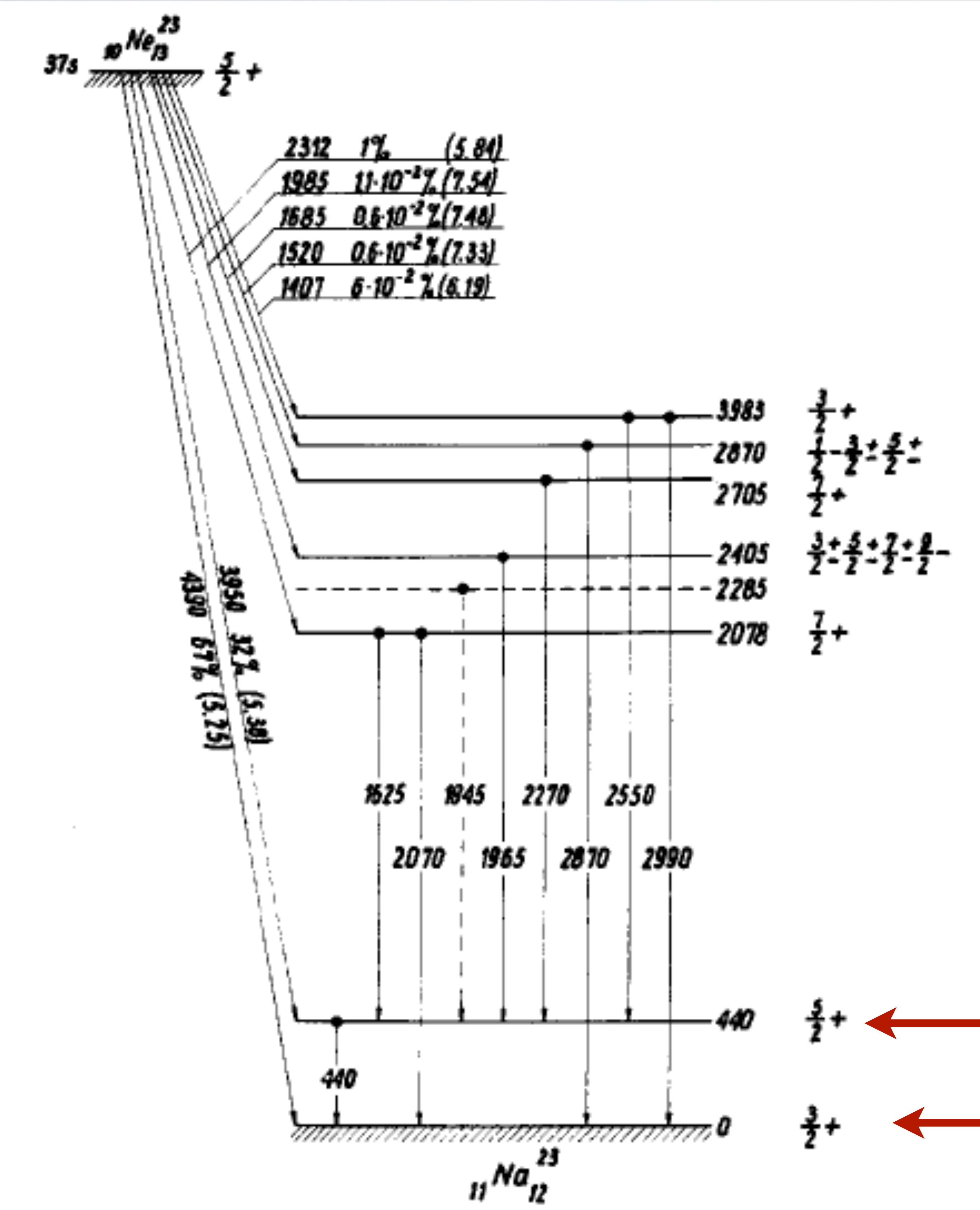
Mirror transition, also gives V_{ud}
O. Naviliat-Cuncic and N. Severijns (2008)

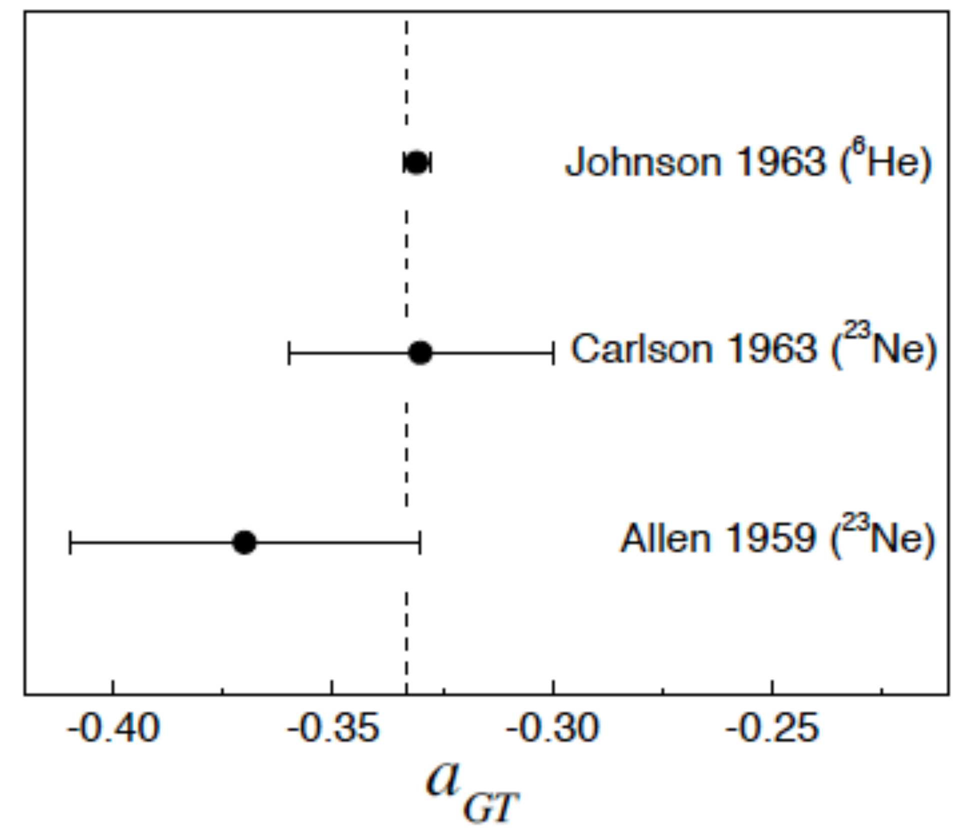
High sensitivity to V+A
(for polarized ^{19}Ne)

Sensitive to SCC

Mixed Fermi / GT

Why ^{23}Ne?

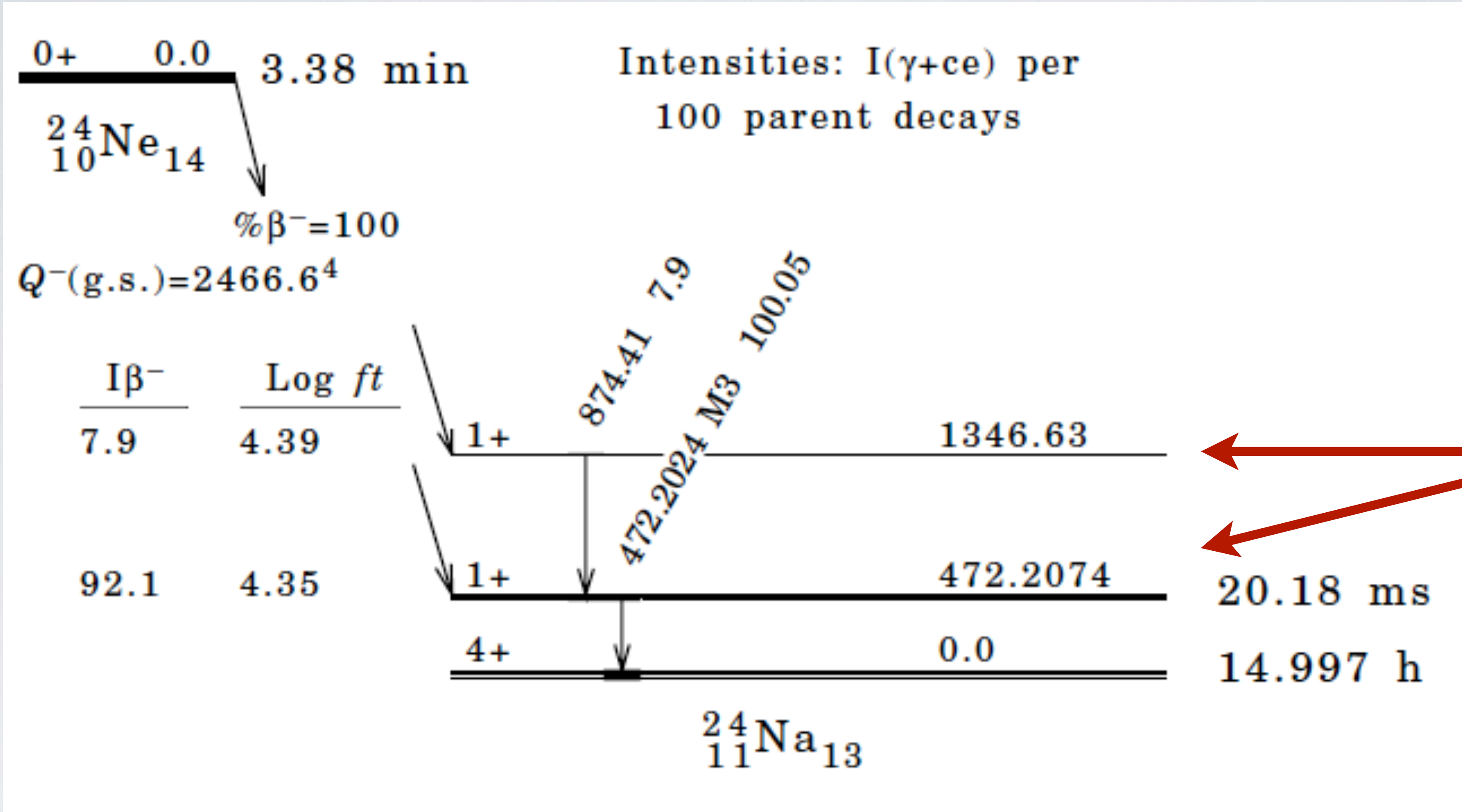




Almost Pure GT Decay

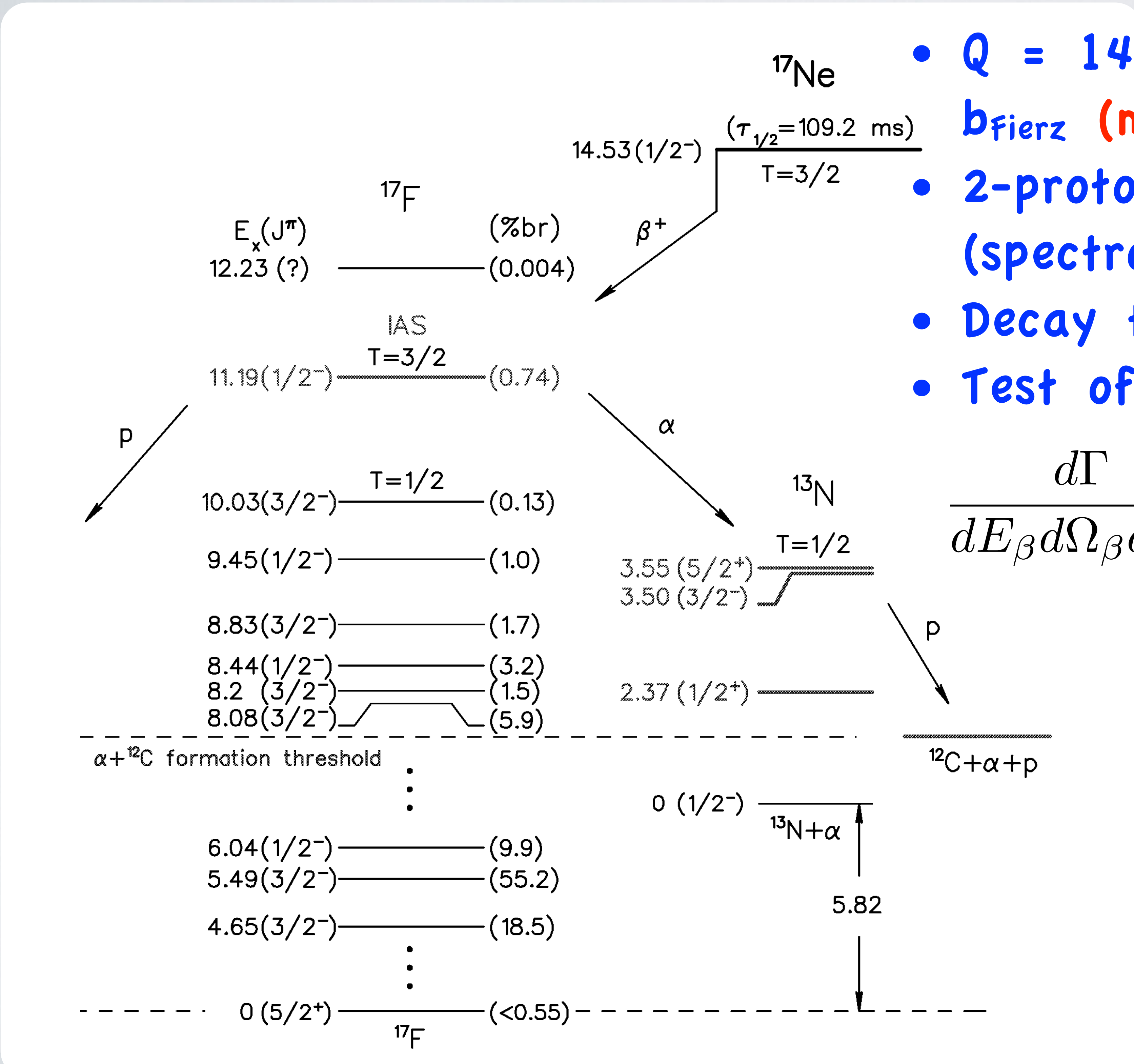
Pure GT Decay

^{24}Ne



Pure GT Decay

Why ^{17}Ne?



- Q = 14MeV - allows extraction of b_{Fierz} (maybe)
- 2-proton Borromean halo nucleus (spectroscopy)
- Decay to halo nucleus ^{17}F
- Test of forbidden β-decays

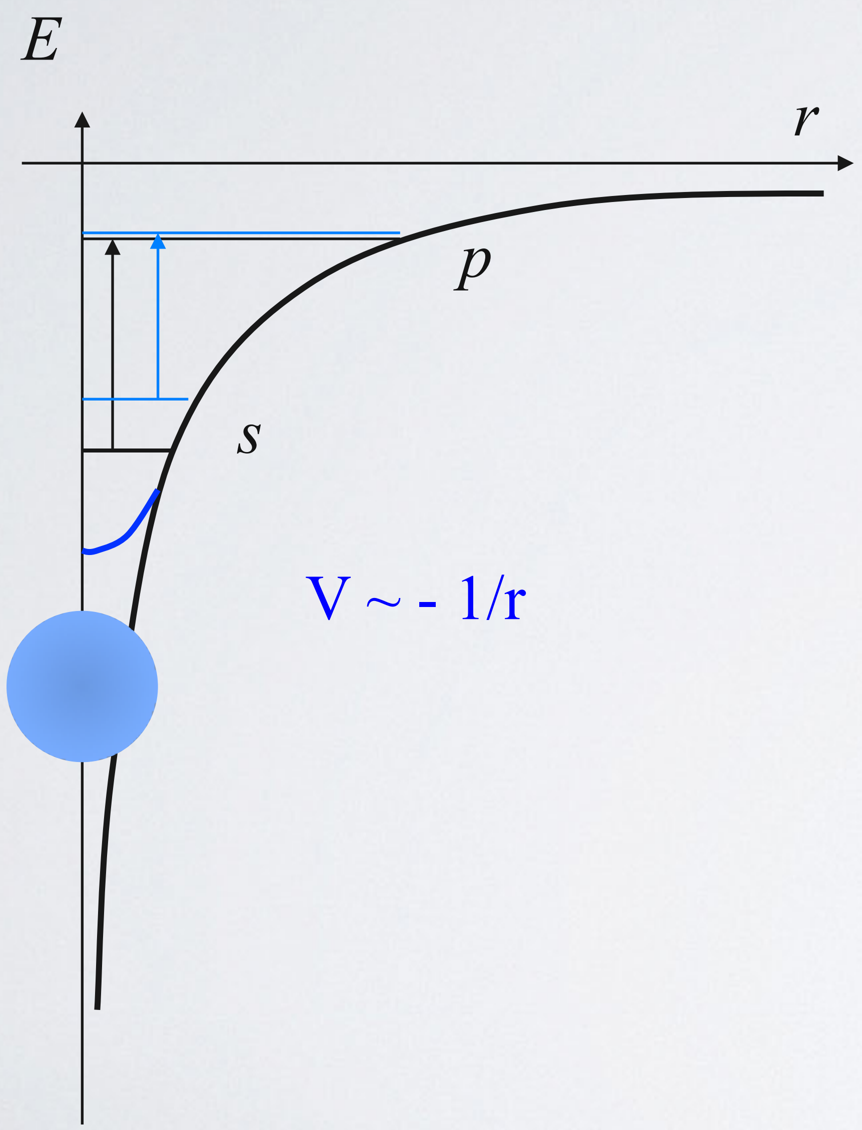
$$\frac{d\Gamma}{dE_\beta d\Omega_\beta d\Omega_\nu} \propto \xi \left\{ 1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e} \right\}$$

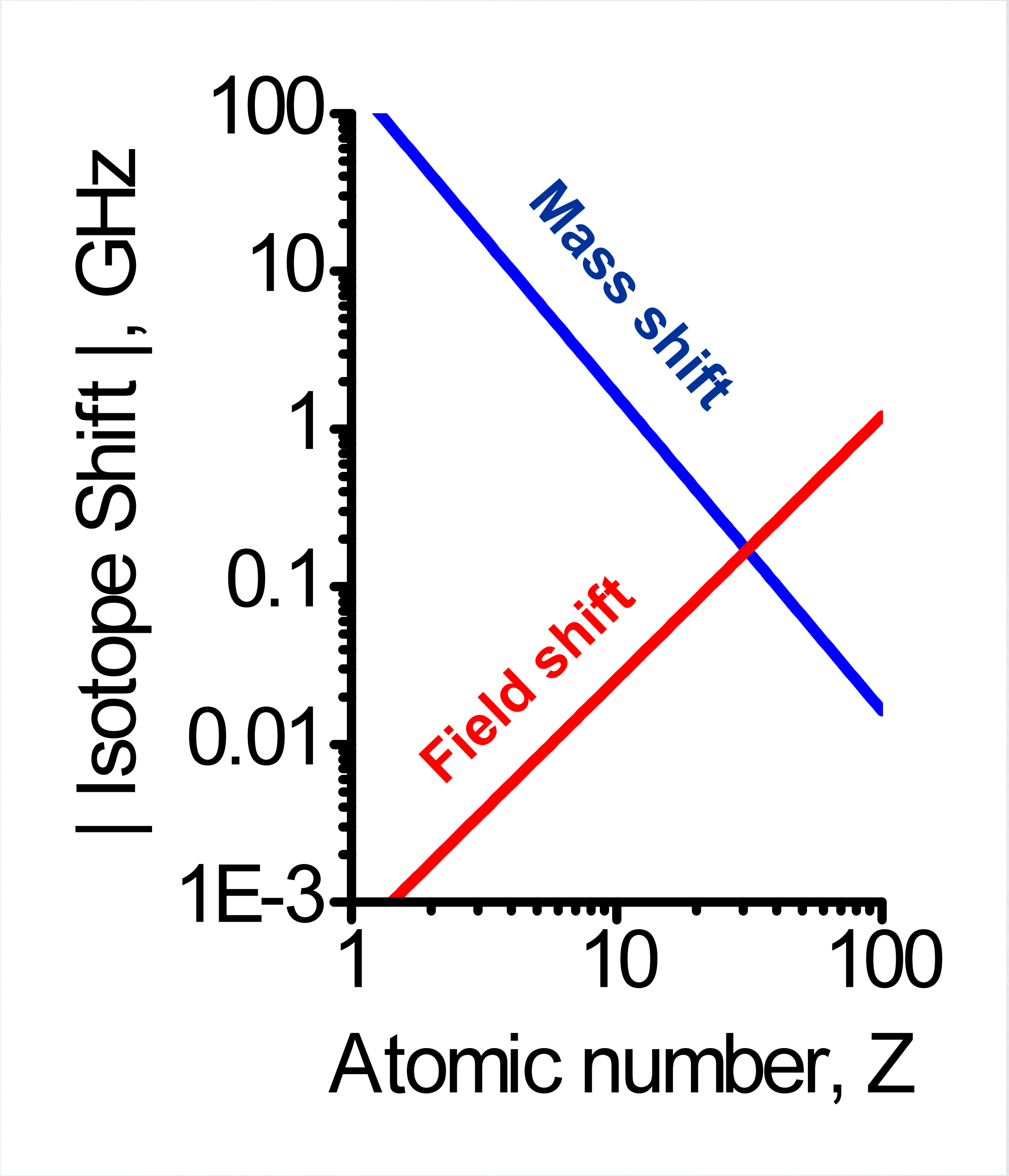
Borromean

Nuclear Structure Tests with Trapped Neon Isotopes

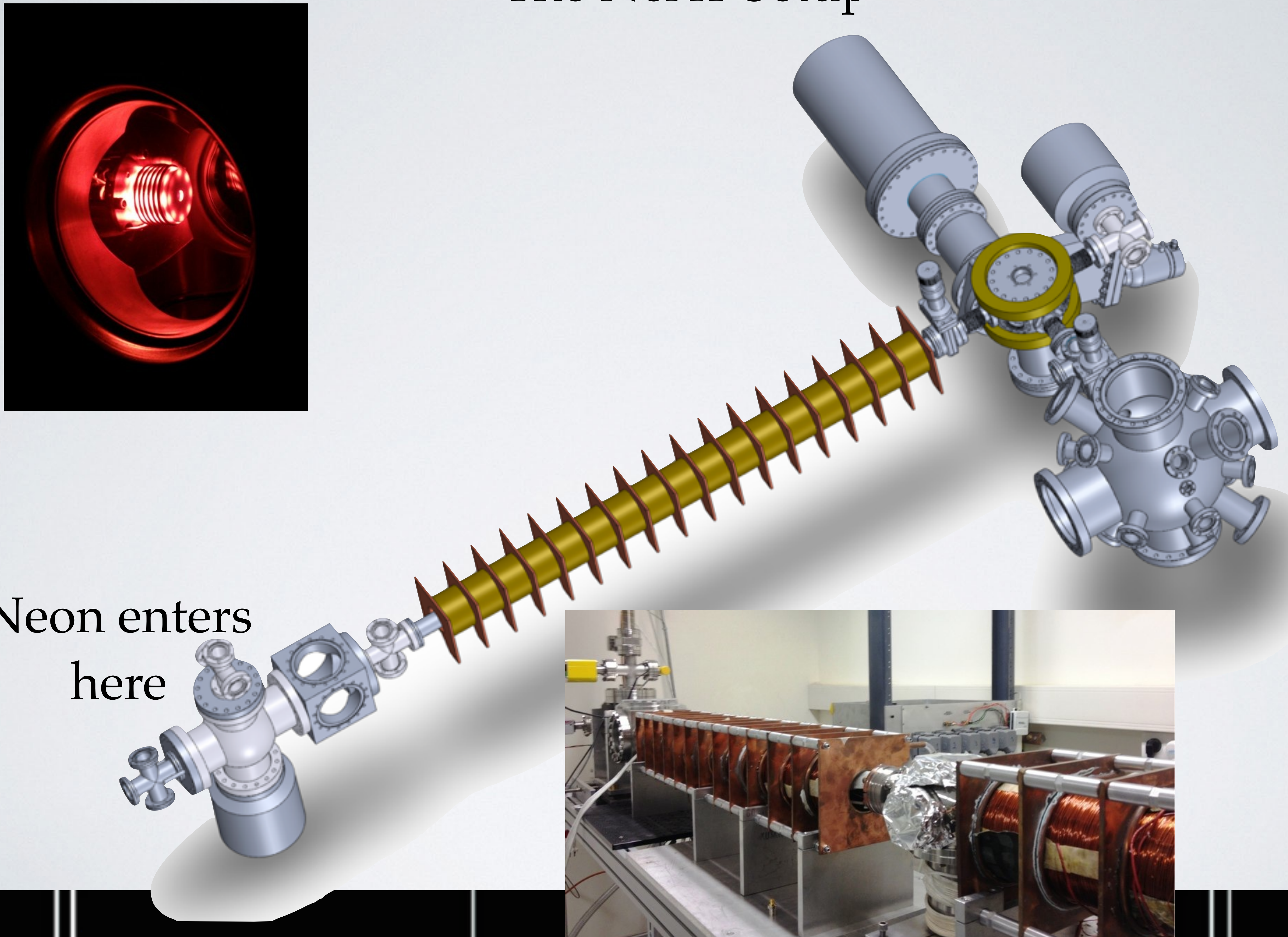
Isotope Shifts

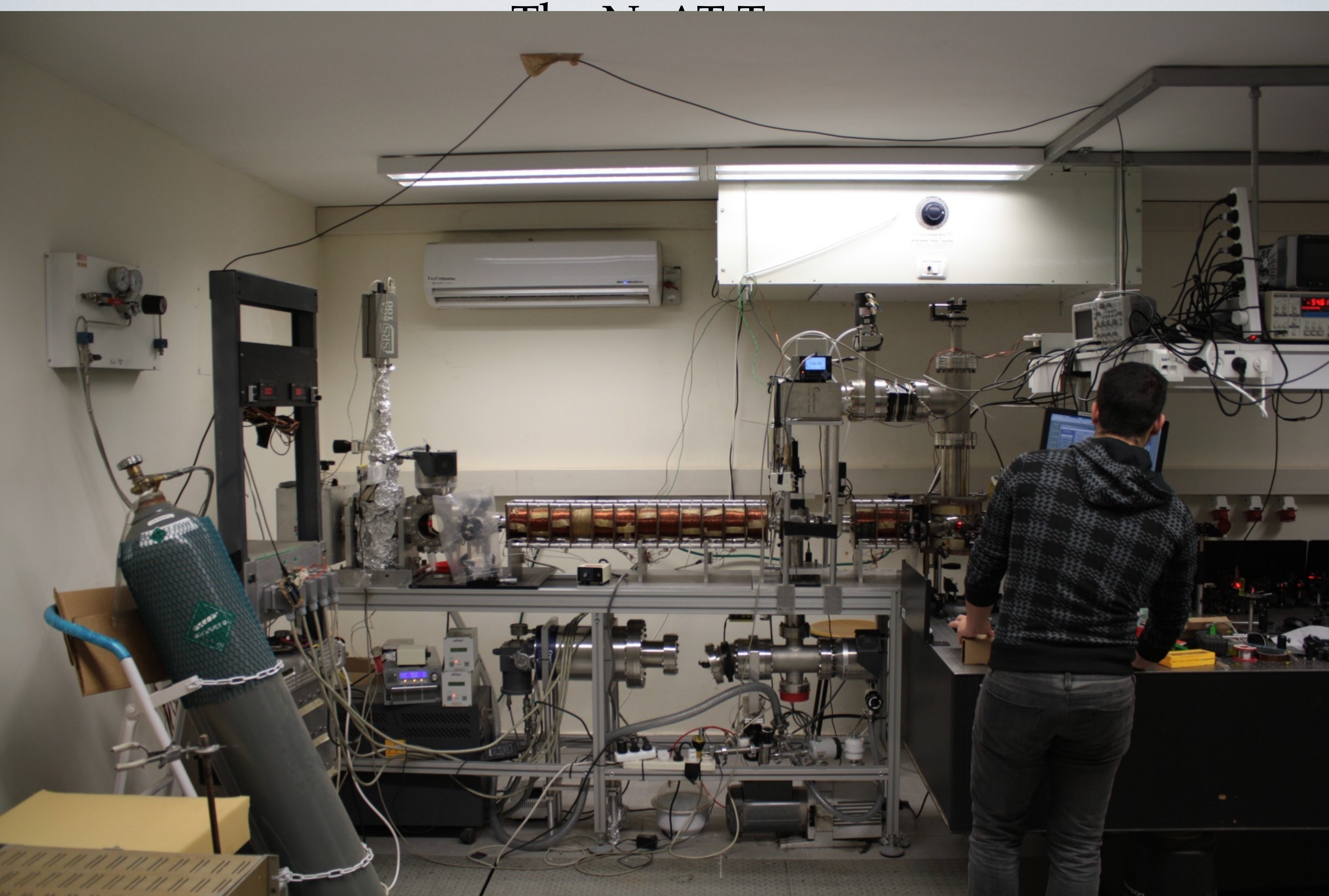
$$\delta\nu_{FS} = -\frac{2\pi}{3} Ze^2 \cdot \Delta |\psi(0)|^2 \cdot \delta \langle r^2 \rangle^{AA'}$$

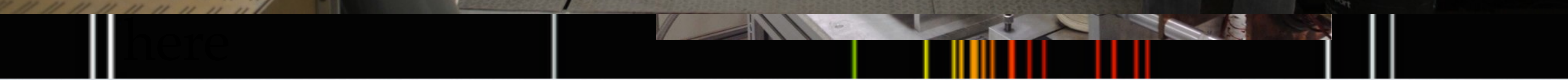




The NeAT Setup







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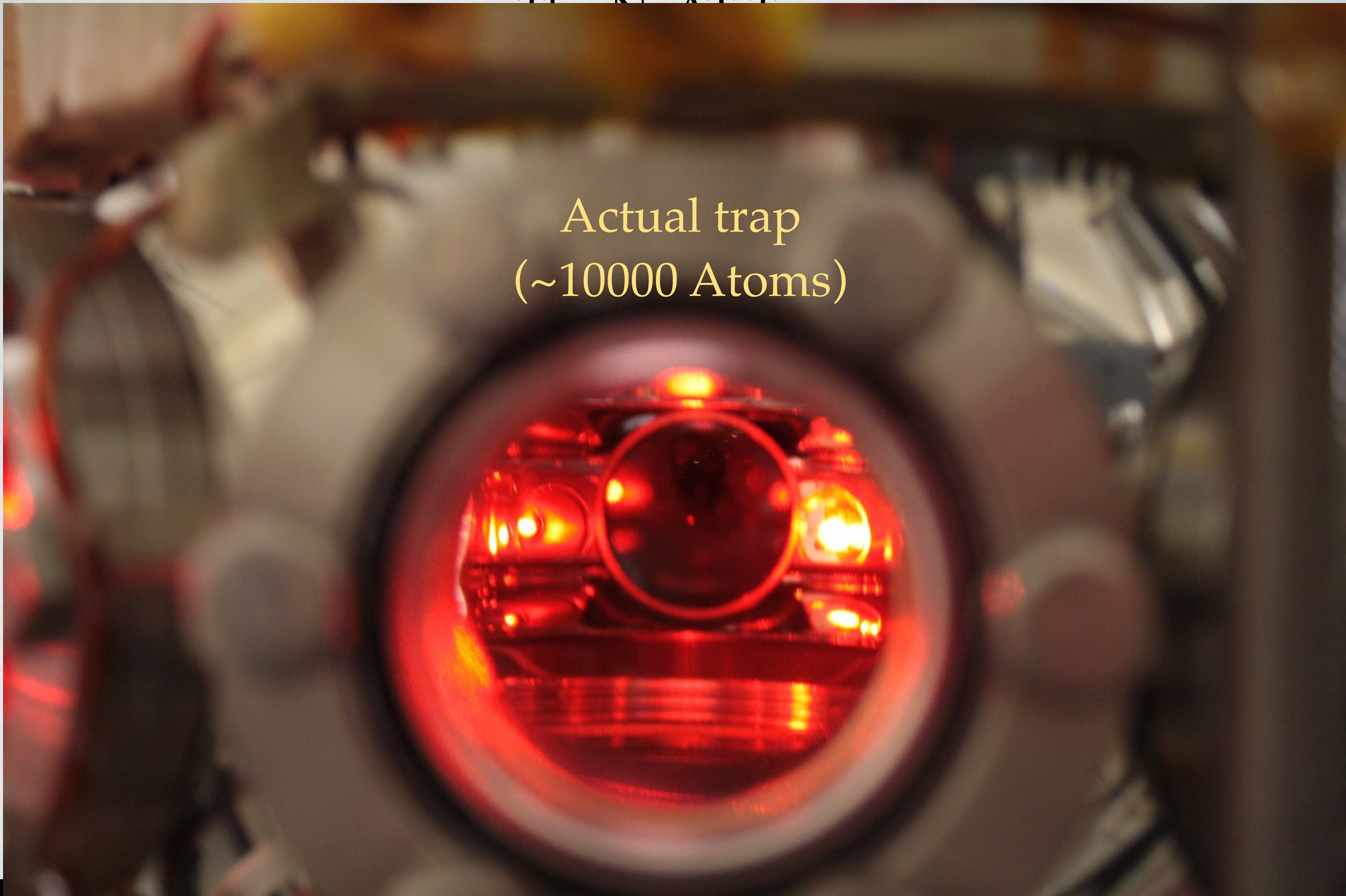

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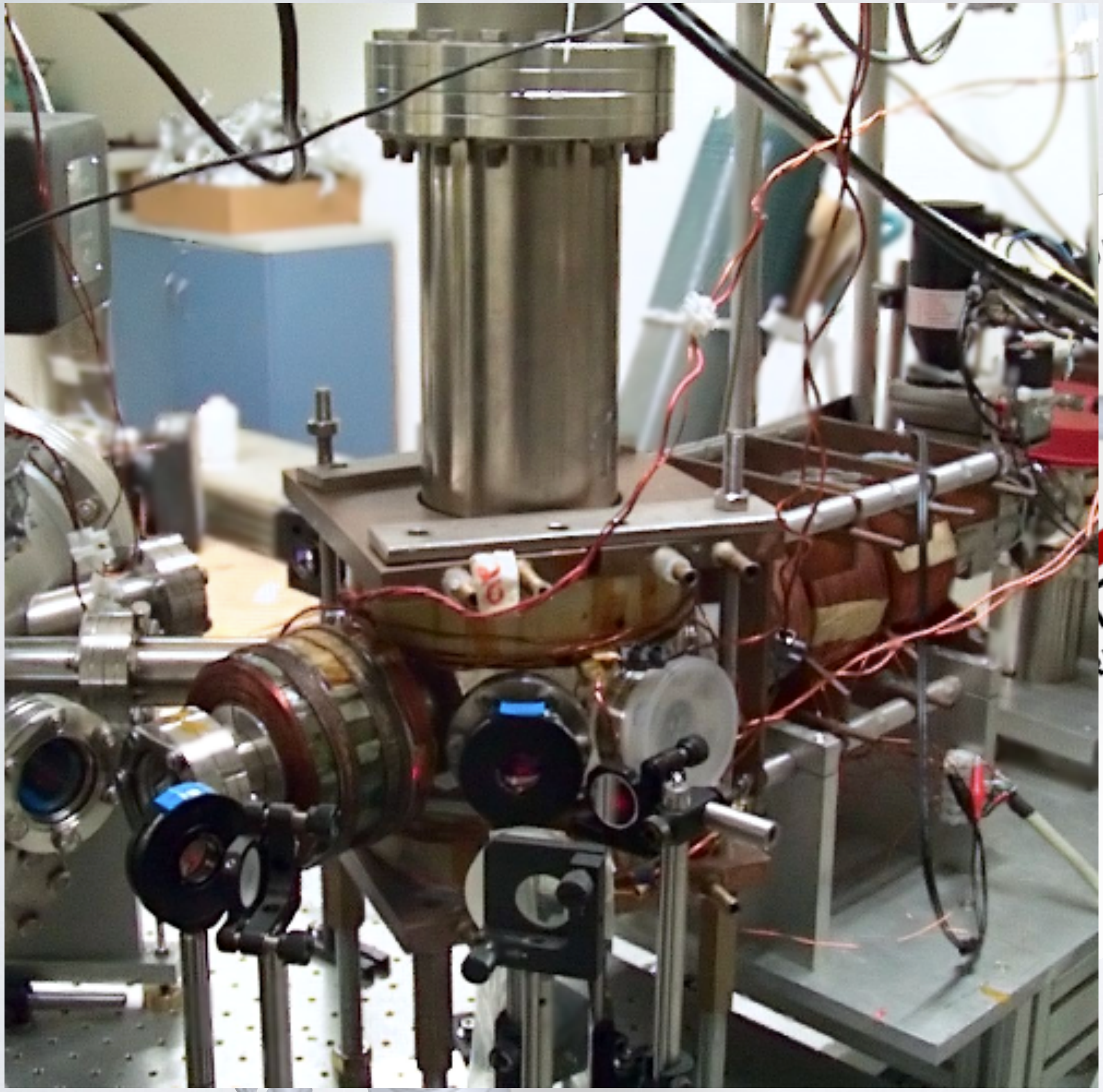
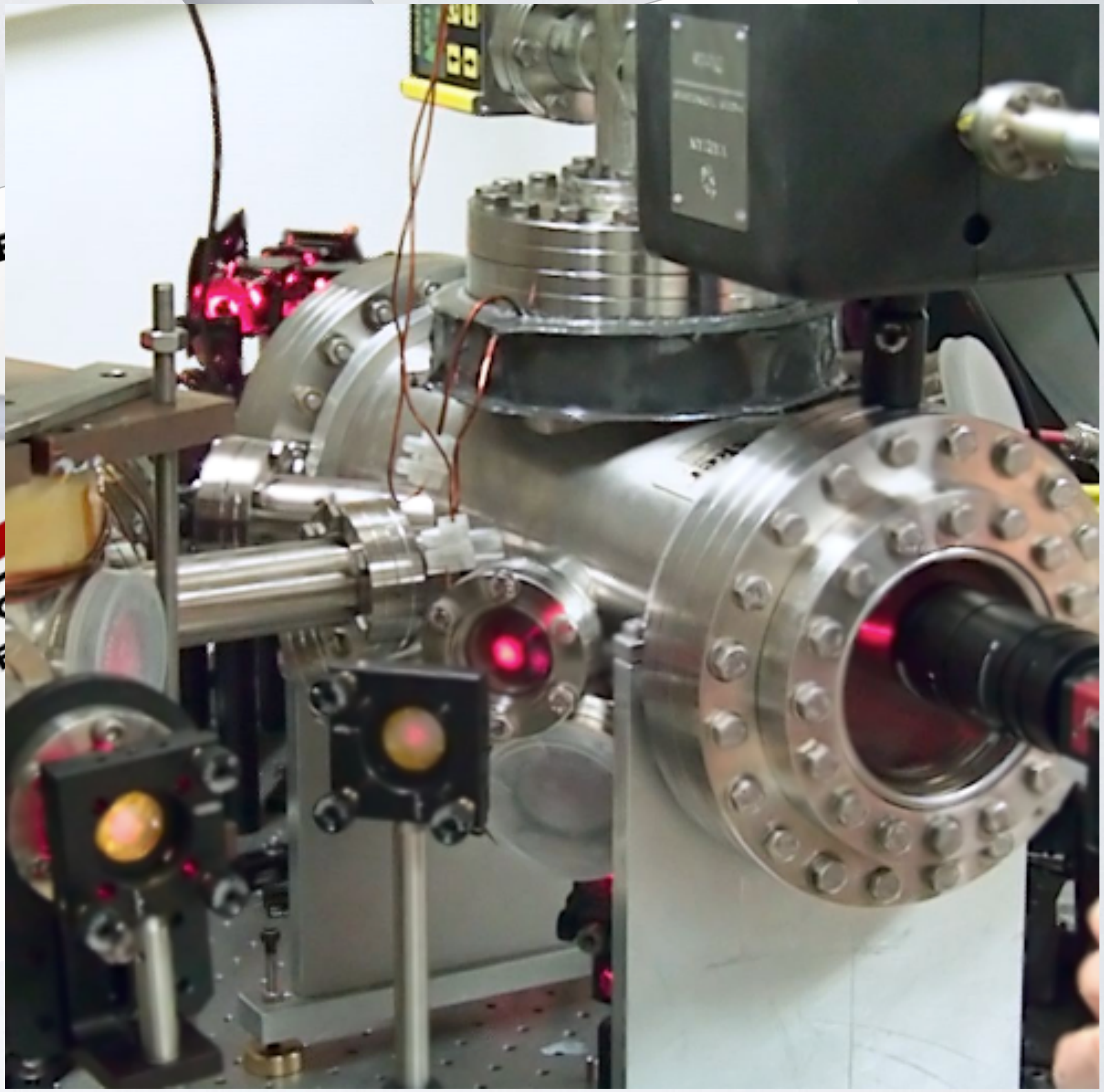
Some Technical Aspects

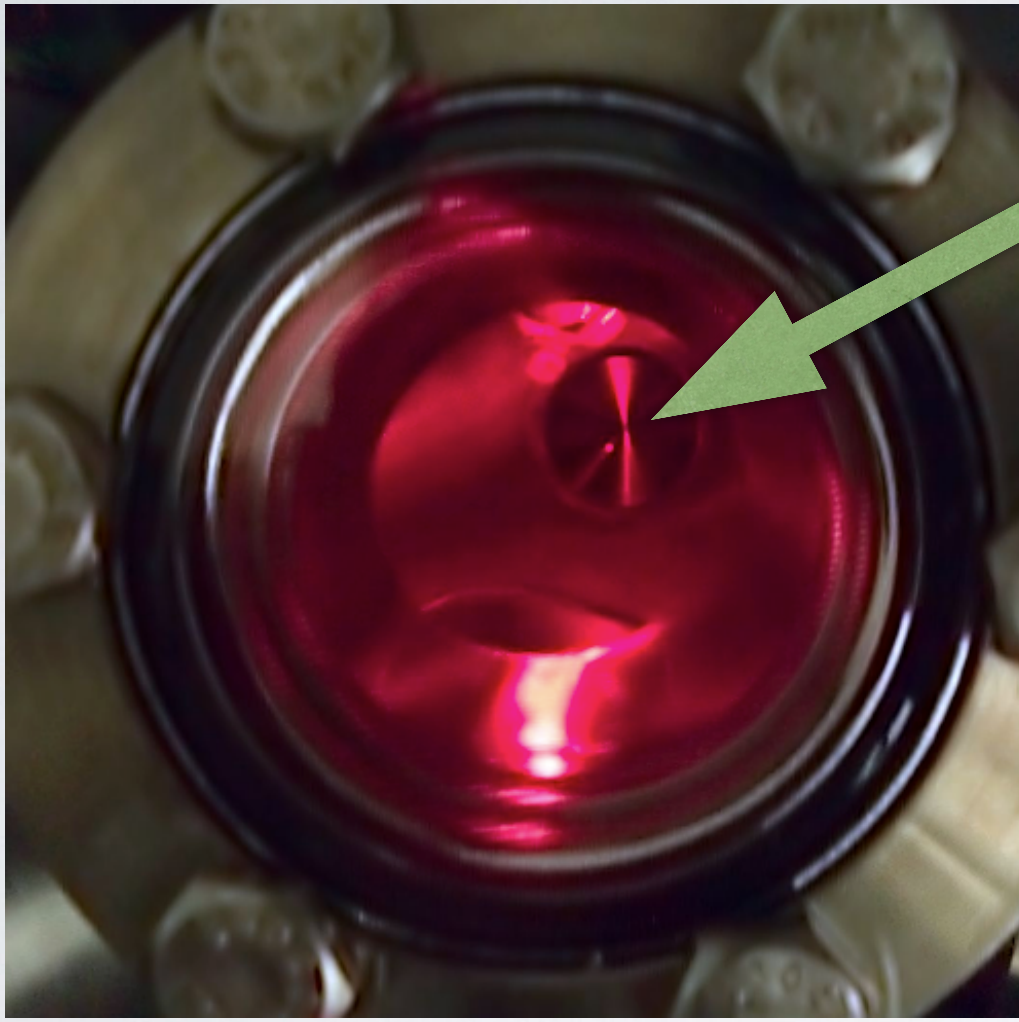


Deflection Chamber

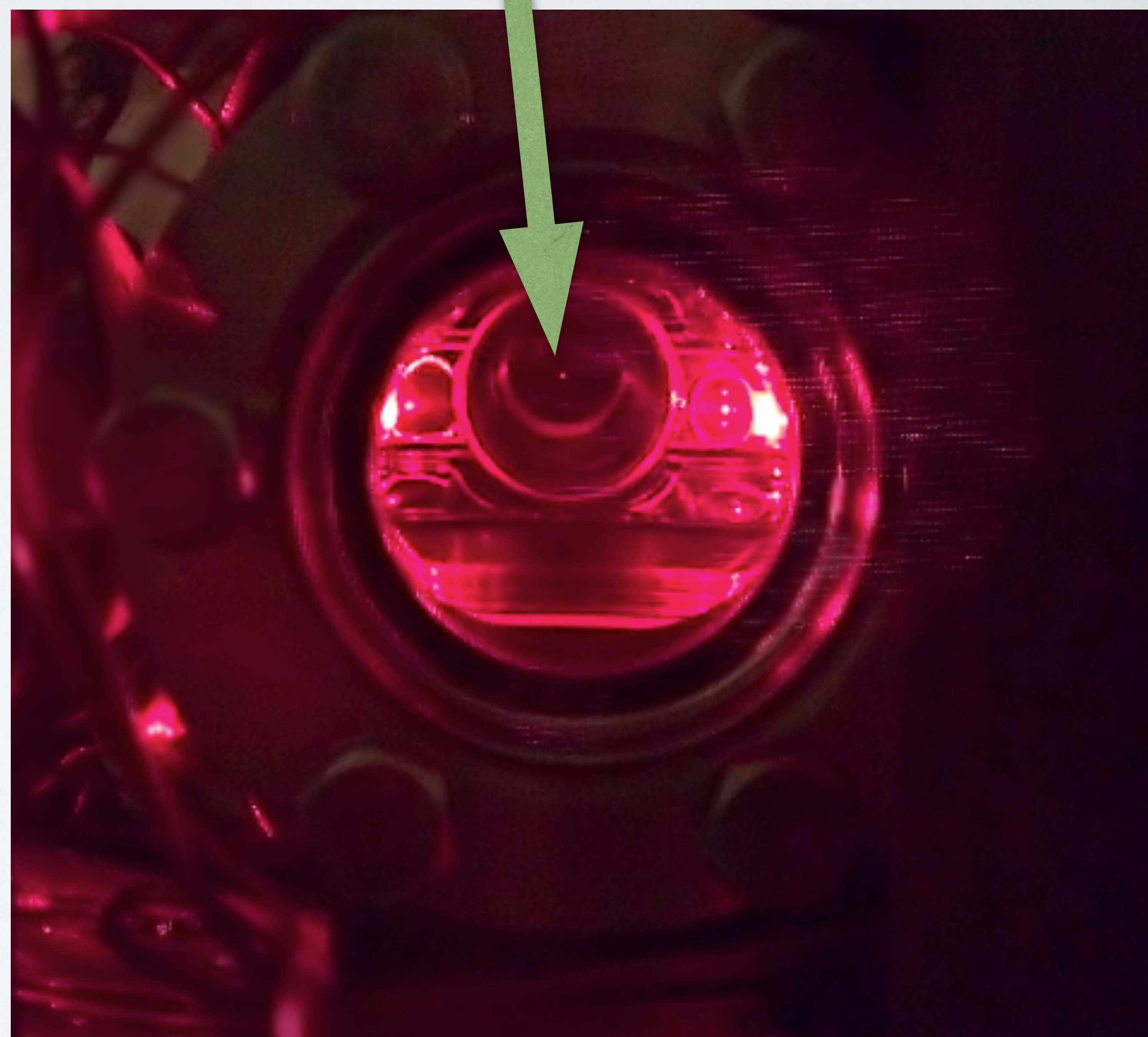


Science Chamber

Some Technical Aspects

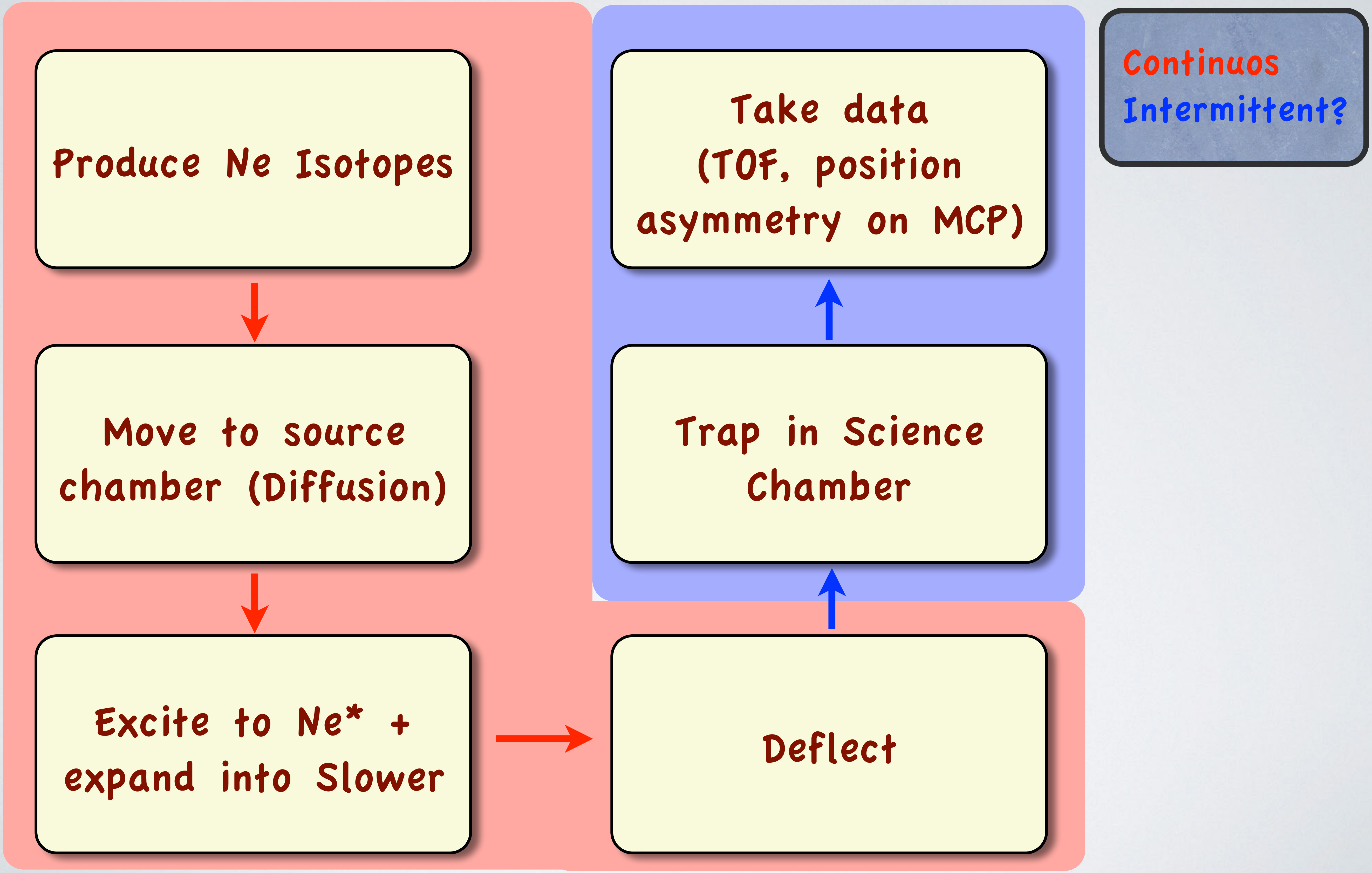


(Almost) first
trap in science chamber



Measurement Scheme

General Scheme



B DECAY 101

Possible observables in nuclei

$$\frac{d\Gamma}{dE_\beta d\Omega_\beta d\Omega_\nu} \propto \xi \left\{ 1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e} + c\left[\frac{1}{3}\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} - \frac{(\vec{p}_e \cdot \vec{j})(\vec{p}_\nu \cdot \vec{j})}{E_e E_\nu}\right] \left[\frac{J(J+1) - 3 < (\vec{J} \cdot \vec{j})^2 >}{J(2J-1)}\right] + \frac{< \vec{J} >}{J} \cdot \left[A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right] \right\}$$

Parameter	Observable	Sensitivity	SM Prediction
a	β-ν (recoil) correlation	Tensor & Scalar terms	1 for pure Fermi -1/3 for pure GT or combination
b (Fierz term)	Comparison of β^+ to EC rate	SV/T/A interference	0
A	β asymmetry for polarized nuclei	Tensor, ST/VA Parity	Nucleus dependent
B	ν asymmetry (recoil) for polarized nuclei	Tensor,TA/ST/VA/SA/VT Parity	Nucleus dependent
D	Triple product	ST/VA Interference TRI	0

A Brief Aside

Optical traps

- Once cooled and trapped by the MOT, atoms can be trapped by the purely dipole force.

Interaction of laser E field and induced dipole moment:

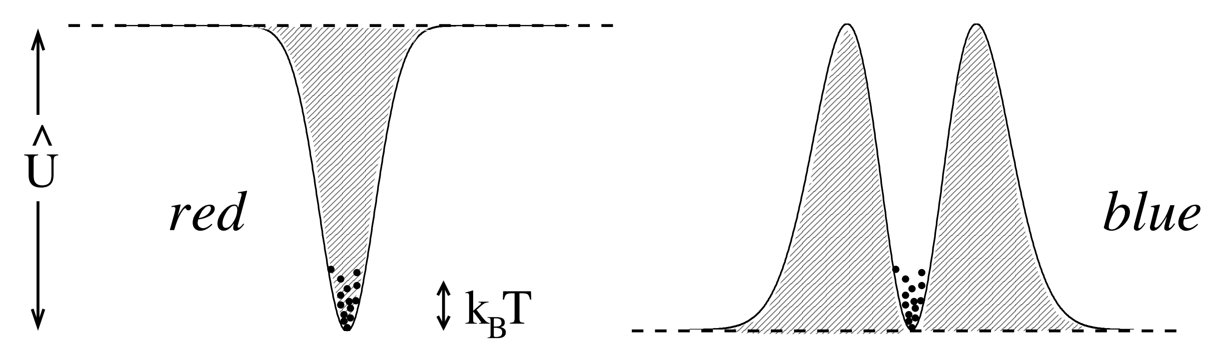
$$\tilde{p} = \alpha \tilde{E}$$

$$U_{dip} = -\frac{1}{2}\langle \mathbf{pE} \rangle$$

$$U_{dip}(\vec{r}) = \frac{3\pi c^2}{2w_0^3}\frac{\Gamma}{\Delta} I(\vec{r})$$

$$\gamma_{sc}(\vec{r}) = \frac{3\pi c^2}{2\hbar w_0^3}\left(\frac{\Gamma}{\Delta}\right)^2 I(\vec{r})$$

$$\Delta = w_{laser} - w_0$$



Red detuned traps are attractive

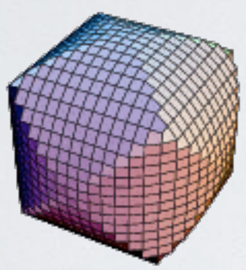
Blue detuned traps are repulsive

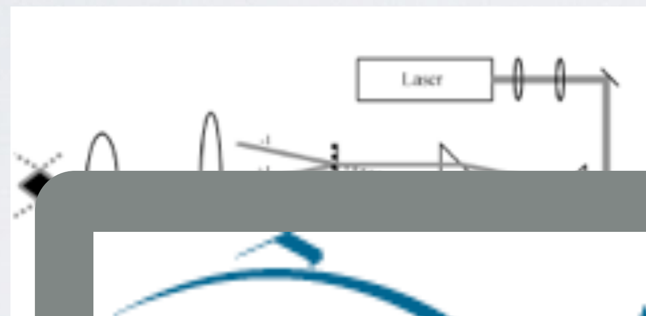
Looking Ahead (Tech IV)

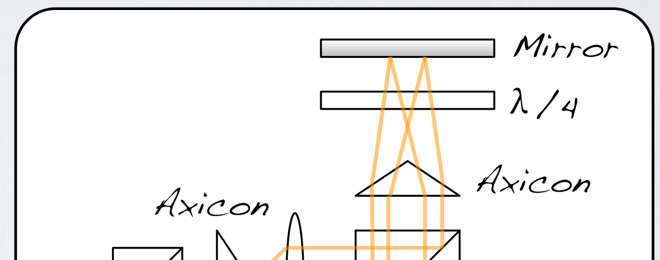
Dark Blue Traps

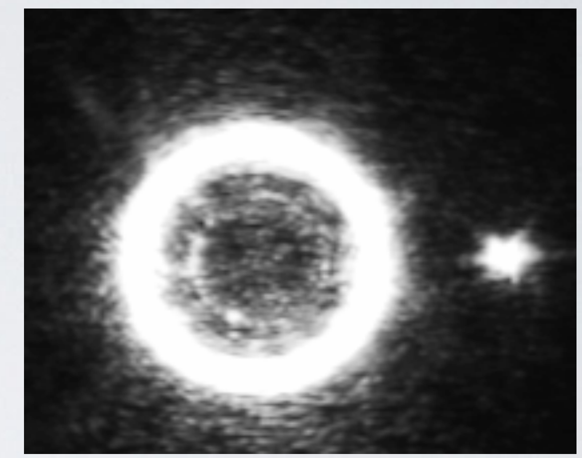
- Currently testing two optical traps (dark cavities surrounded by blue detuned light). Based on designs by Davidson *et al.* (slightly modified).

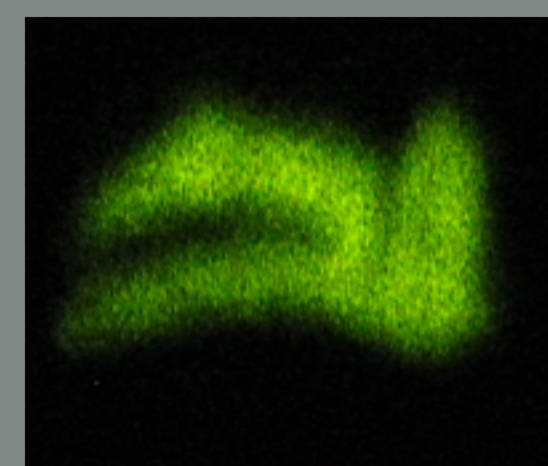
Single beam "axicon" trap



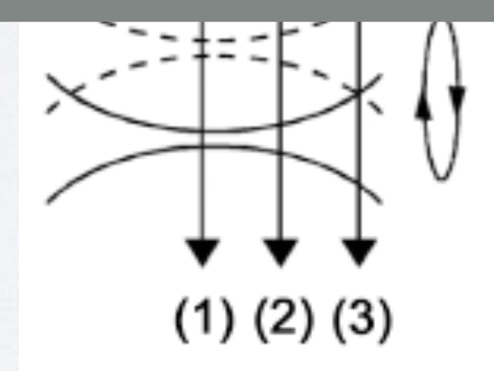


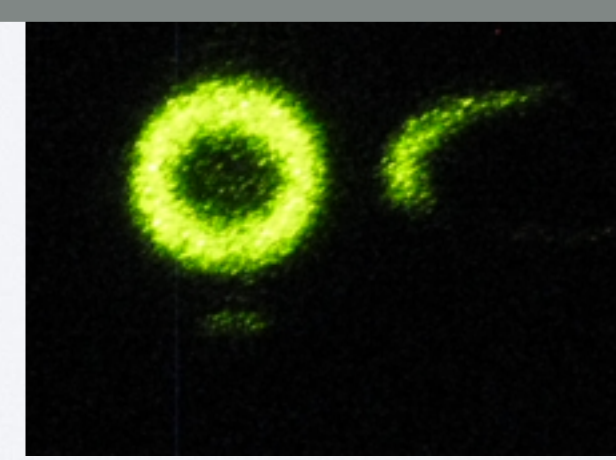


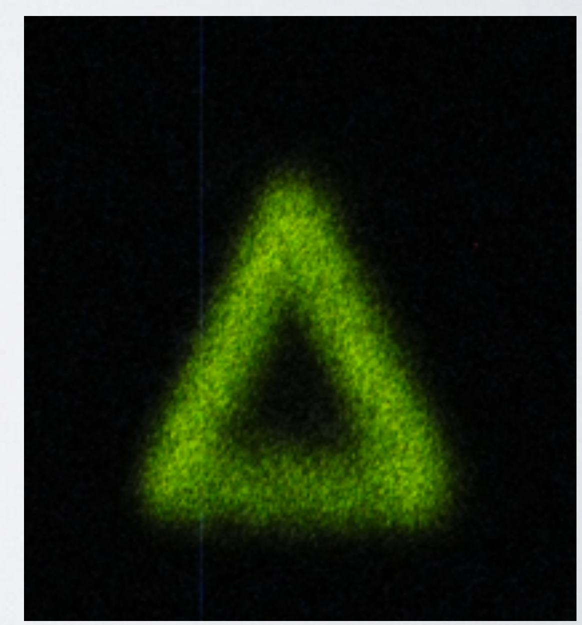




ROtating Beam Optical Trap (but in 2 orthogonal directions)





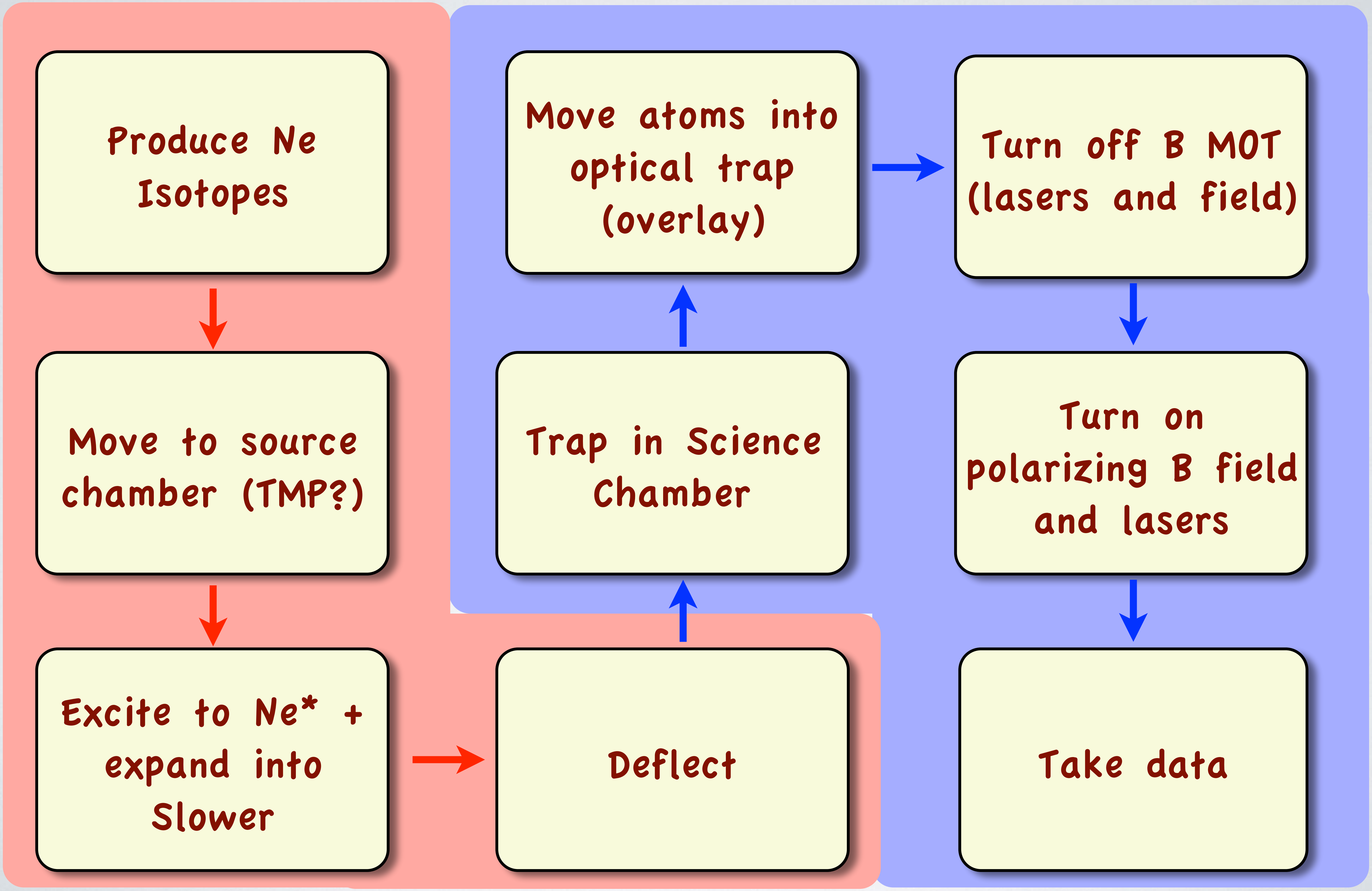


Digitally controlled

Friedman, N., Kaplan, A., and Davidson, N. Adv. At. Mol. Opt. Phys., 48:99 (2002).

Polarization Measurement

General Scheme



Some discussion of Ion Traps

General Principles

- 3D trapping requires a potential minimum. Conveniently taken to be harmonic.

$$F \propto -\vec{r}$$

$$F = -\nabla U$$

$$\Phi = \frac{\Phi_0}{d^2}(Ax^2 + Bx^2 + Cz^2)$$

- In general Φ can be a time-dependent function.
- Also note that this means no electrostatic traps.

$$\nabla^2 \Phi = 0 \Rightarrow A + B + C = 0$$

General Principles

- 3D trapping requires a potential minimum. Conveniently taken to be harmonic.

$$F \propto -\vec{r}$$

$$F = -\nabla U$$

$$\Phi = \frac{\Phi_0}{d^2}(Ax^2 + Bx^2 + Cz^2)$$

- In general Φ can be a time-dependent function.

- Also note that this means no electrostatic traps.

Only saddles in 3D.
"Ernshaw's Theorem"
(more on this later)

$$A + B + C = 0$$

Ernshaw's Theorem

S. Earnshaw, Trans. Cambridge Philos. Soc. 7, 97 (1842)

A collection of point charges cannot be maintained in a stable stationary equilibrium configuration solely by the electrostatic interaction of the charges.

Restatement of Gauss' Law (for free space)

$$\nabla \cdot E \propto \nabla \cdot F = -\nabla^2 \phi = 0$$

No local minima or maxima in free space (only saddle points).

Naively speaking → No electrostatic ion traps

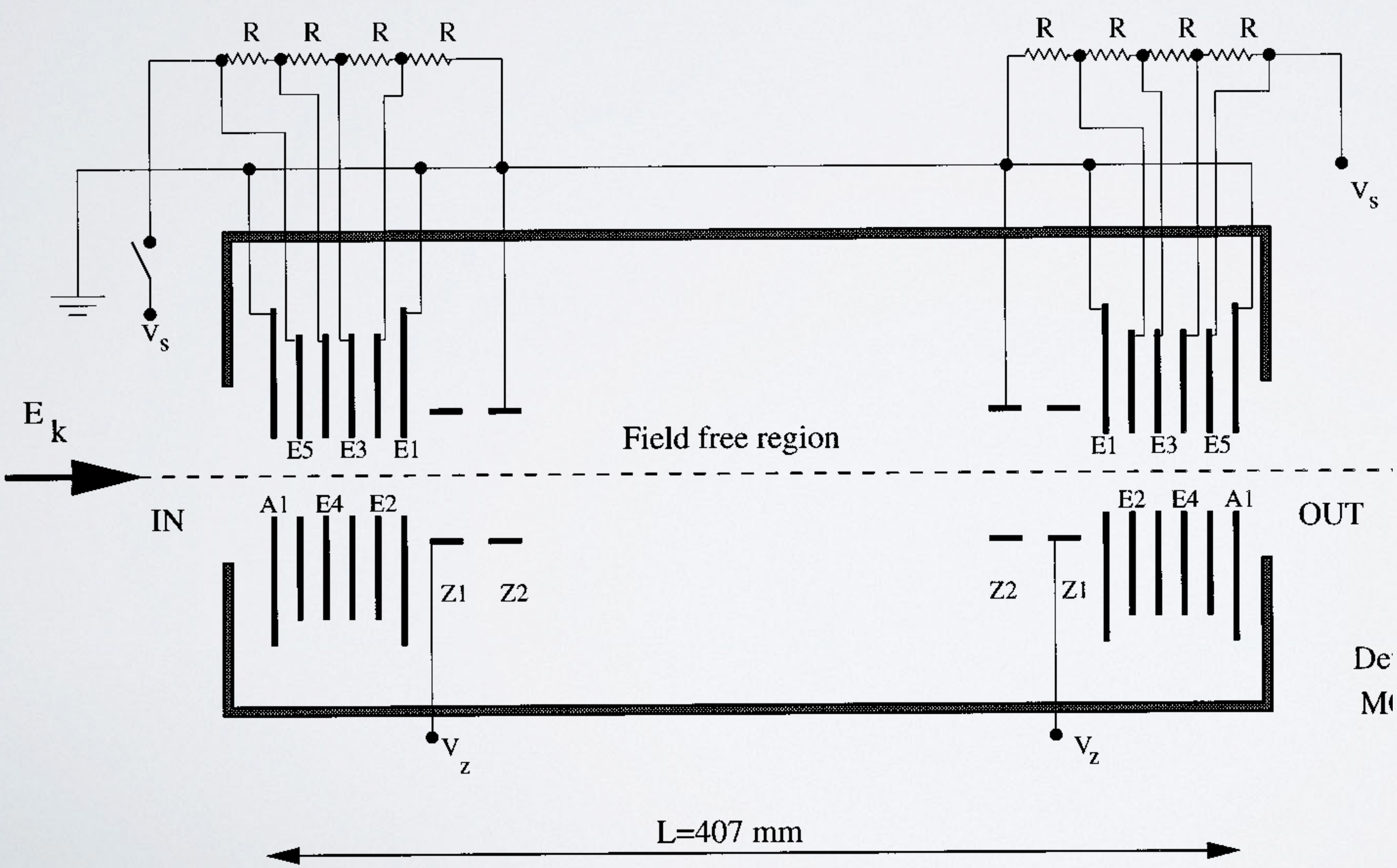
Non Electrostatic:
Time varying ("Paul trap", MOT) & Magnetic fields ("Penning trap").
Electronic correction.

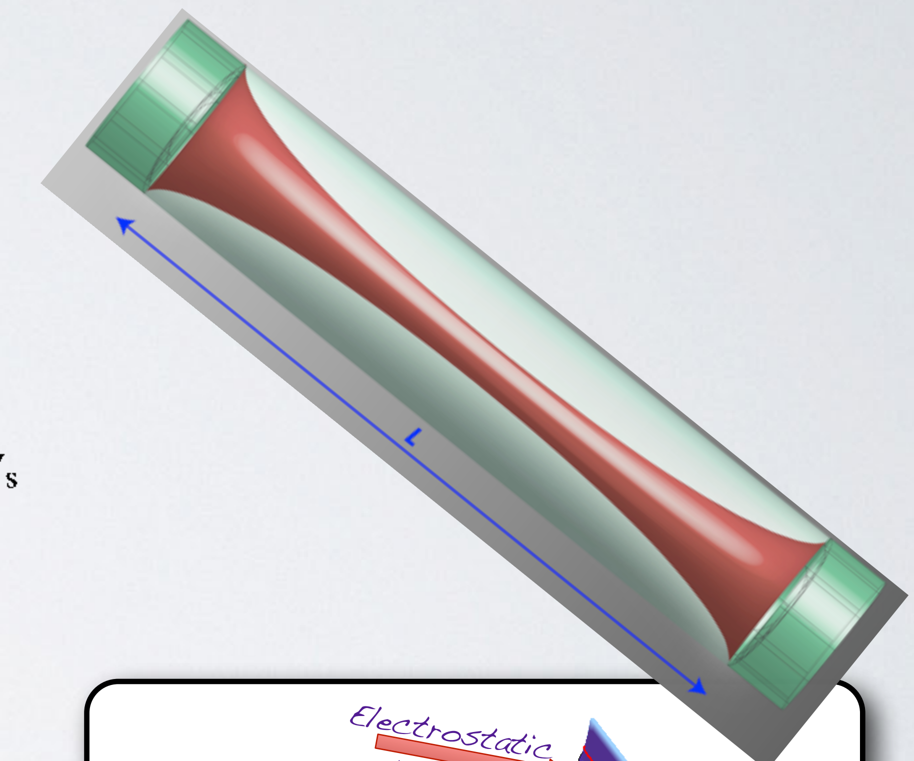
But what about moving ions...

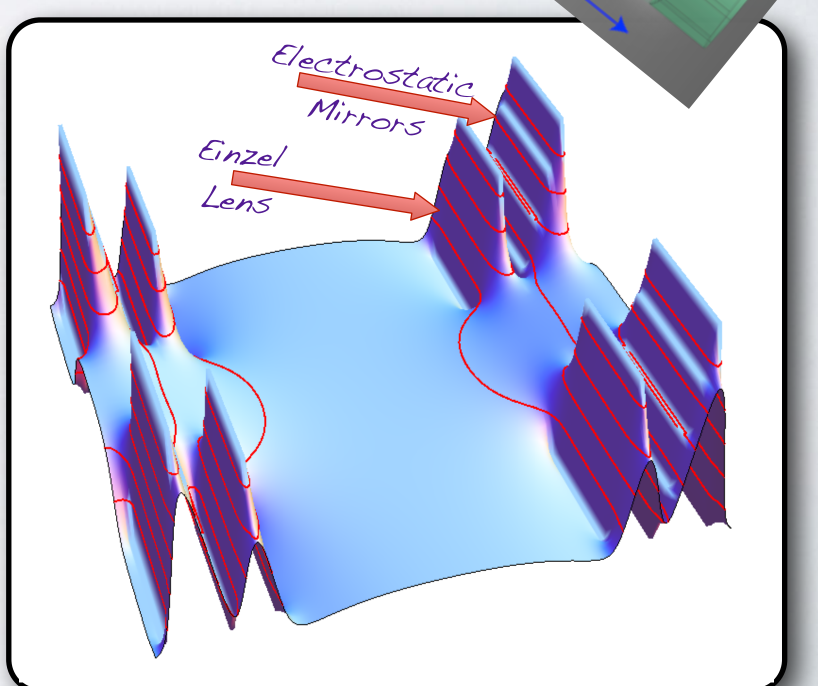
Ernshaw's theorem talks about stationary charges.

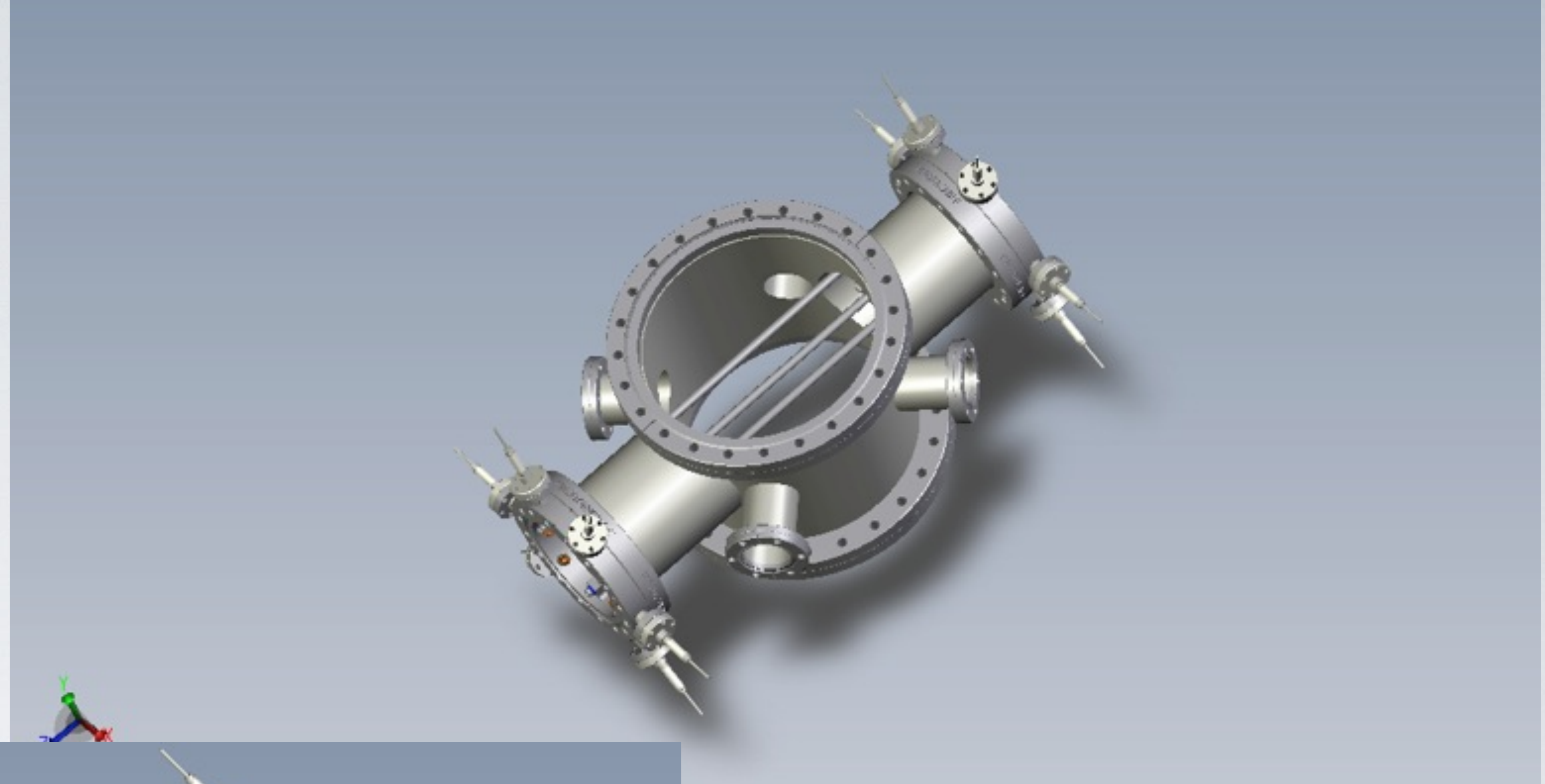
Moving charges in an electrostatic field actually "see" changing fields.

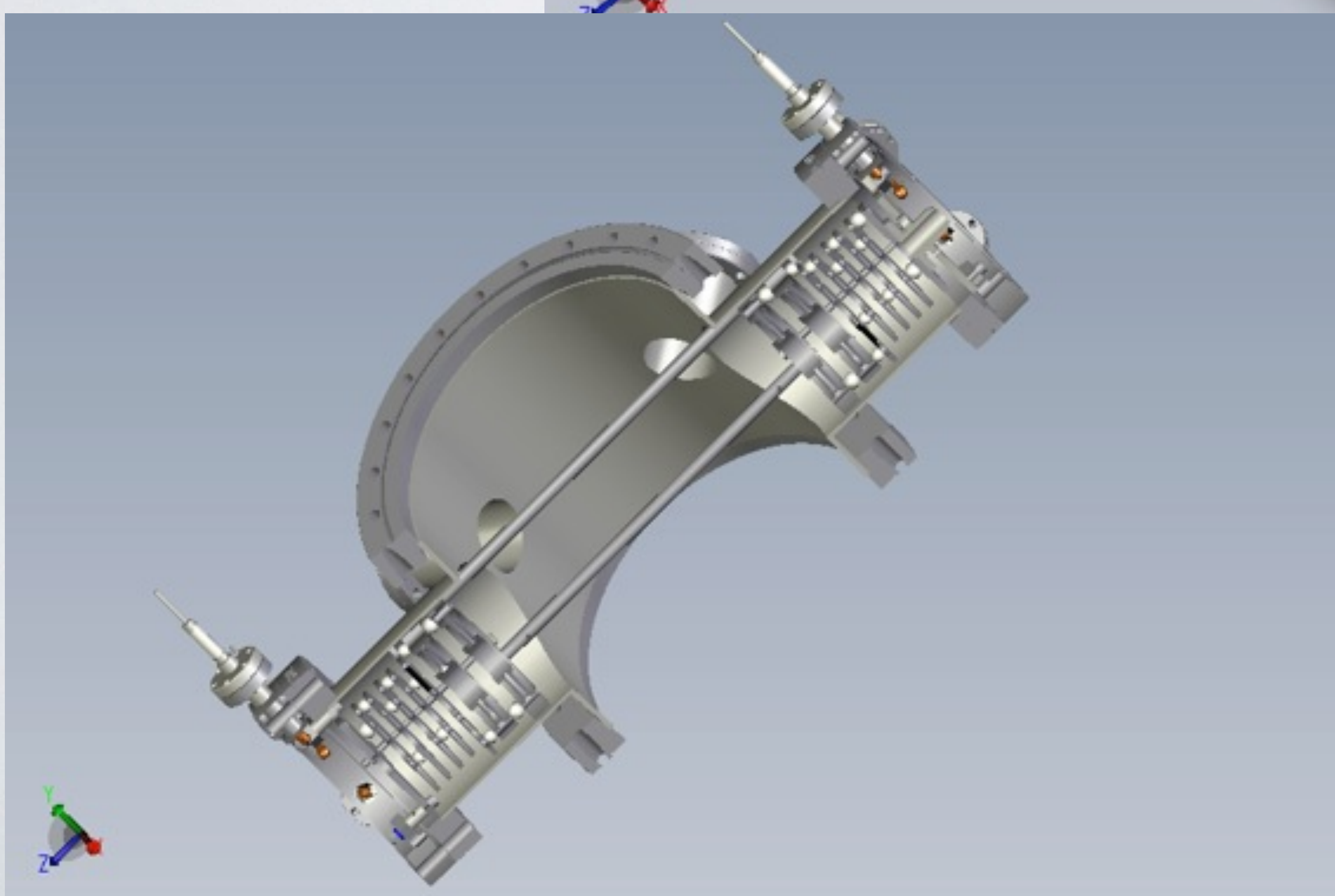
Trap design very similar to a resonant cavity for laser light.

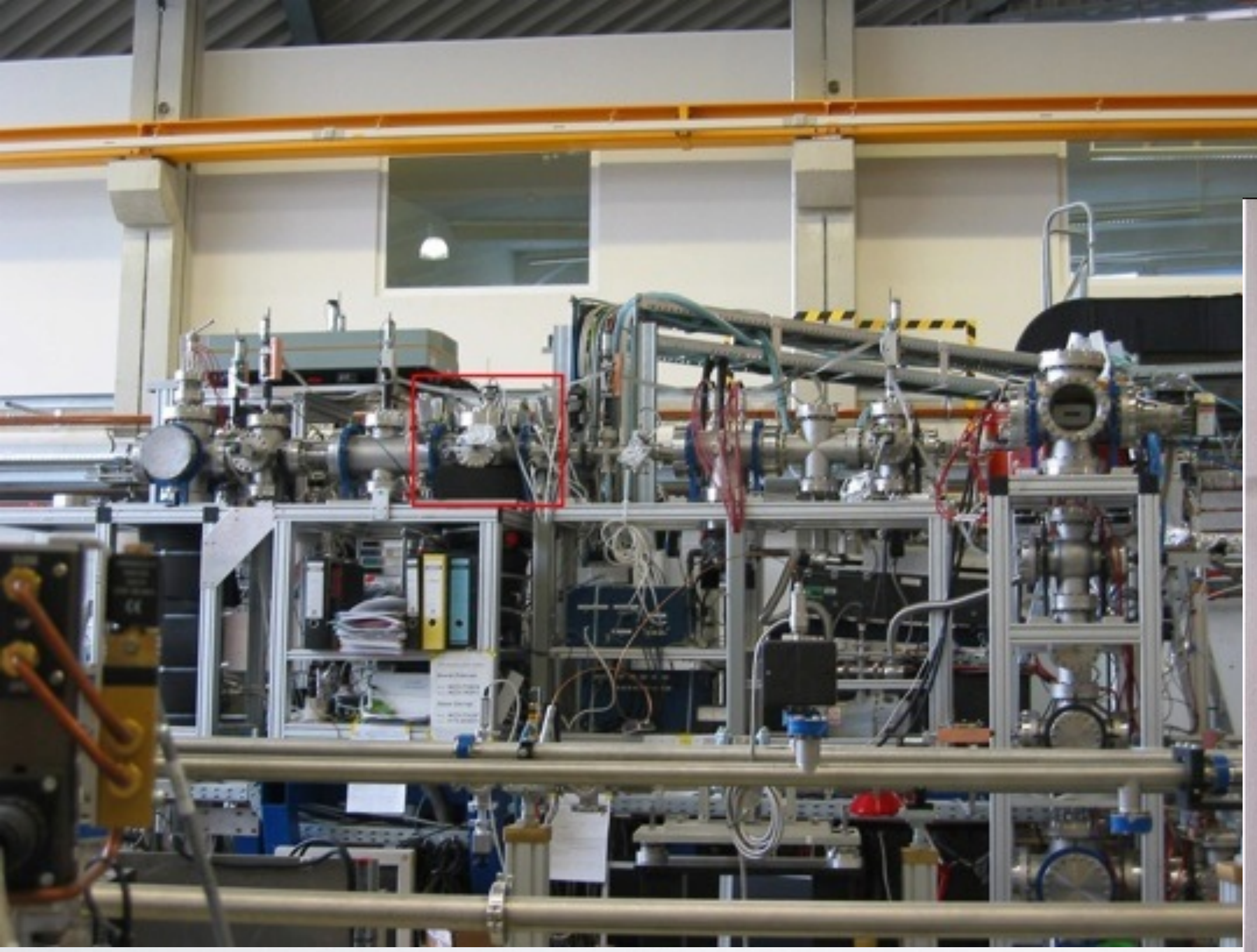




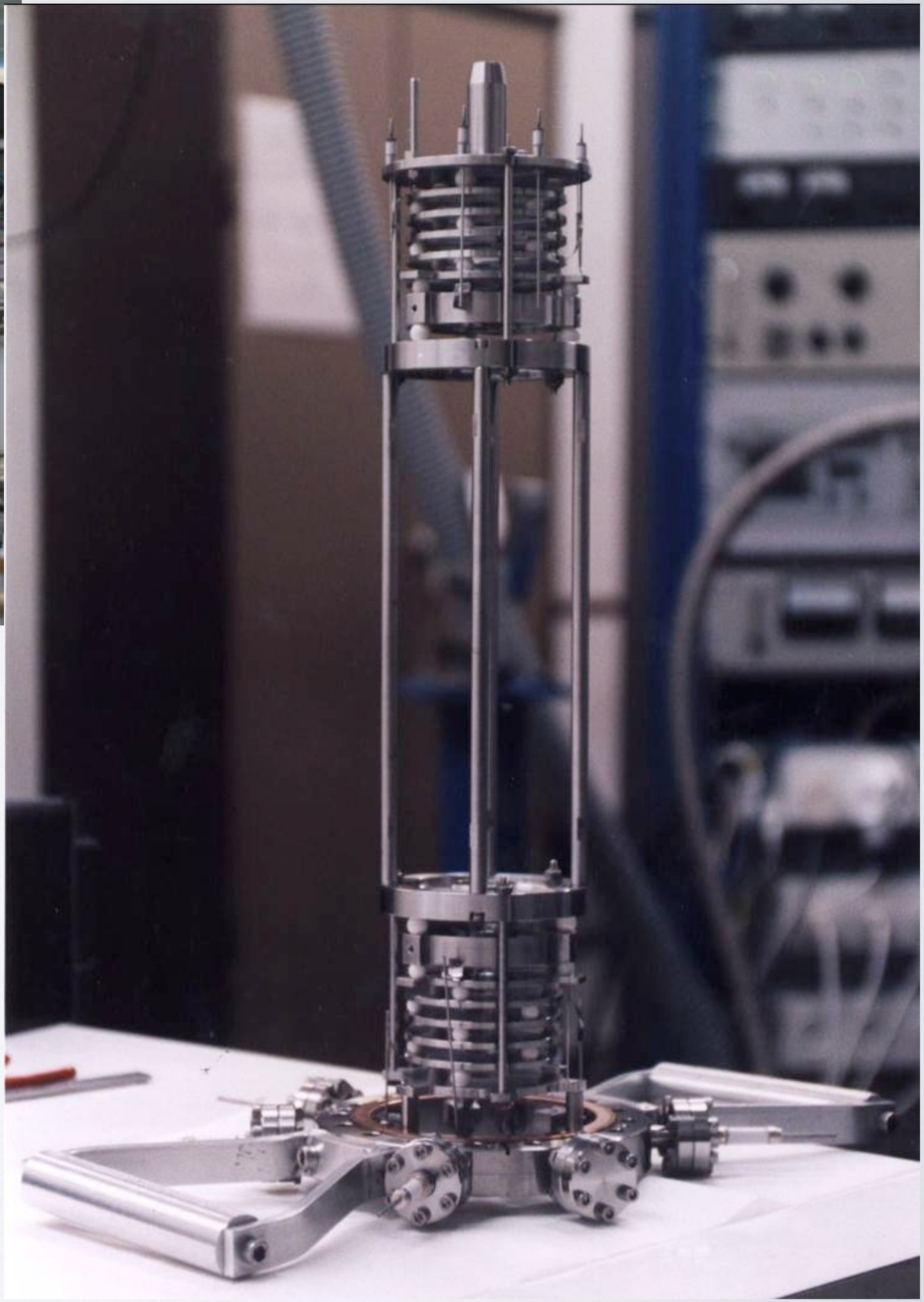








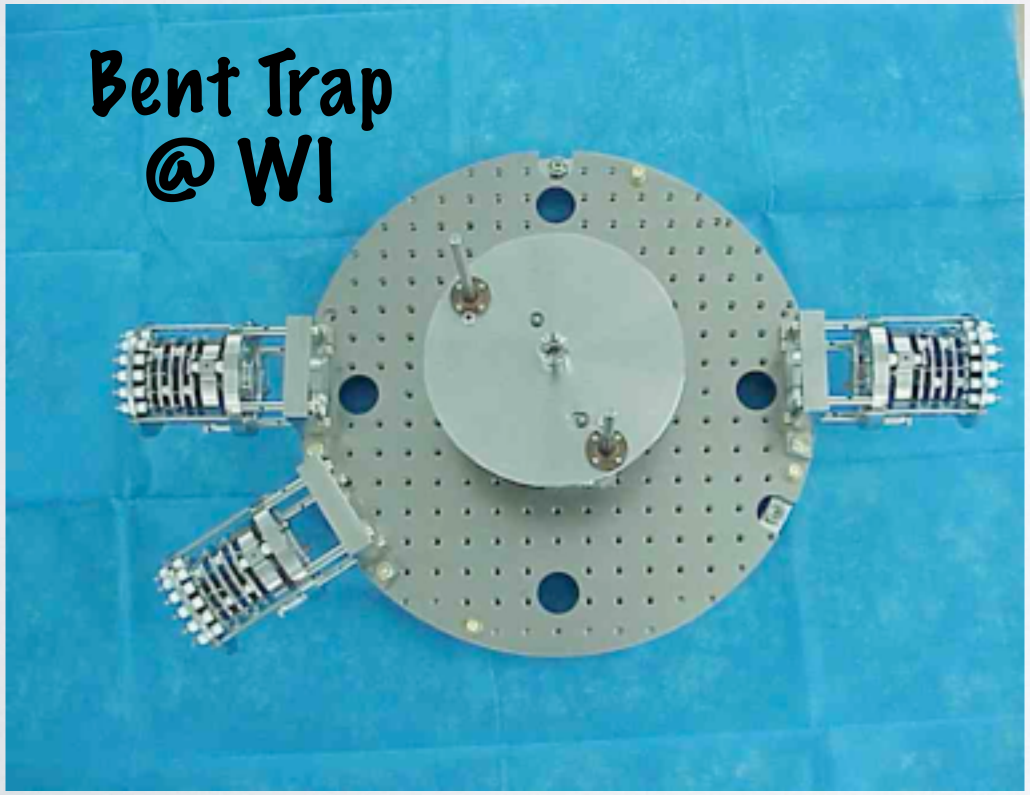
Heidelberg Trap



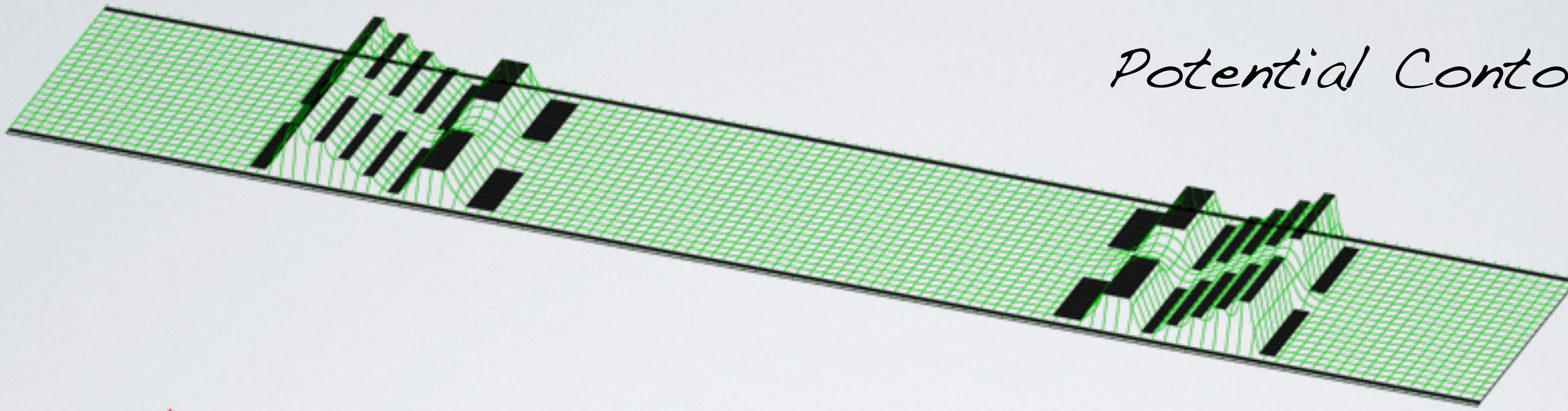
Trap
@
Weizmann
Institue


Construction
@ LBL

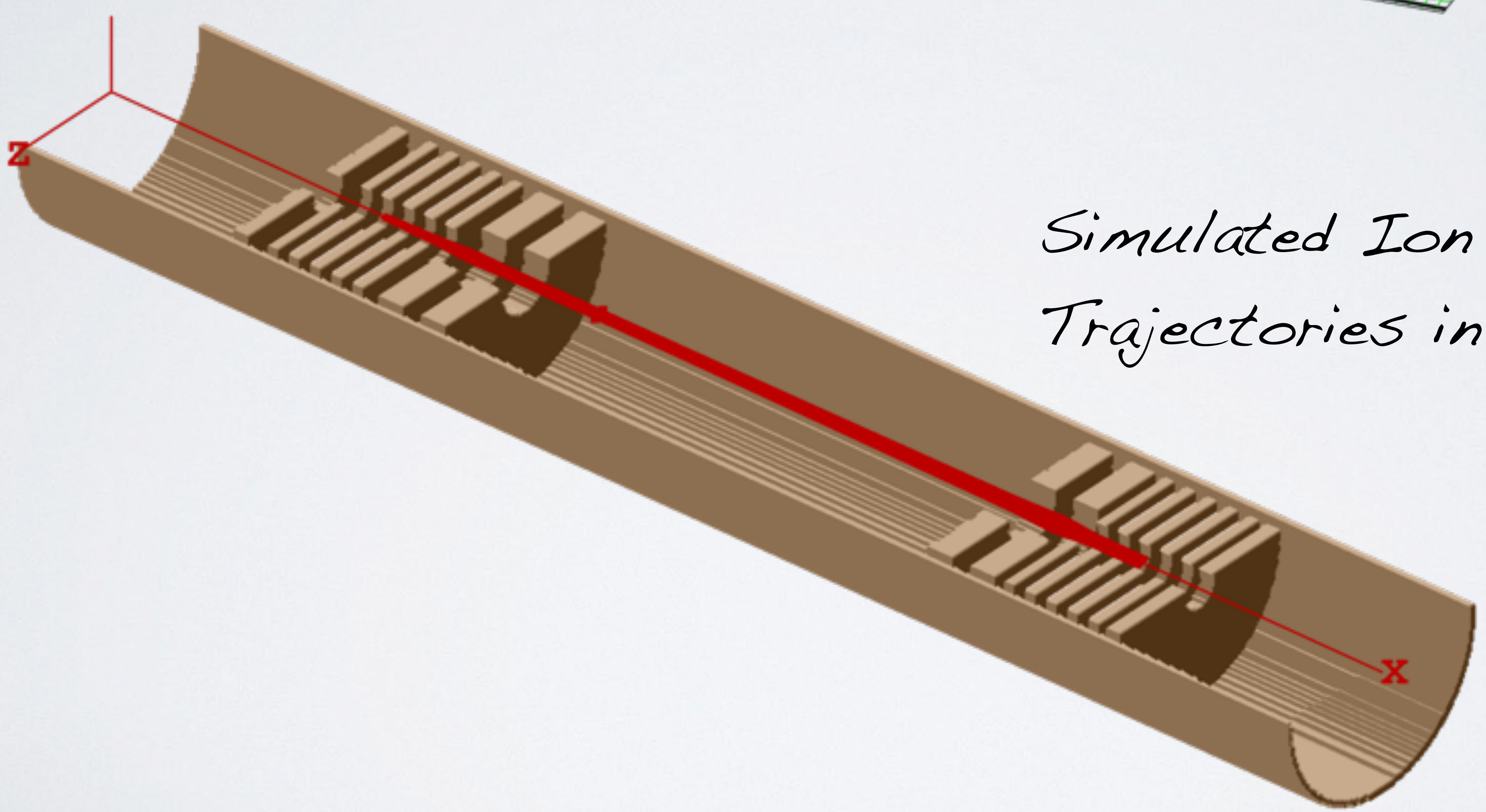

Andrew Wong (undergrad)
@ Berkeley


Bent Trap
@ WI

Potential Contours



Simulated Ion Trajectories in Trap



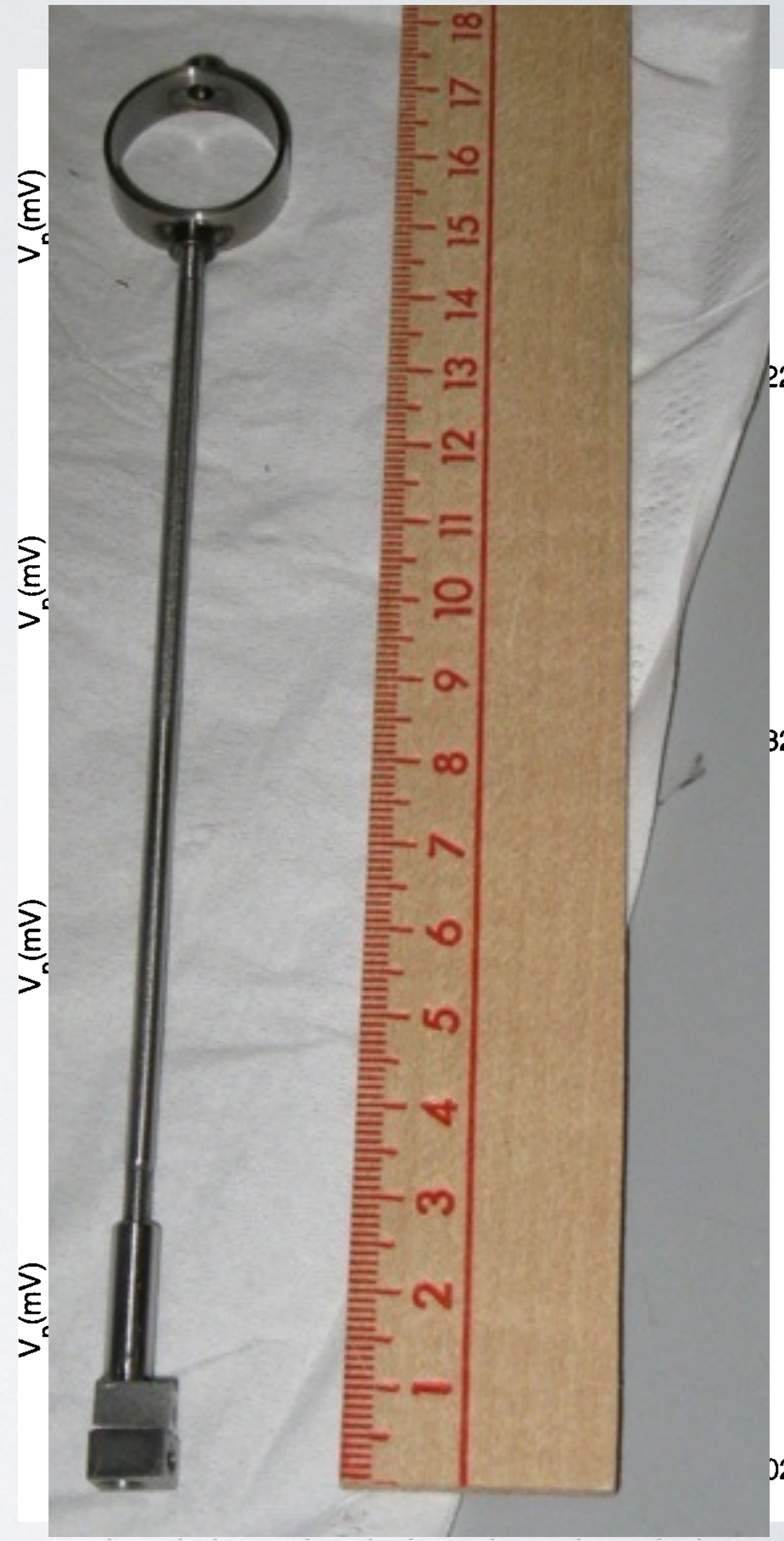
Ion Behavior In the Trap

From simple arguments the width of the ion cloud in the trap should
increase as a function of the oscillation number (not all ion have the exact same energy).

$$W_n = (W_0^2 + n^2 \Delta T^2)^{1/2}$$

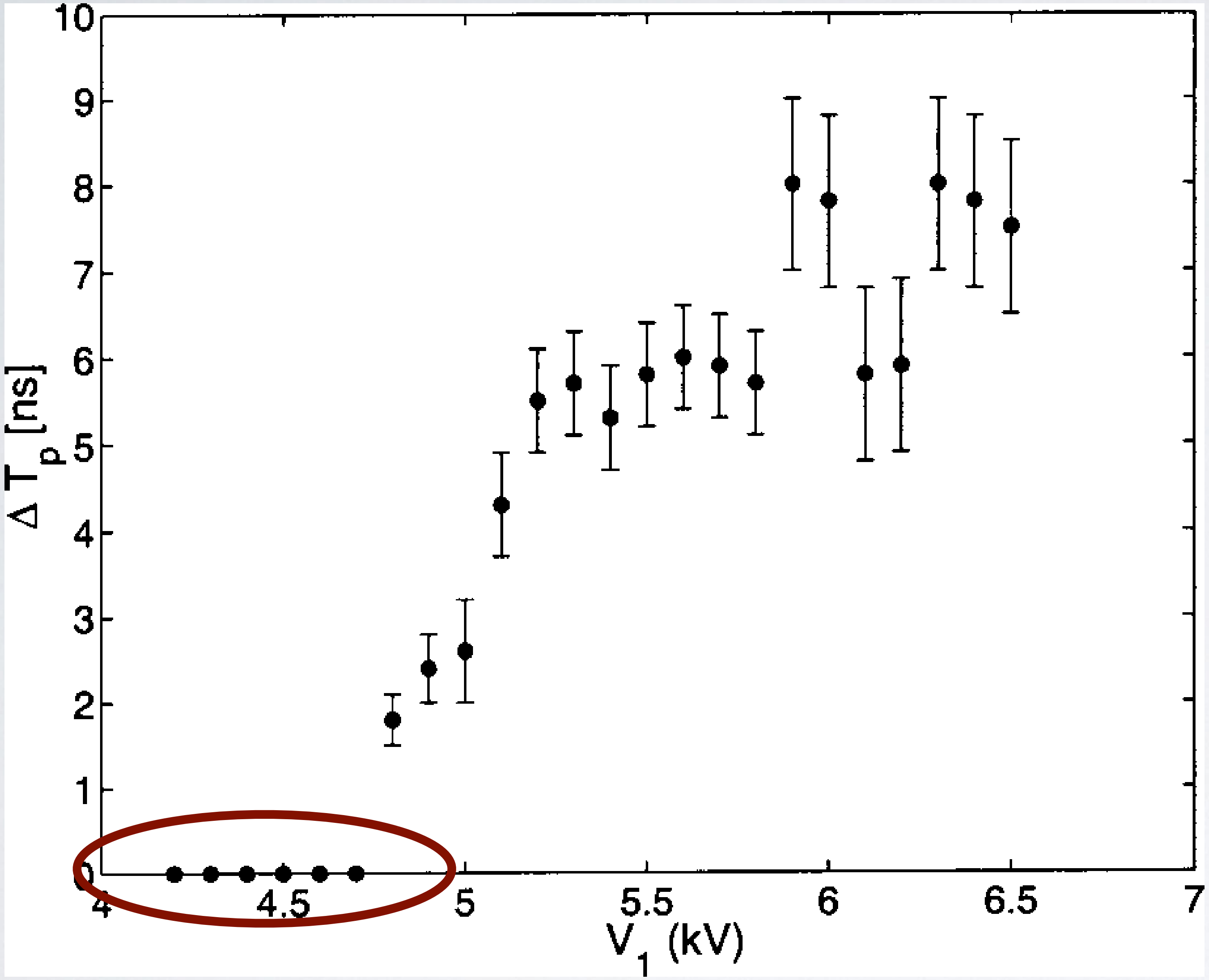
Signal in pickup electrode for different times after injection.

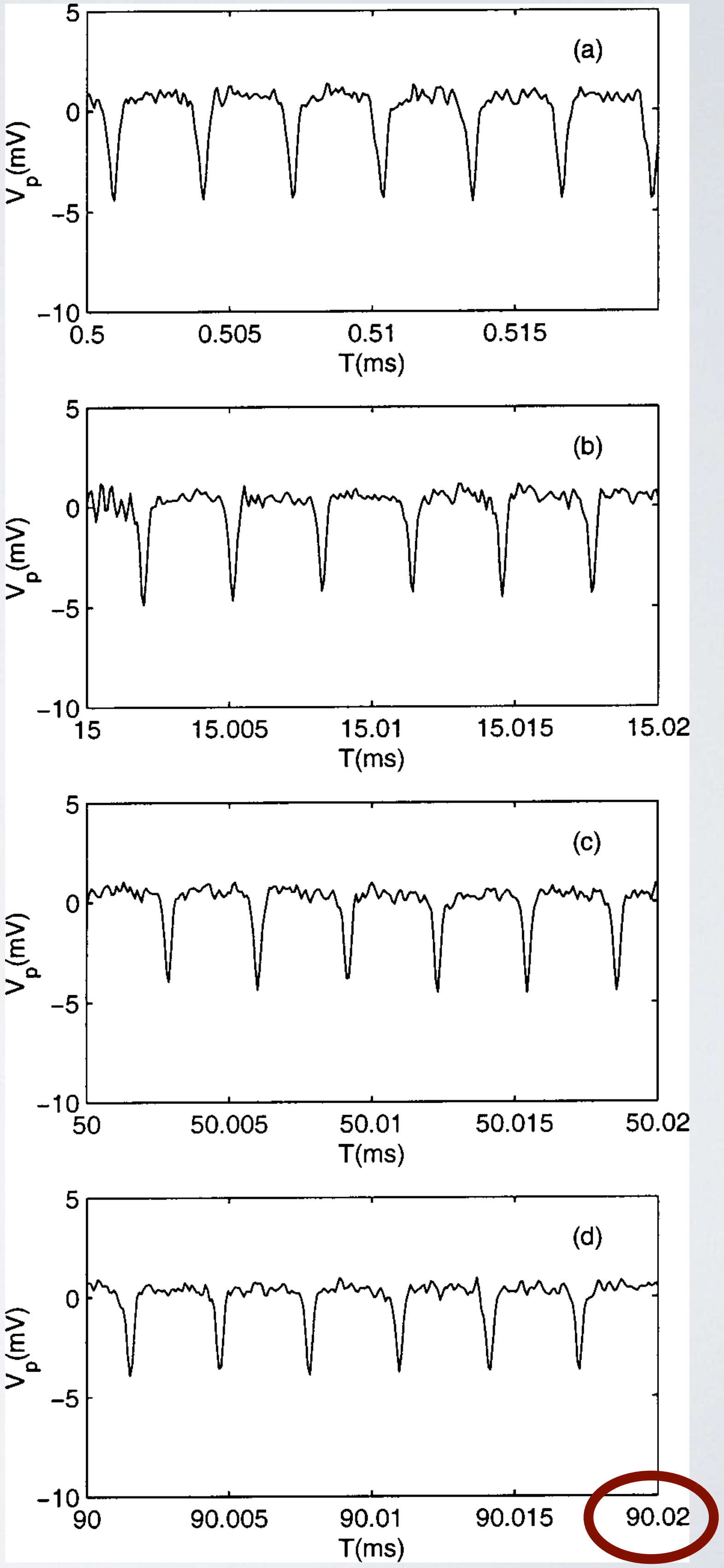
Using the pickup, it is possible to measure the detuning coefficient for different values of the (outer) electrode potential.



D. Zajfman et al., J. Opt. Soc. Am. B20, 1028 (2003)

Surprise...





For some values of the potential there is no dispersion!

Why?

$$V(x) = \begin{cases} 0 & |x| \le L/2 \\ F(|x| - L/2) & |x| > L/2 \end{cases}$$

1D model for the potential in the trap

$T = 4 \Big($ ... ion with

$\dfrac{dT}{d\nu} = \dfrac{4m}{qF}$ ... condition

For ... keV

Ar^+ ions) $dT/d\nu > 0$

If you were an accelerator physicist you would call this: "Negative Mass Instability"

(And try to avoid it!)

Higher energy ions spend longer in the mirror region. On the way back they speed up the lower energy ions and get slowed by them.

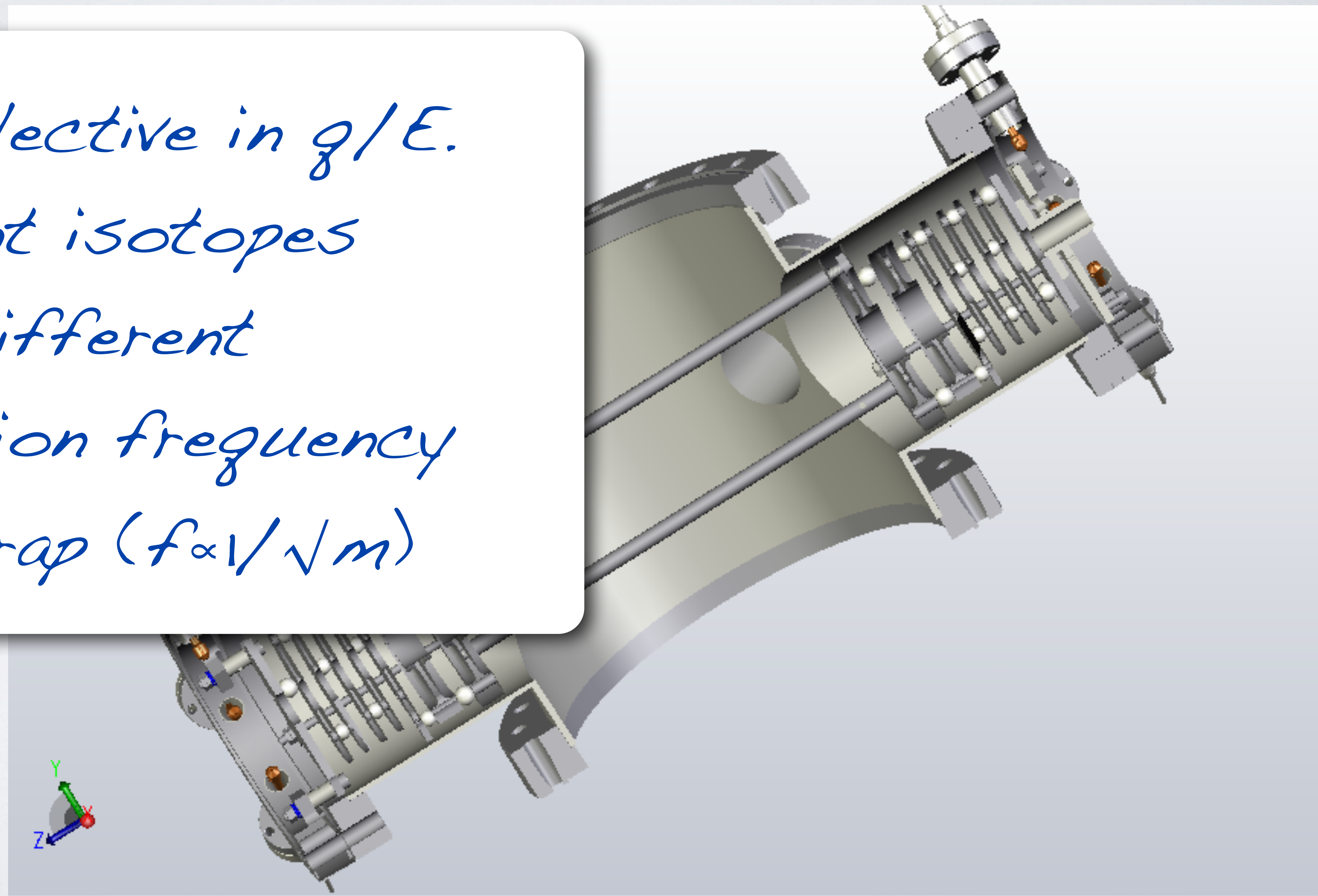
(SOME) POSSIBLE APPLICATIONS

So what is it good for? (1)

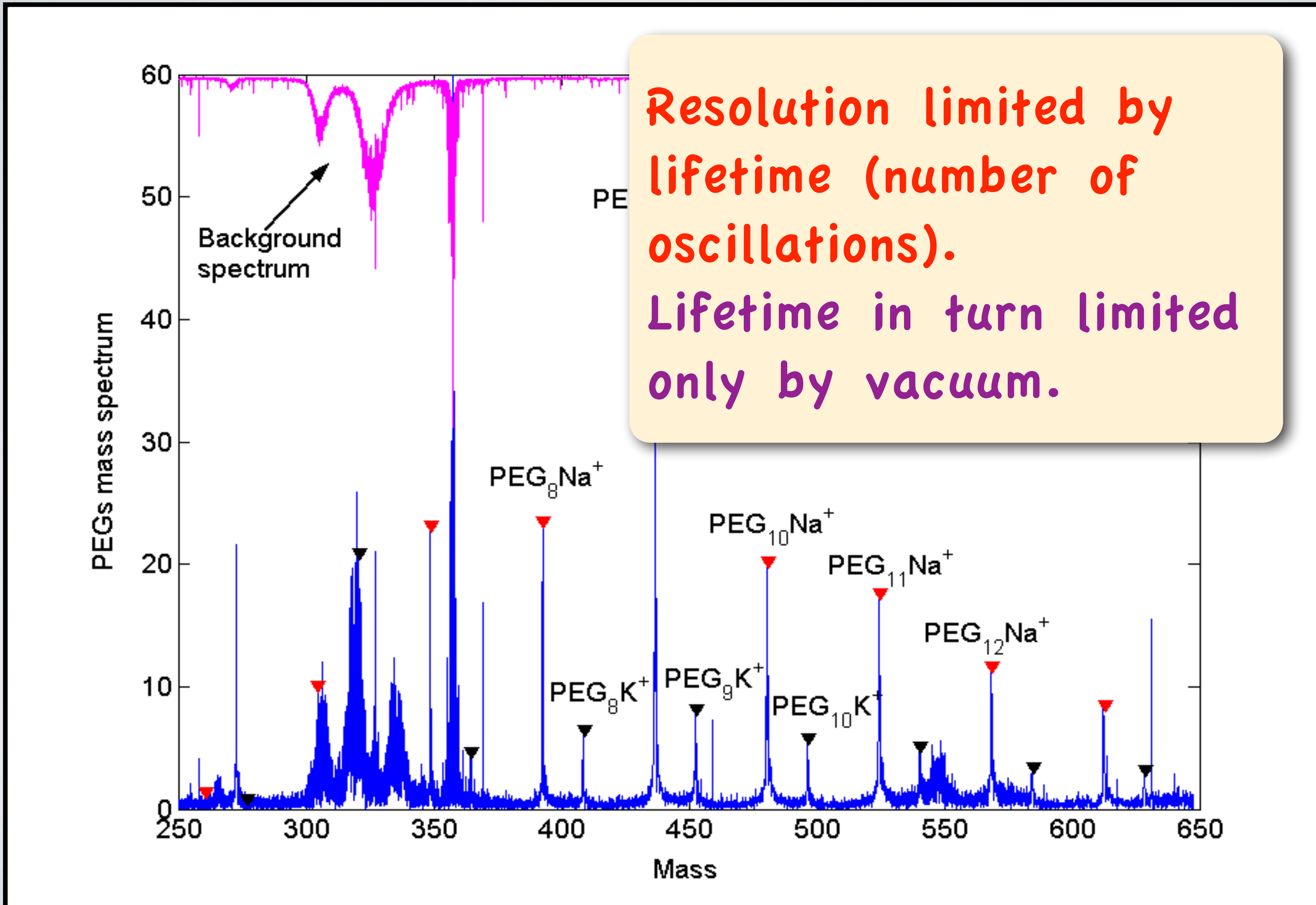
Mass

Spectroscopy

Trap selective in q/E.
Different isotopes
have a different
oscillation frequency
in the trap ($f \propto 1/\sqrt{m}$)



Fourier Transform the pickup charge

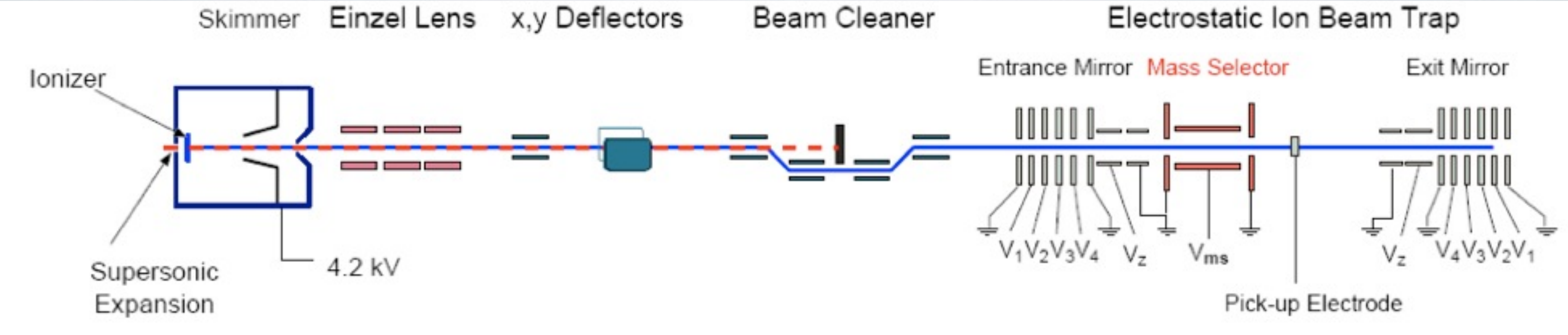


Resolution limited by lifetime (number of oscillations).

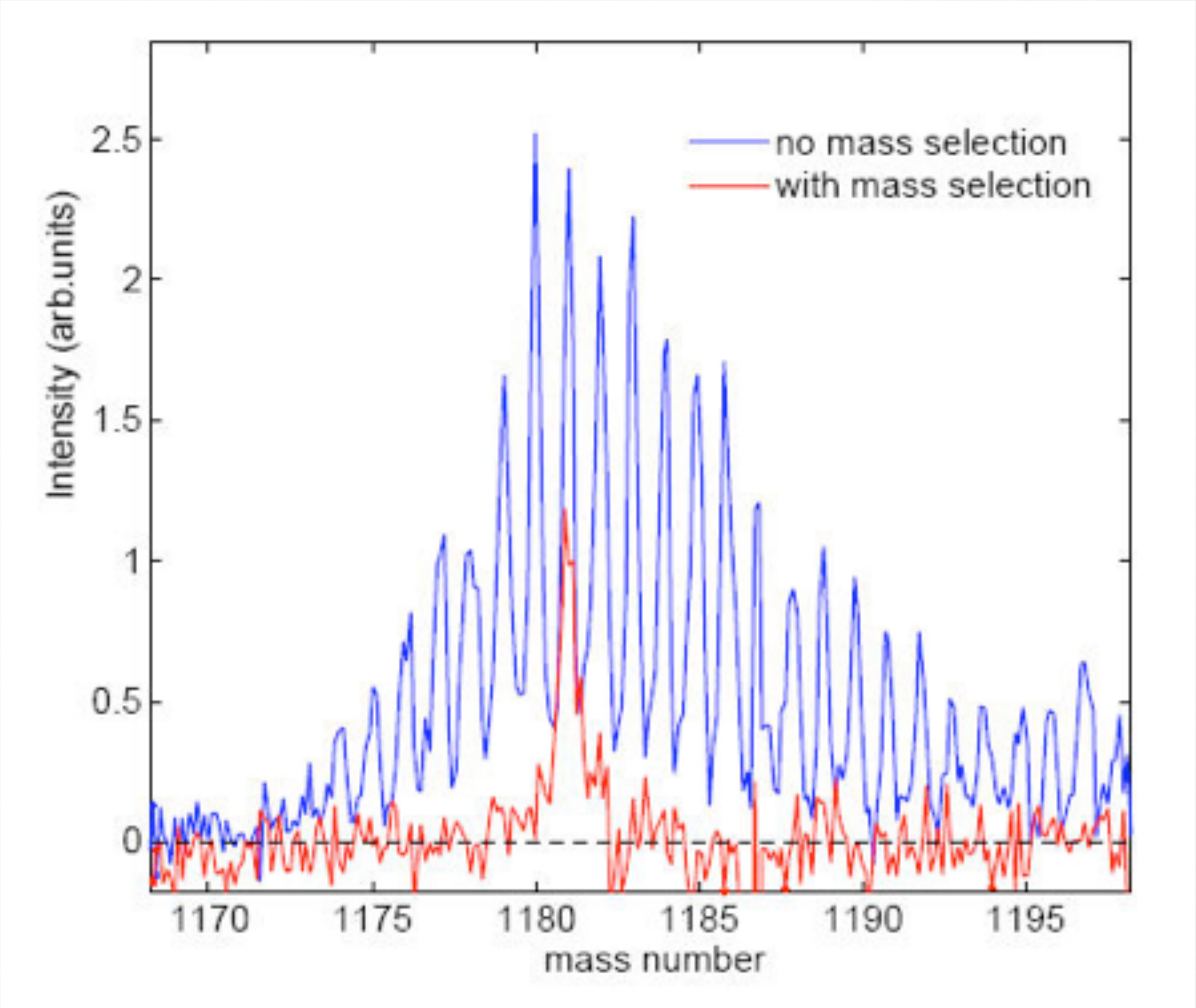
Lifetime in turn limited only by vacuum.

So what is it good for? (2)

Mass Selection



Apply RF pulse at correct frequency to “kick out” bunches with incorrect oscillation frequency.



The β-Decay EIBT Scheme

So what is it good for? (3)

Trap moving ions in Electrostatic Ion Beam Trap.

Simple, cheap setup.

No need for acceleration of products - simple detection scheme.

Kinematic focusing.

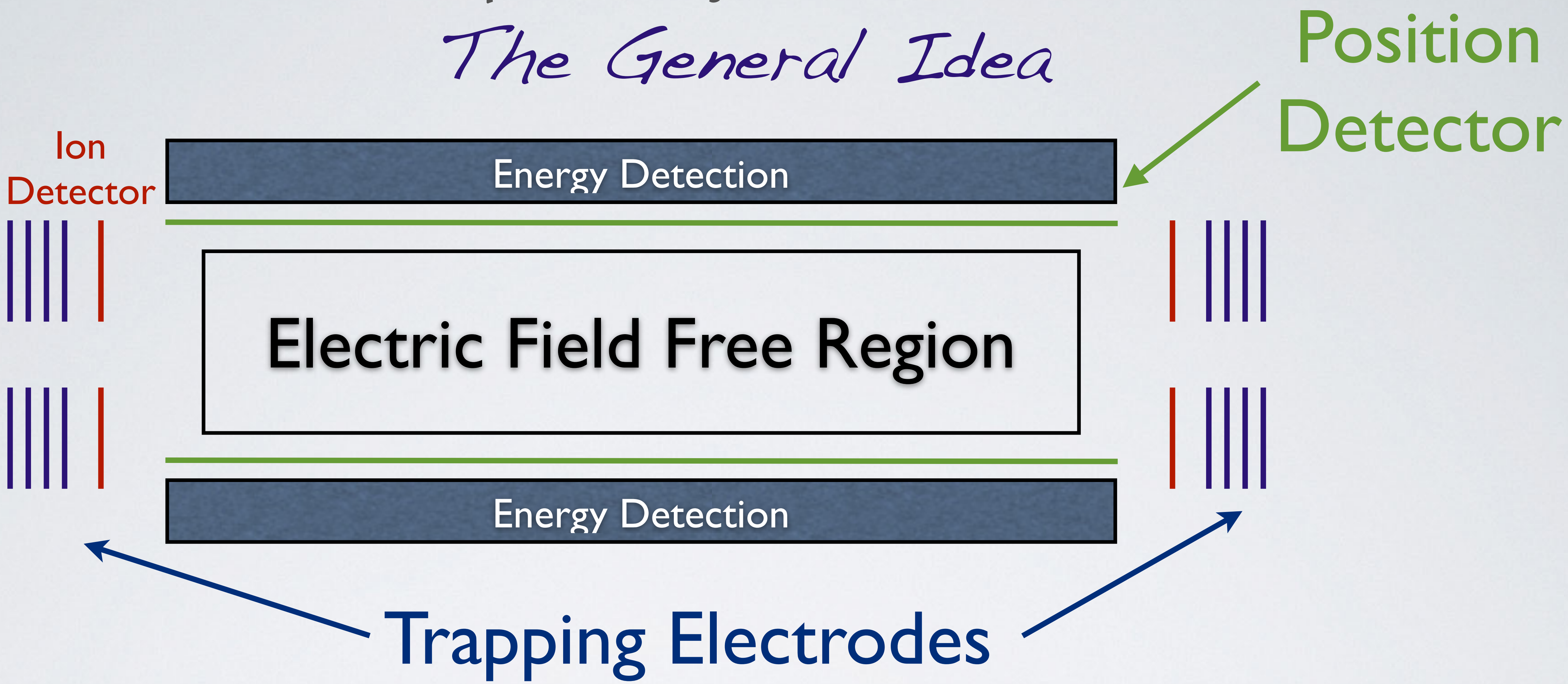
Decay in field free region.

Moving system - position of decay harder to infer.

Large initial spatial extent (bunch).

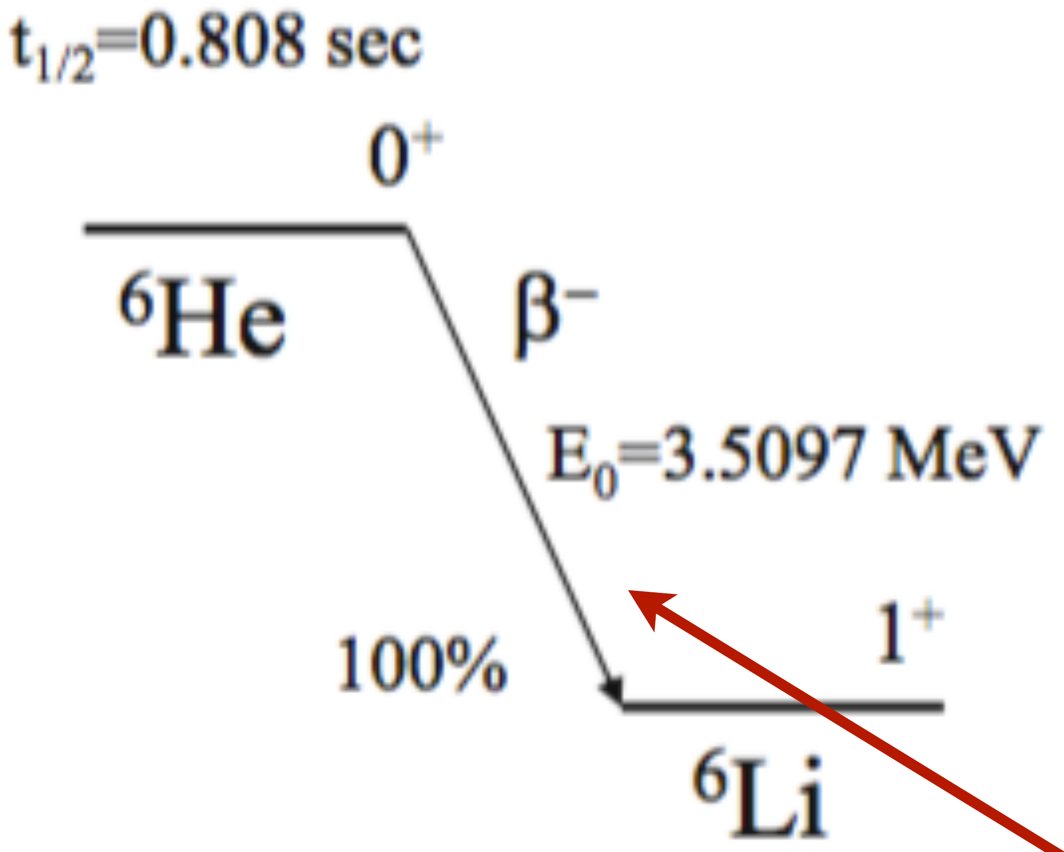
β-Decay Studies

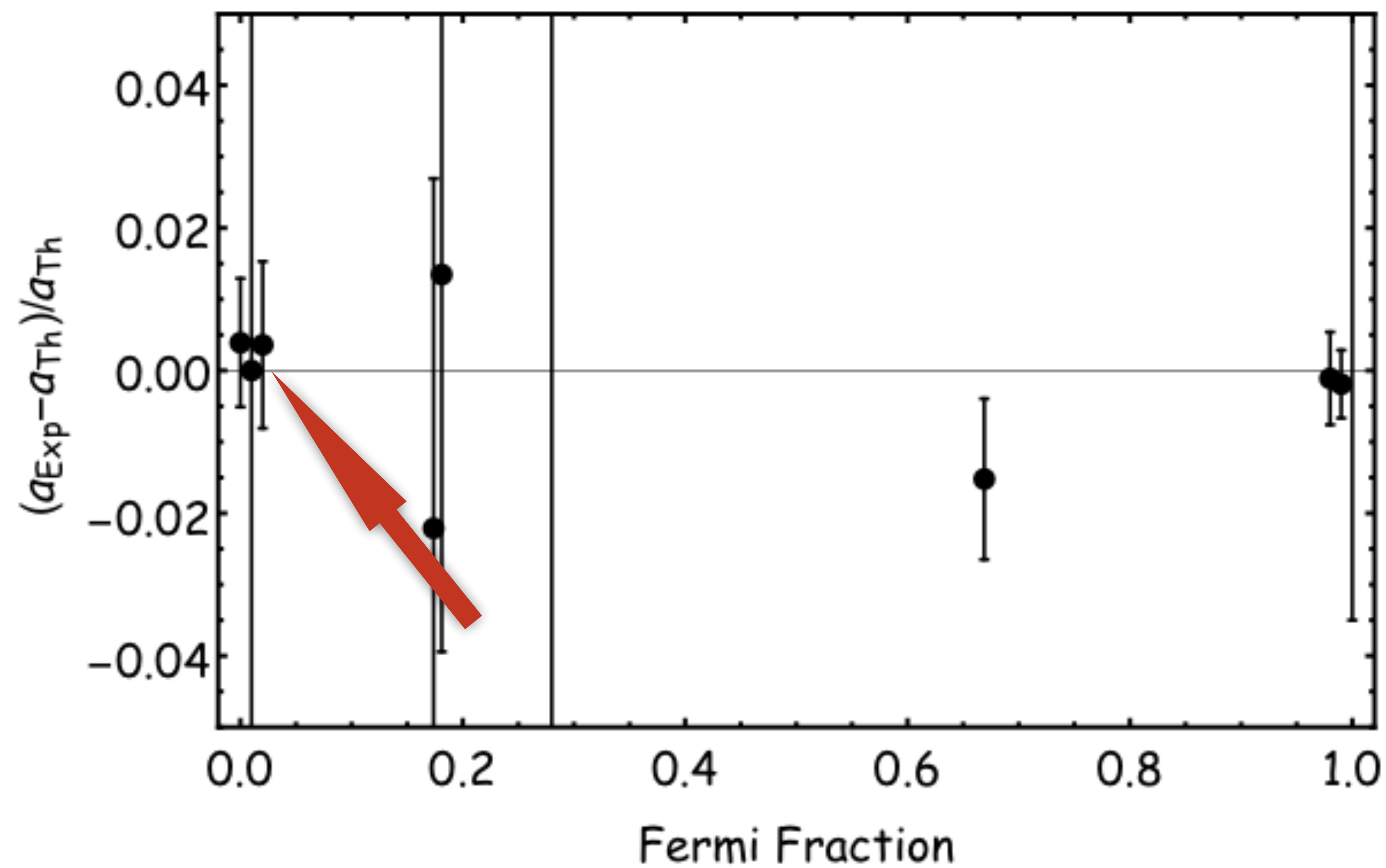
The General Idea



- Recoil ion detected in MCP.
- β detected in position detectors.
- Need bunch position for full reconstruction (multiple scattering of β in detectors).
- Large solid angle + kinematic focussing → detection efficiency > 50%.
- No need for electrostatic acceleration (ions at ~keV). Decay in field free region.

Why ^{6}He?





Best experimental limit:

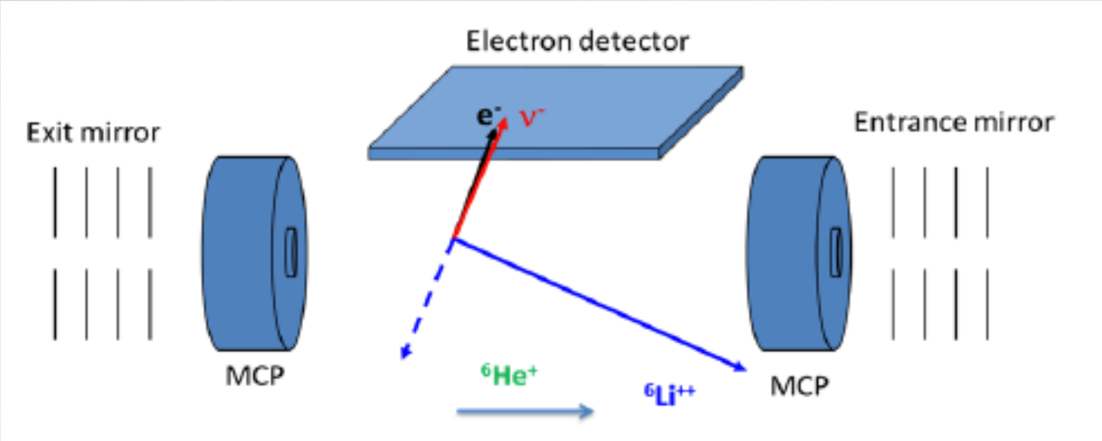
$a = - 0.3343 \pm 0.0030$

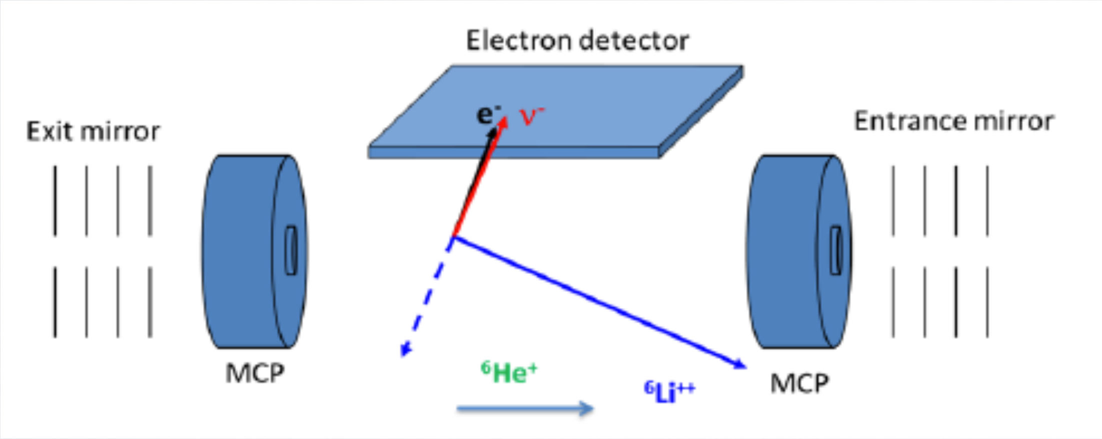
$$\frac{|C_T|^2 + |C_T'|^2}{|C_A|^2 + |C_A'|^2} \leq 0.4\%$$

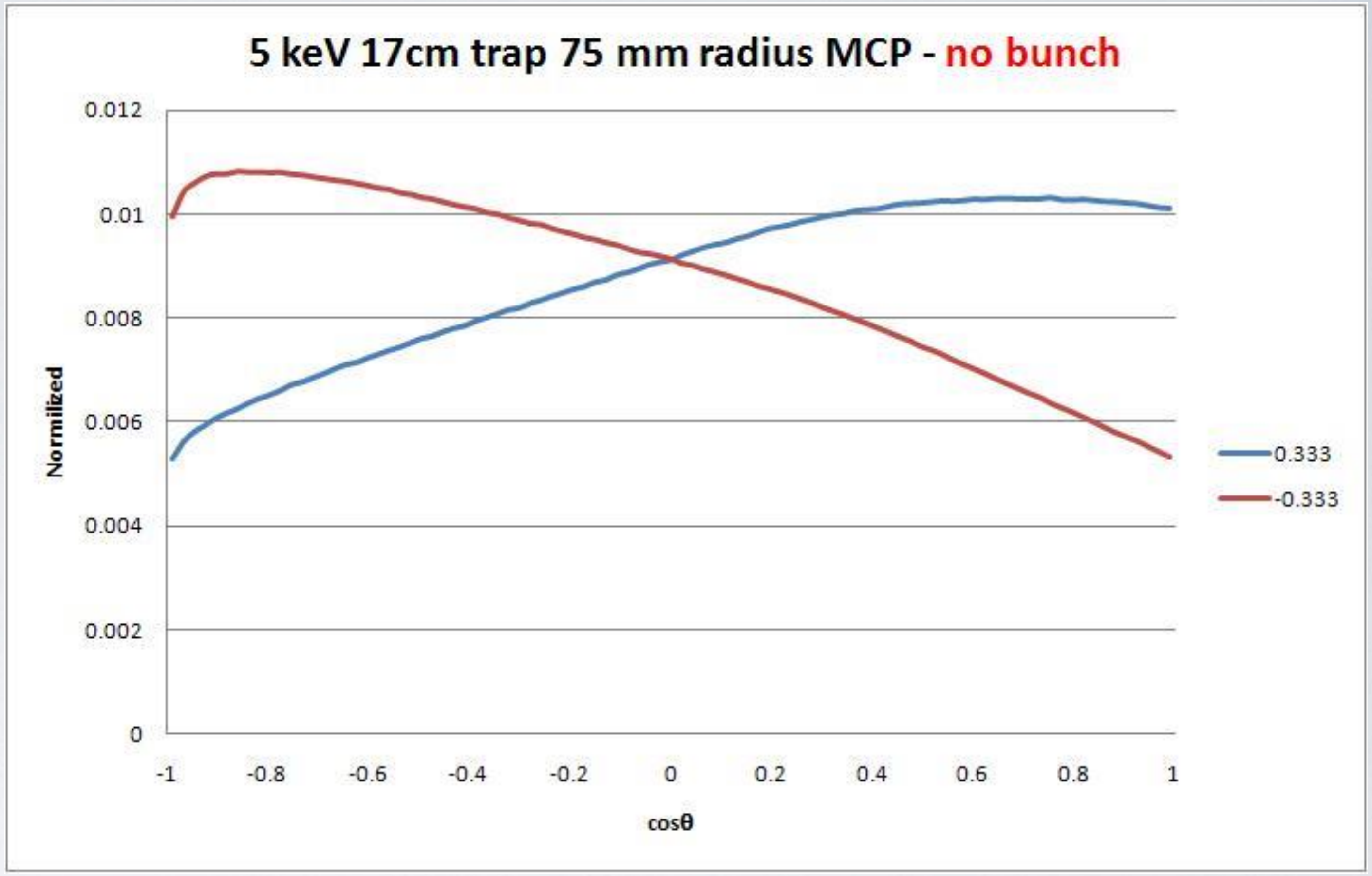
Johnson et al., Phys. Rev. (1963)

Pure GT Decay

Recoil order corrections well under control







1e6 events gives 0.6% stat. uncertainty

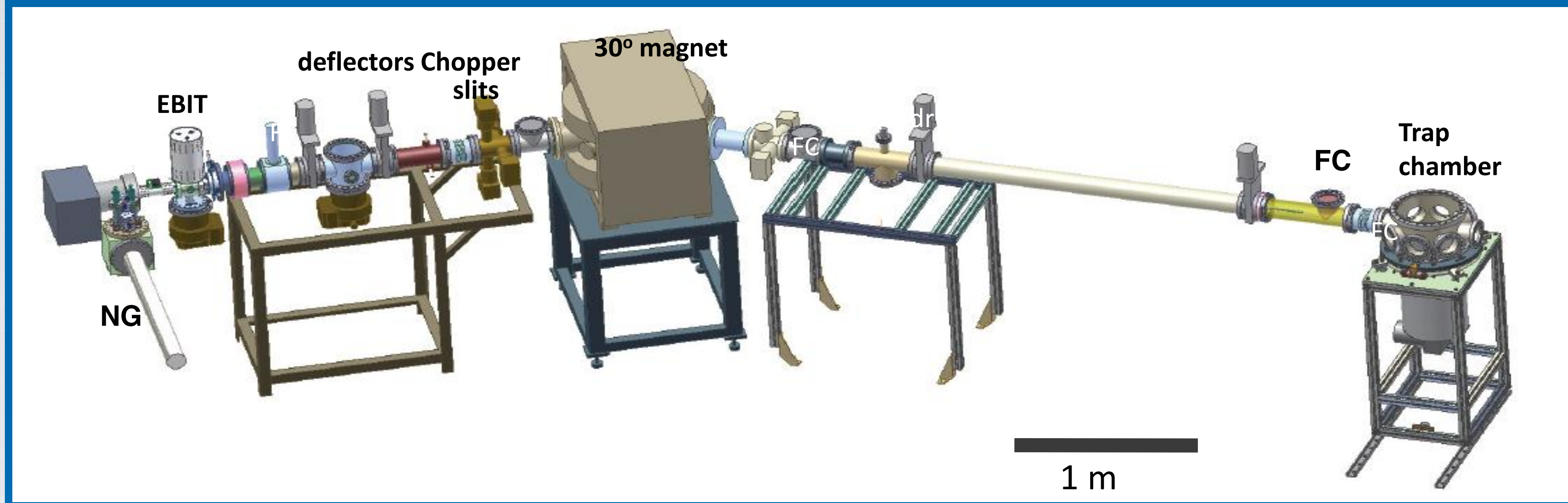
- Recoil ion detected in MCP.
- β detected in position detectors.
- Need bunch position for full reconstruction (multiple scattering of β in detectors).
- Large solid angle + kinematic focussing → detection efficiency > 50%.
- No need for electrostatic acceleration (ions at ~keV). Decay in field free region.

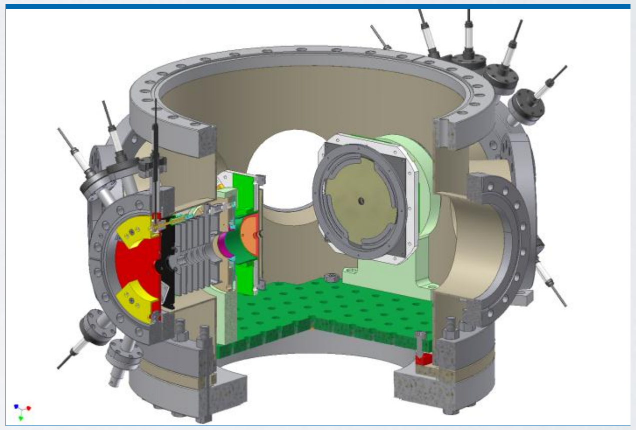
Where are we now @ WI/HUJI?

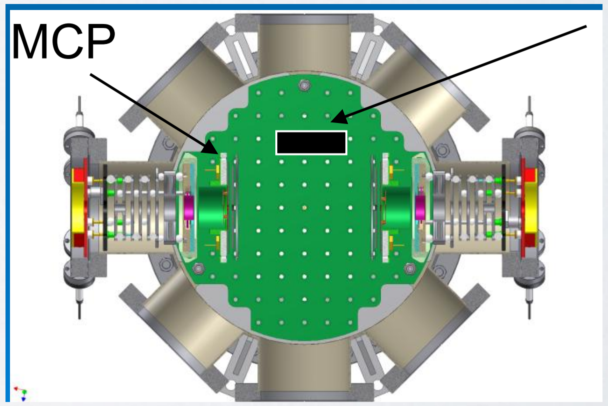
WIRED

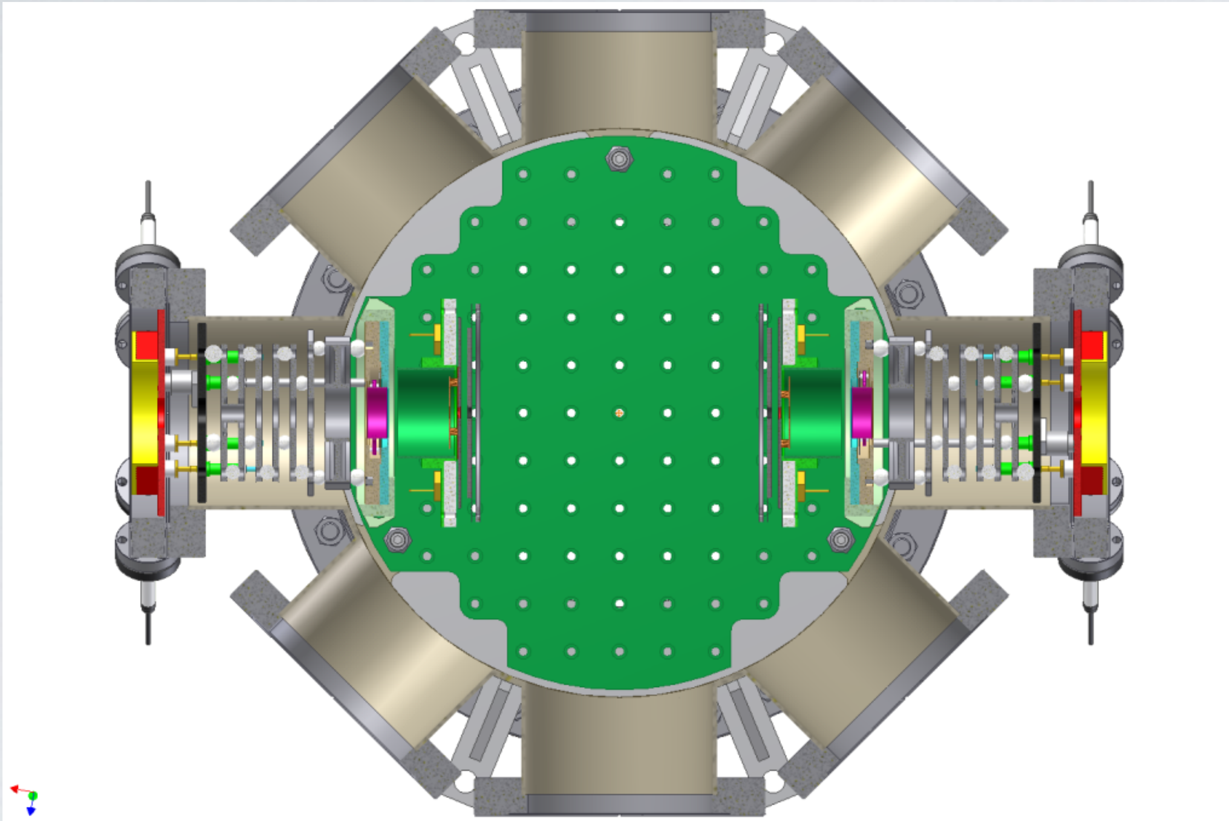
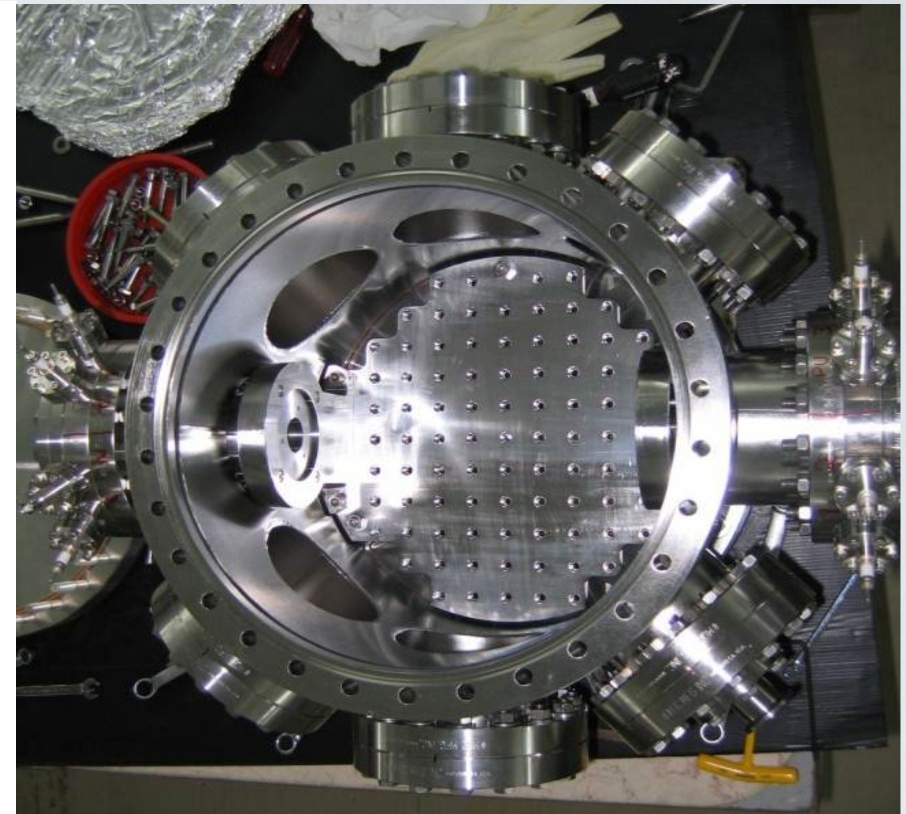
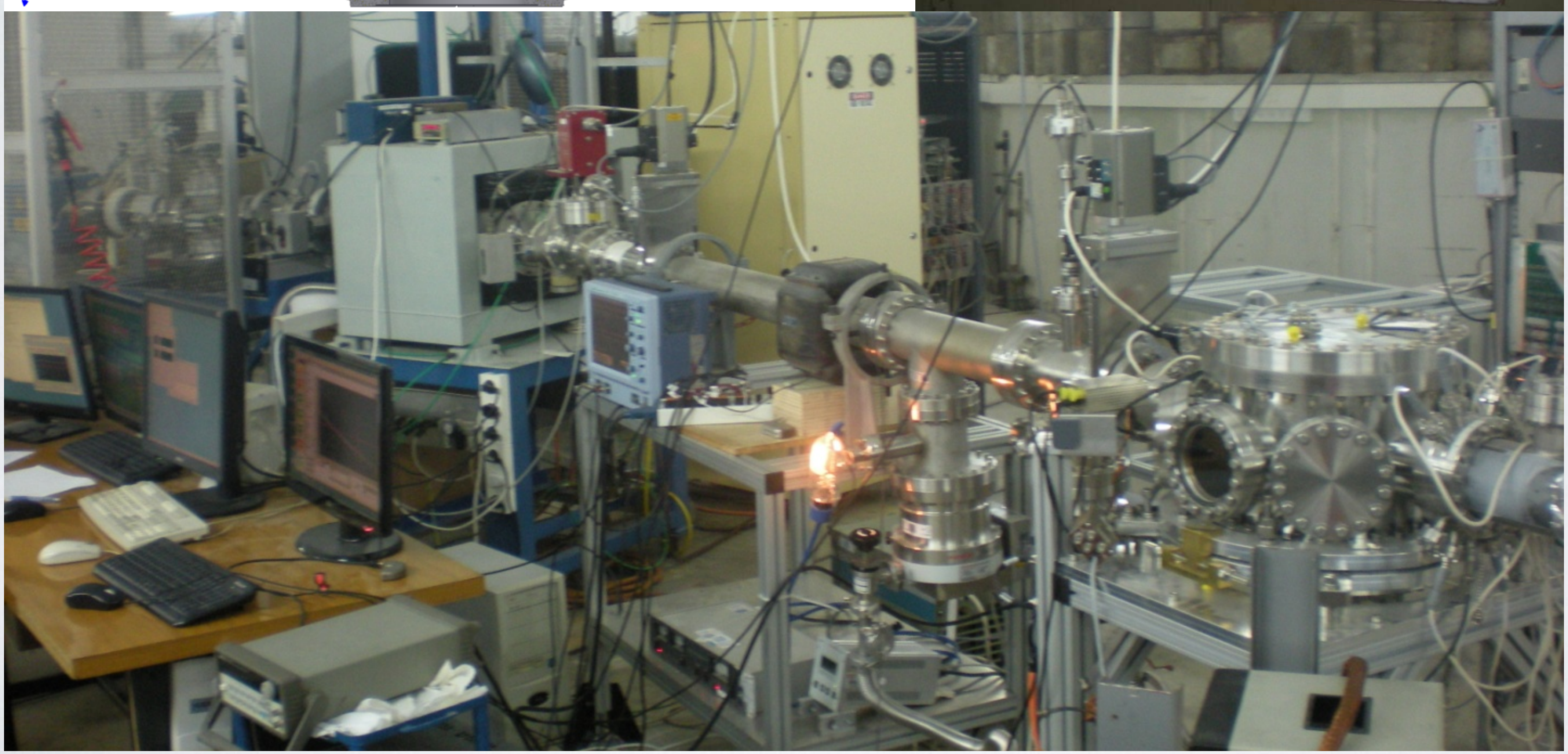
Weizmann Institute Radioactive Electrostatic Device

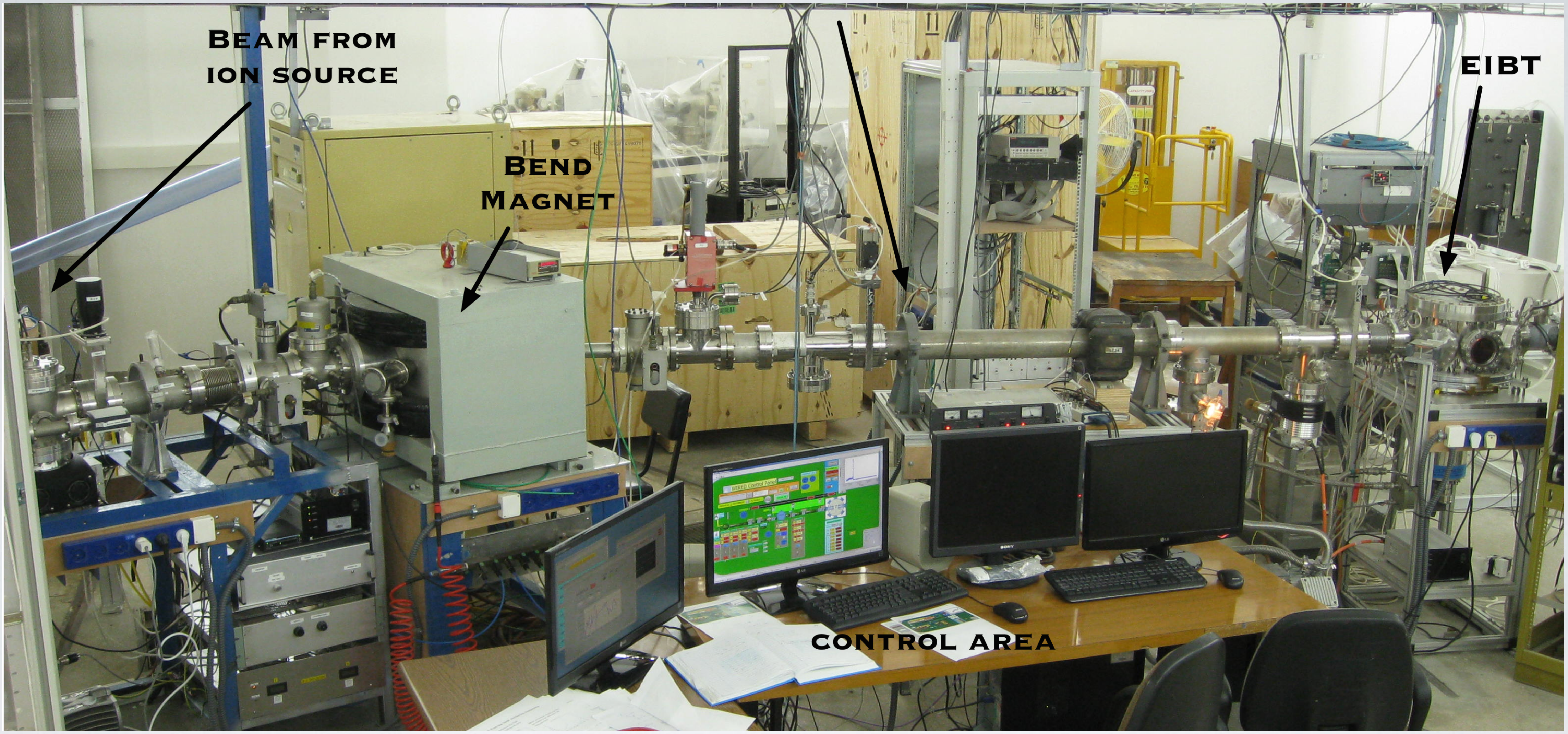
Experimental scheme

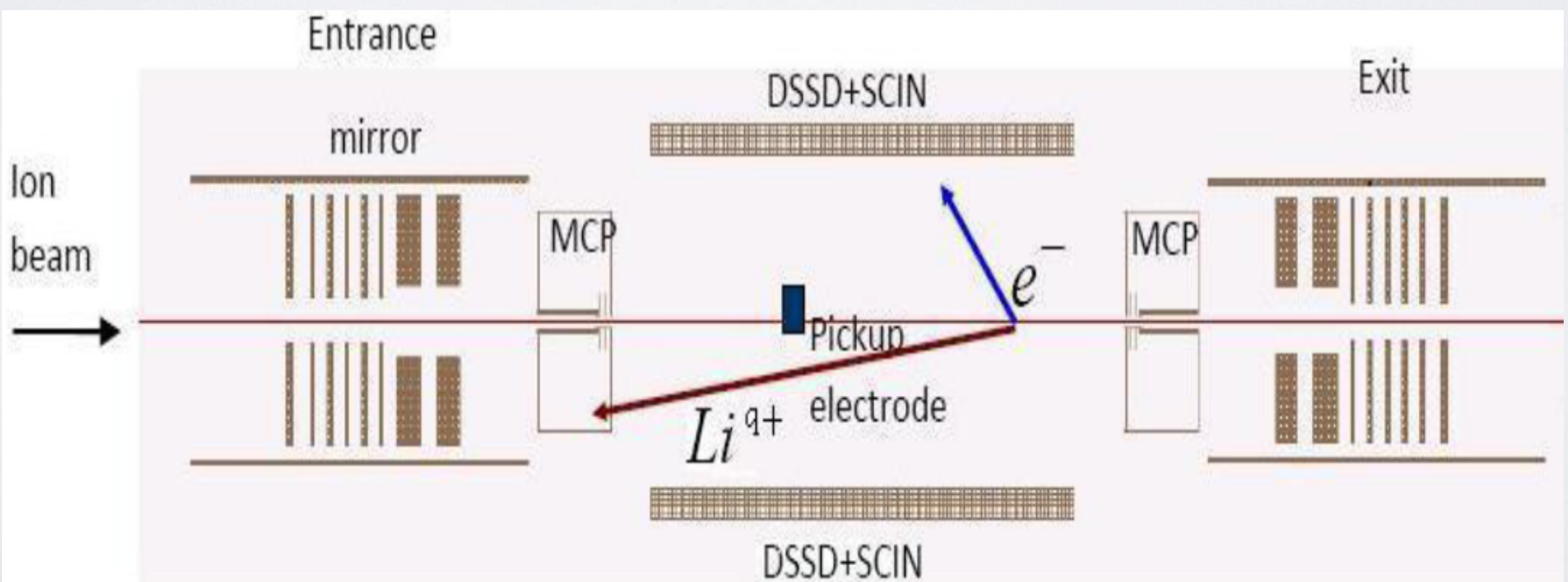




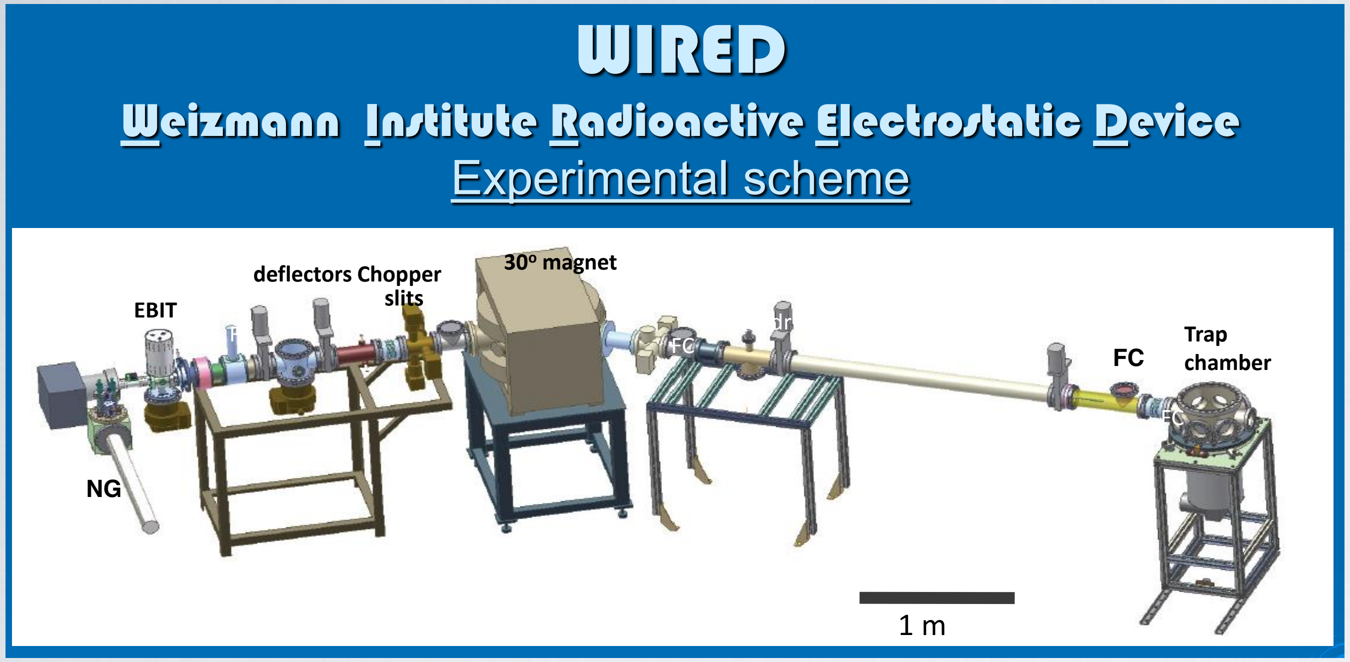



Beam from
ion source
Bend
Magnet
EIBT
control area


Entrance
Exit
DSSD+SCIN
mirror
Ion
beam
MCP
MCP
Pickup
electrode
e^-
Li^{q+}
DSSD+SCIN

Trap

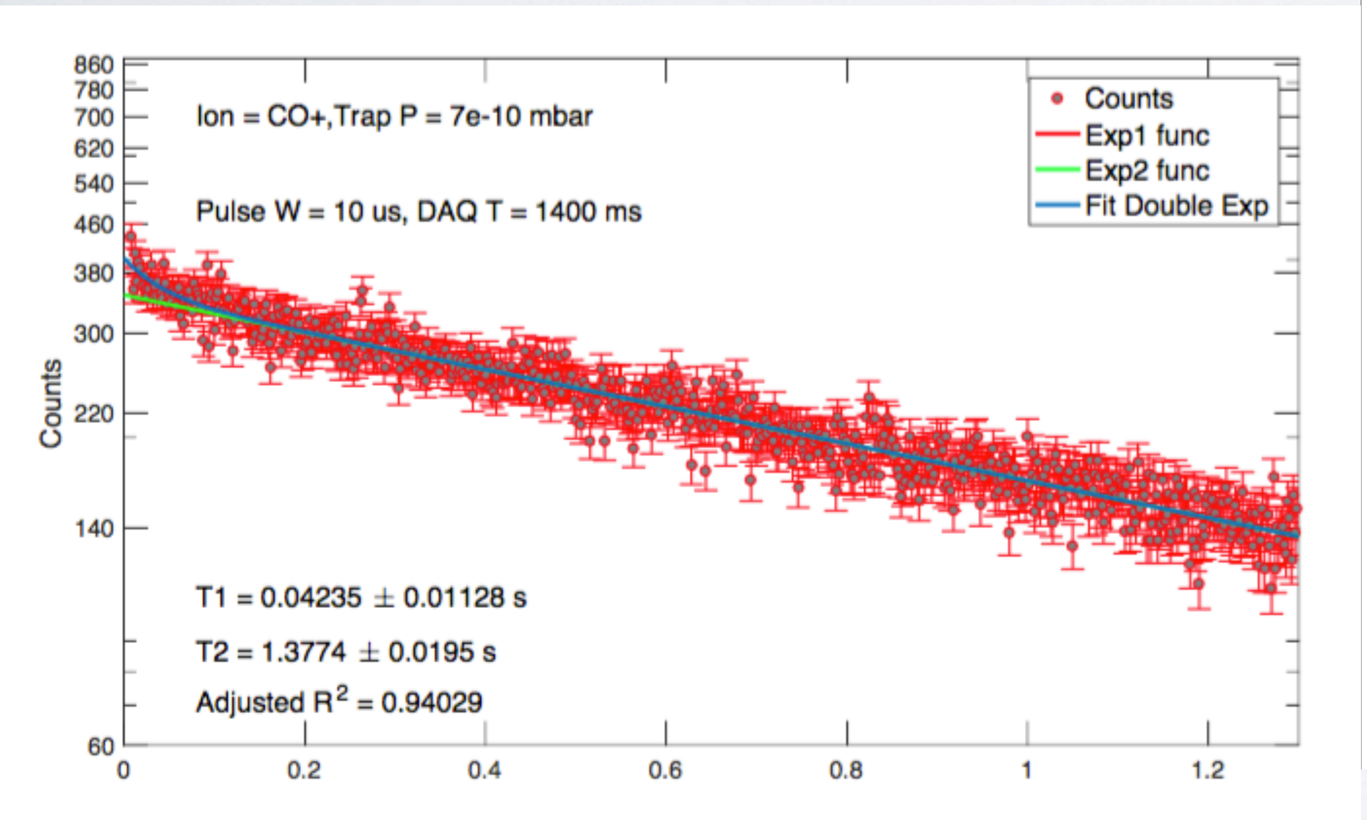


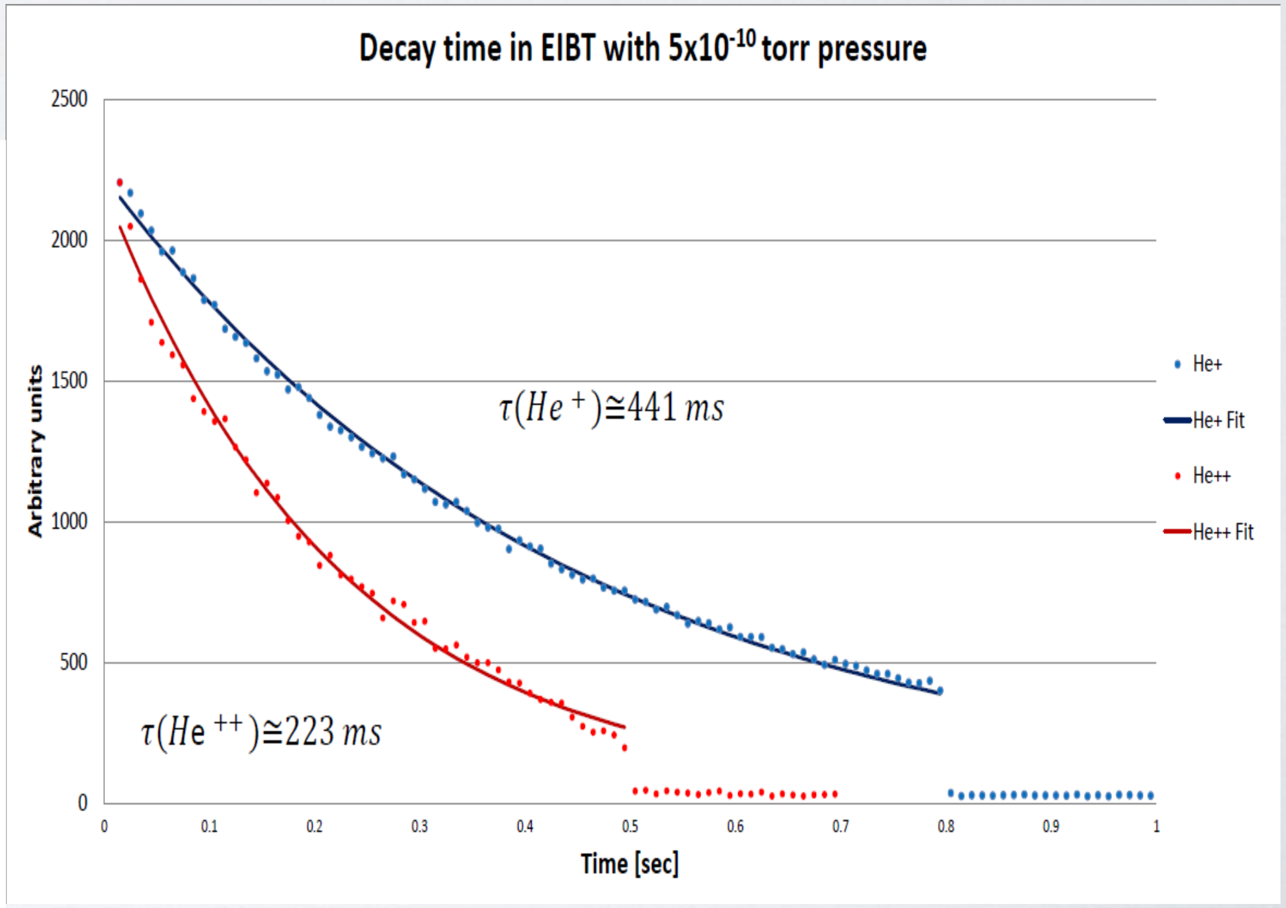
Stable isotopes trapped

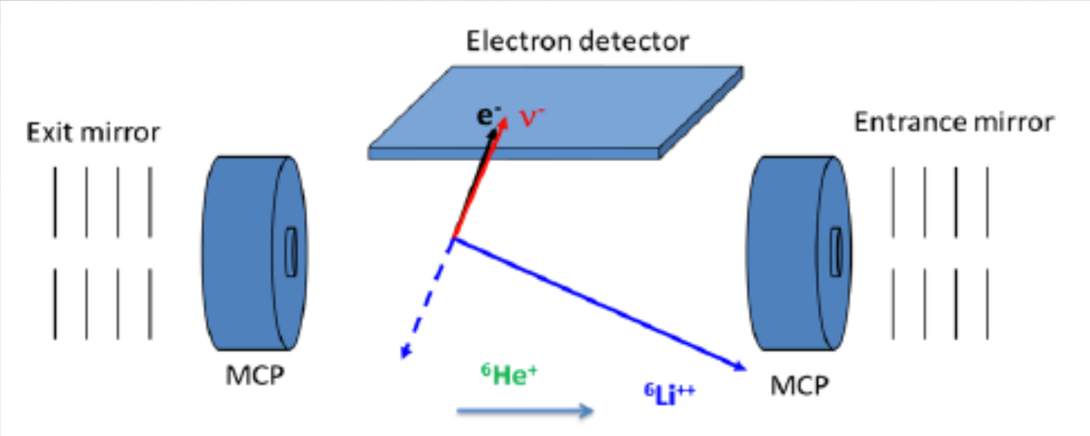
Detectors:

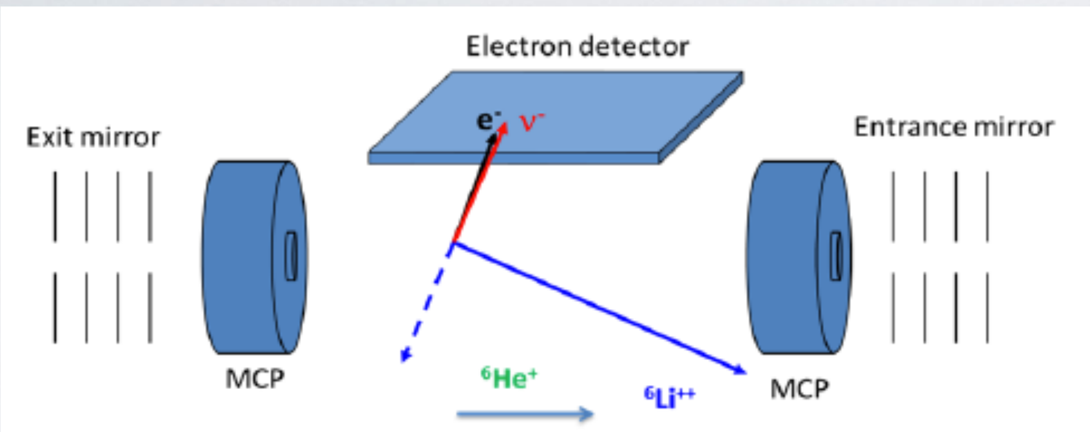
- MCP's
- Plastic Scintillator with multiple photomultipliers

Electronics - ADC, TDC,...

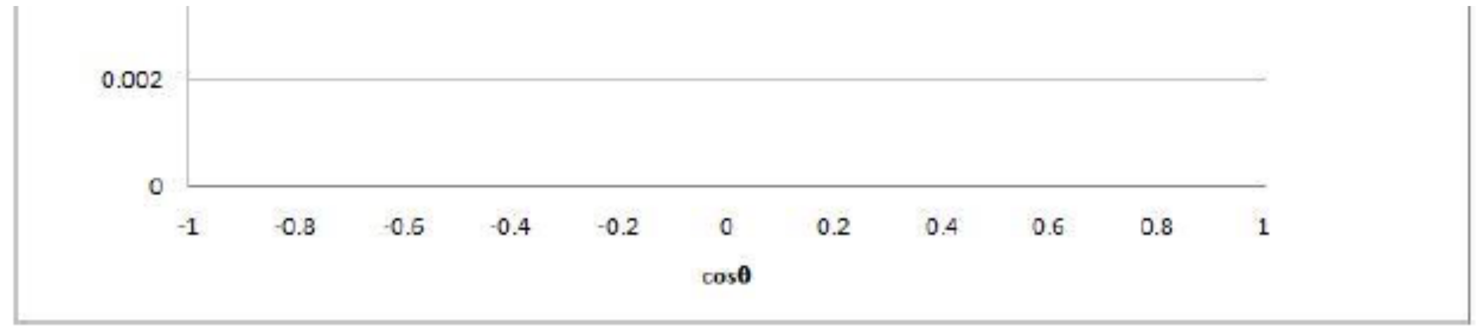








Source	Uncertainty	$\Delta a_{\beta\nu}$ ($\times 10^{-3}$)
LAPS Energy	5 %	0.86
LAPS Position	5 mm	0.71
MCP Position	1 mm	0.22
^{6}Li TOF	5 ns	0.23
Bunch size	1 cm	1.38
Total		1.80



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Neon Isotope Production

^{17}Ne:

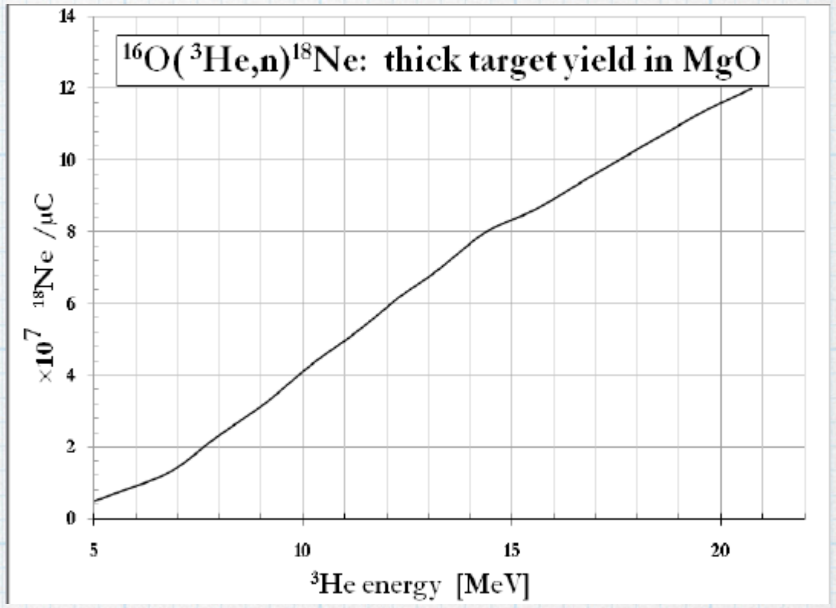
^{16}O + ^{3}He → ^{17}Ne + 2n - 26.7 MeV Thershold
^{19}F + p → ^{17}Ne + 3n - 36.6 MeV Threshold (LiF Target)
^{20}Ne + ^{3}He → ^{17}Ne + ^{6}He - 27 MeV Threshold

^{18}Ne: Explored as a possible source for β beams

^{19}F + p → ^{18}Ne + 2n

- 13 MeV Protons of LiF target, 3×10^{-5}/p (*Takayama (2009)*)

^{16}O + ^{3}He → ^{18}Ne + n - 3.2 MeV threshold
^{20}Ne + p → ^{18}Ne + t - 20 MeV threshold

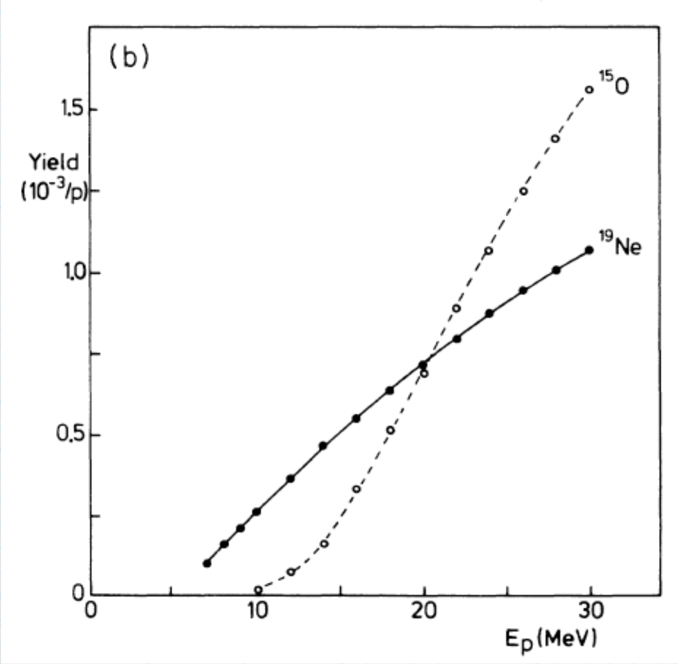


^{19}Ne:

^{20}Ne + n → ^{19}Ne + 2n - 16.8 MeV threshold
^{20}Ne + p → ^{19}Ne + d - 15 MeV Threshold
^{19}F + p → ^{19}Ne + n

- 4 MeV Threshold
- (10^{-3}/p for thick LiF, *Kitwanga et. al (1990)*).

^{19}F + ^{3}He → ^{19}Ne + t - 3.2 MeV Threshold

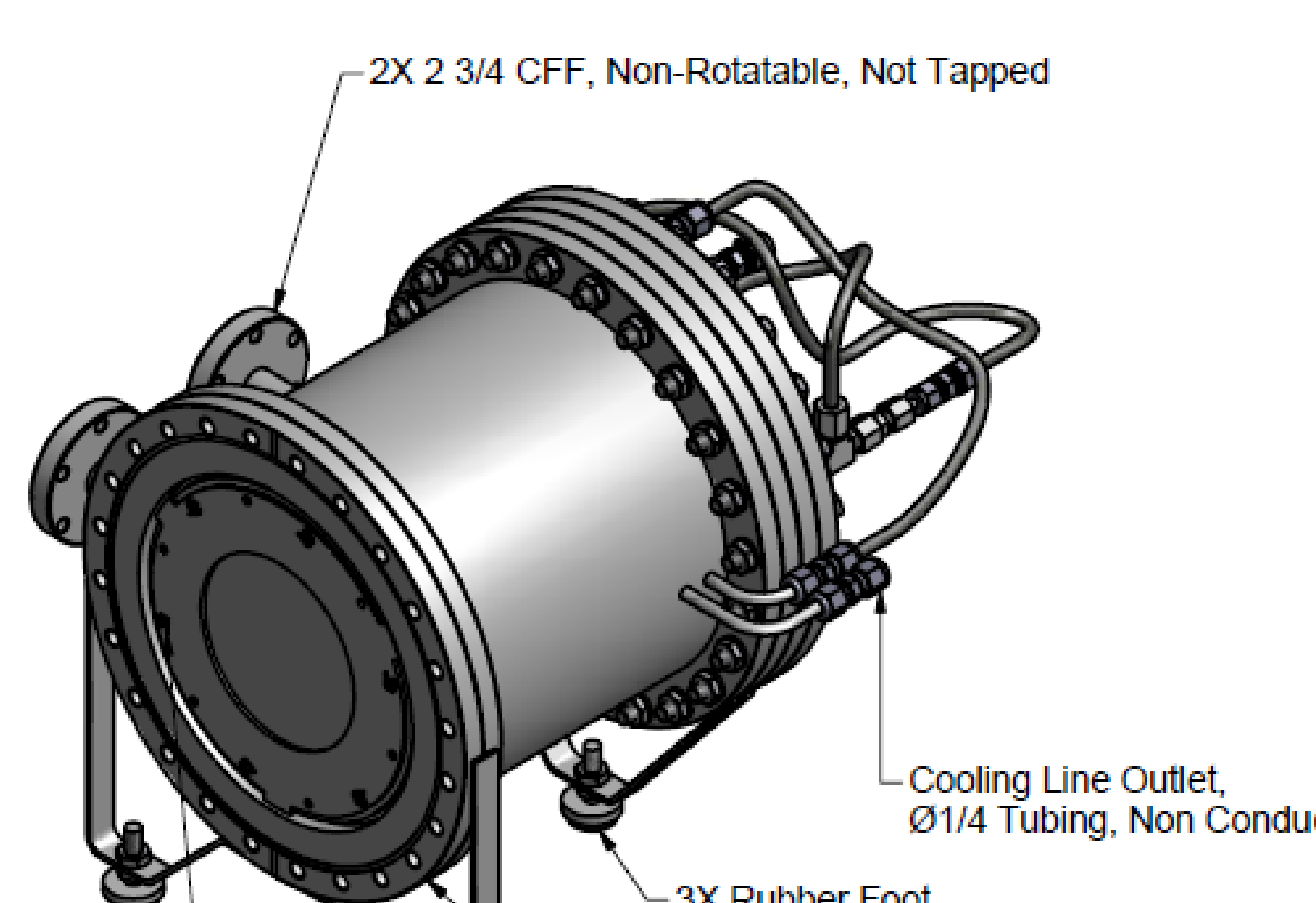


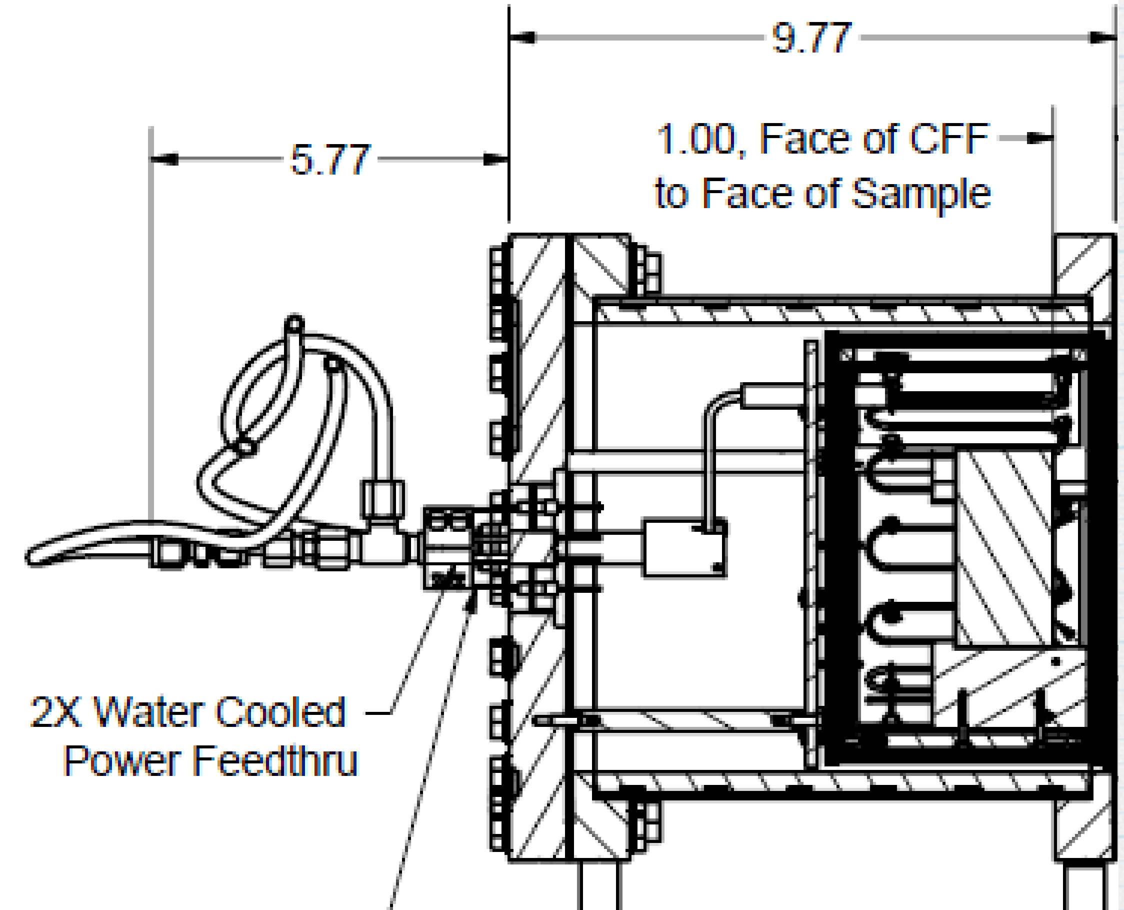
^{23}Ne:

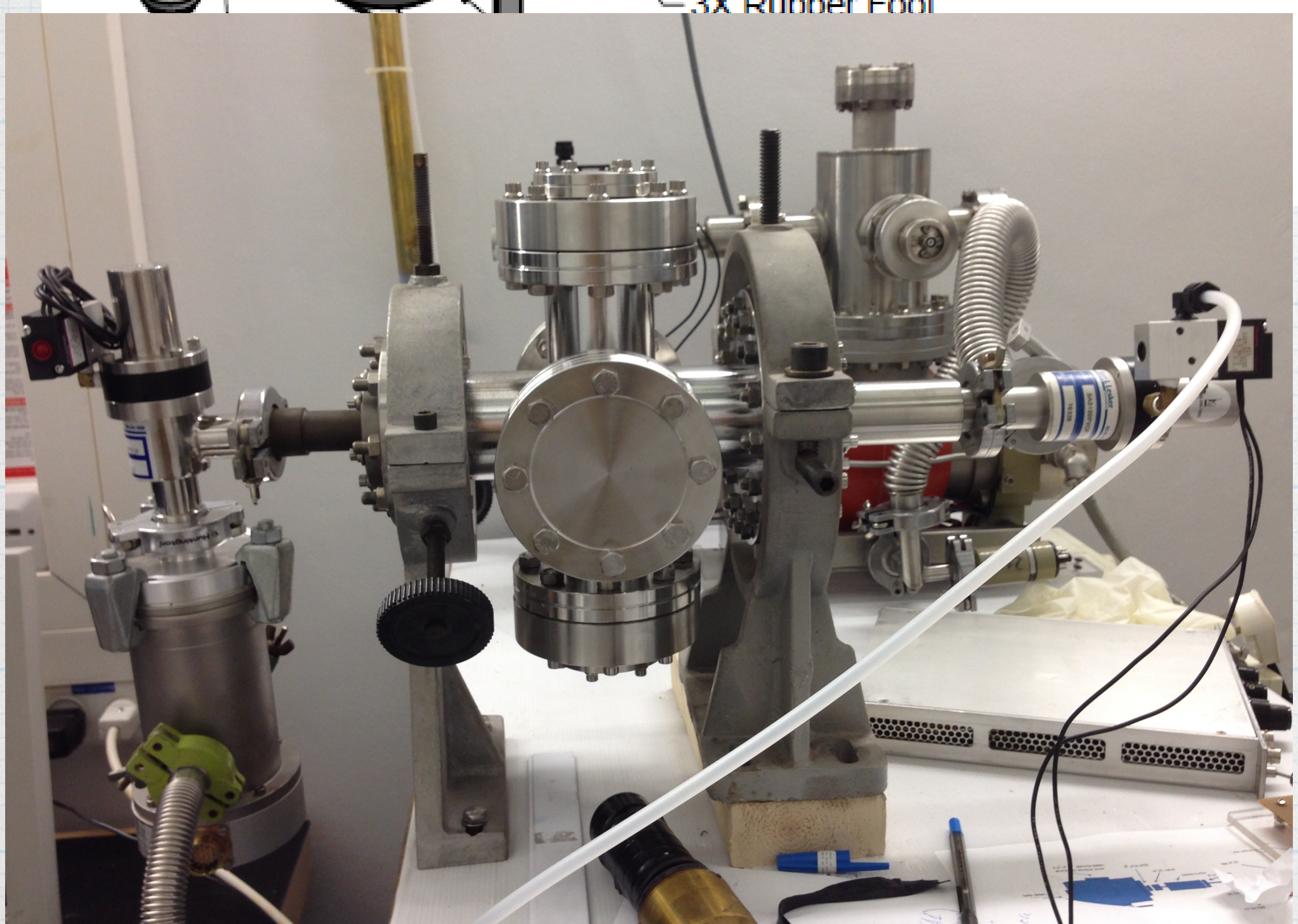
^{23}Na + n → ^{23}Ne + p - 3.7 MeV threshold (neutron production target).
^{26}Mg + n → ^{23}Ne + alpha - 5.6 MeV threshold (neutron production target).

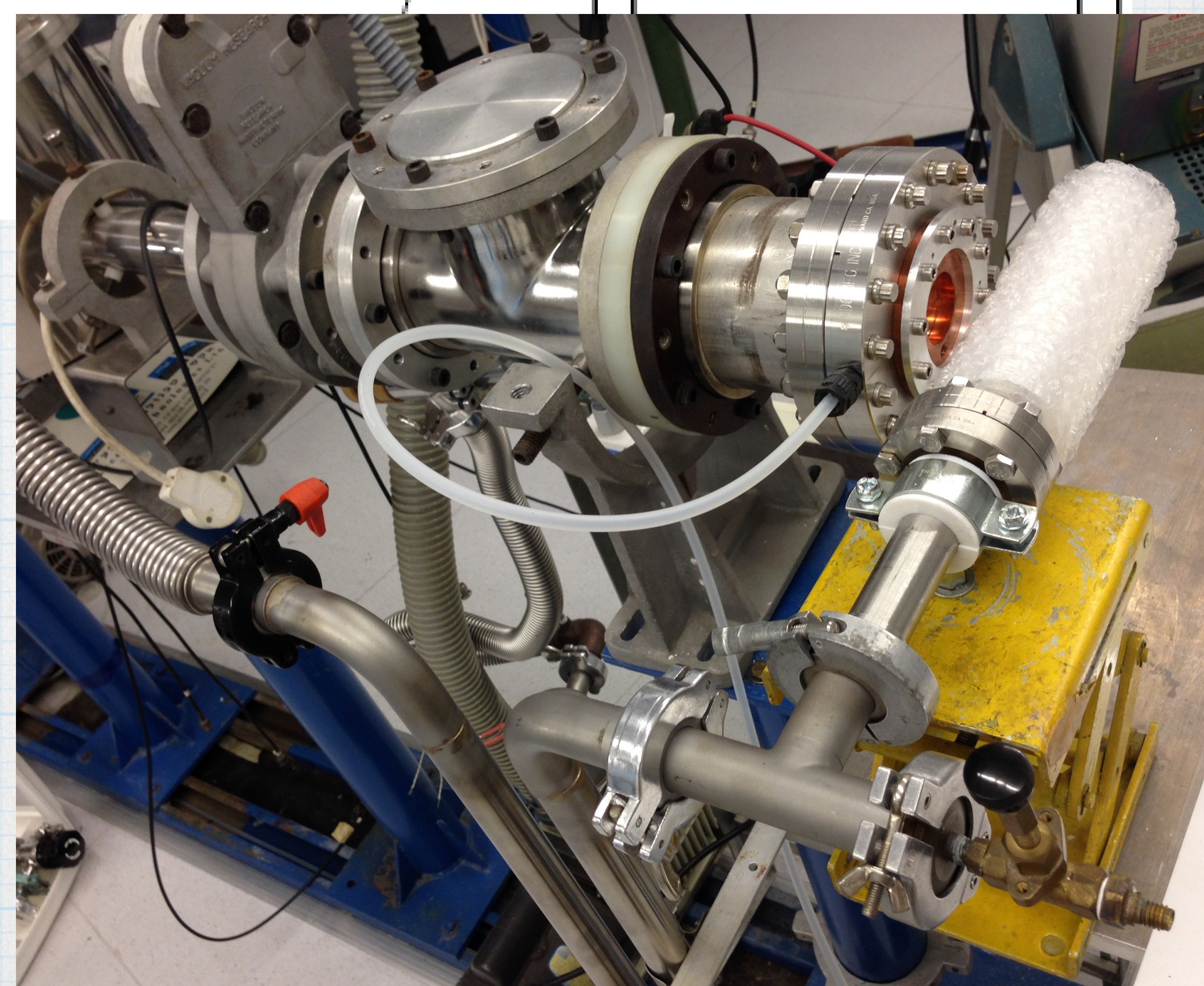
^{24}Ne:

^{26}Mg + n → ^{23}Ne + ^{3}He - 18 MeV threshold (neutron production target).

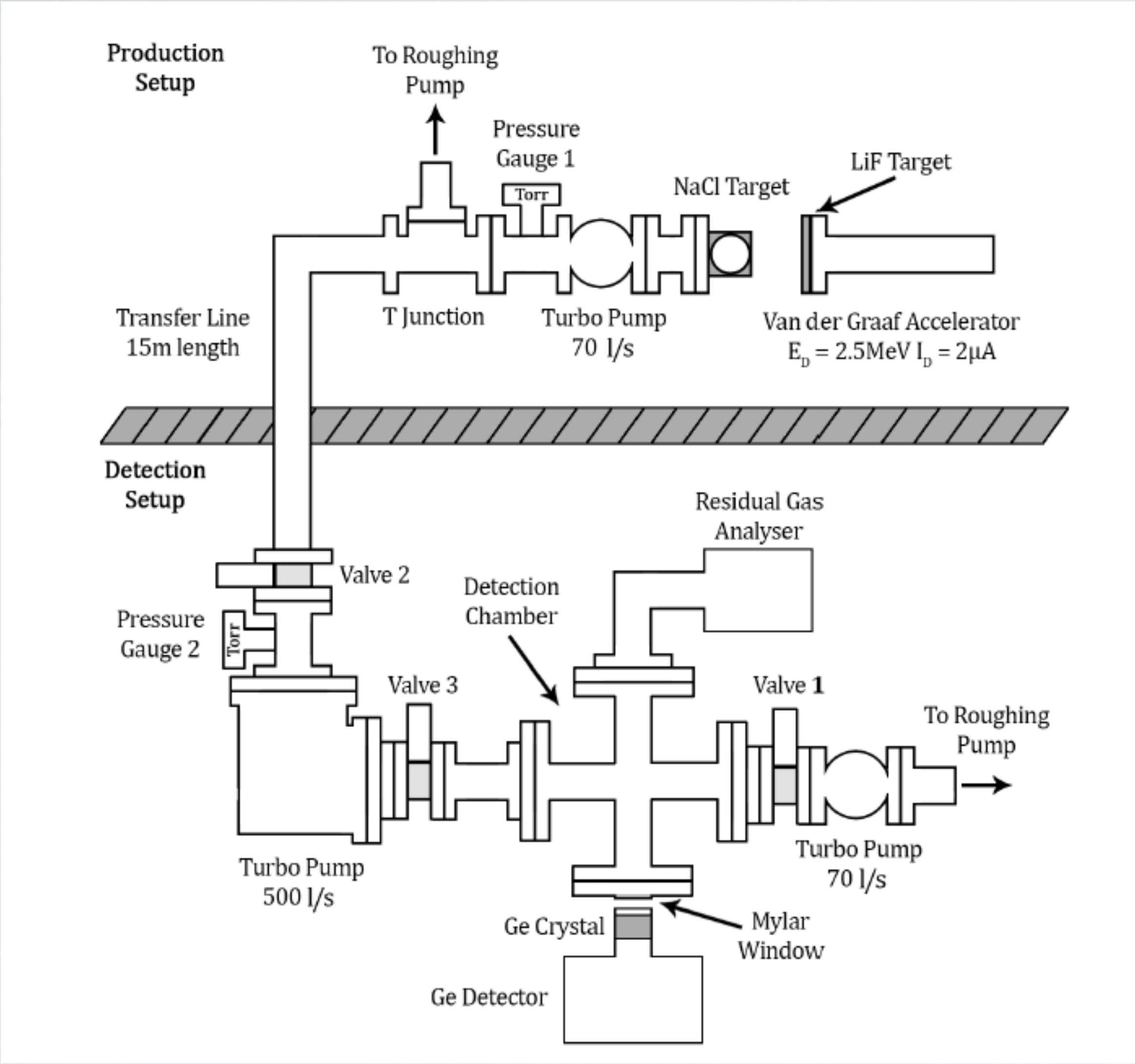

2X 2 3/4 CFF, Non-Rotatable, Not Tapped
Cooling Line Outlet,
Ø1/4 Tubing, Non Conduc
3X Rubber Foot

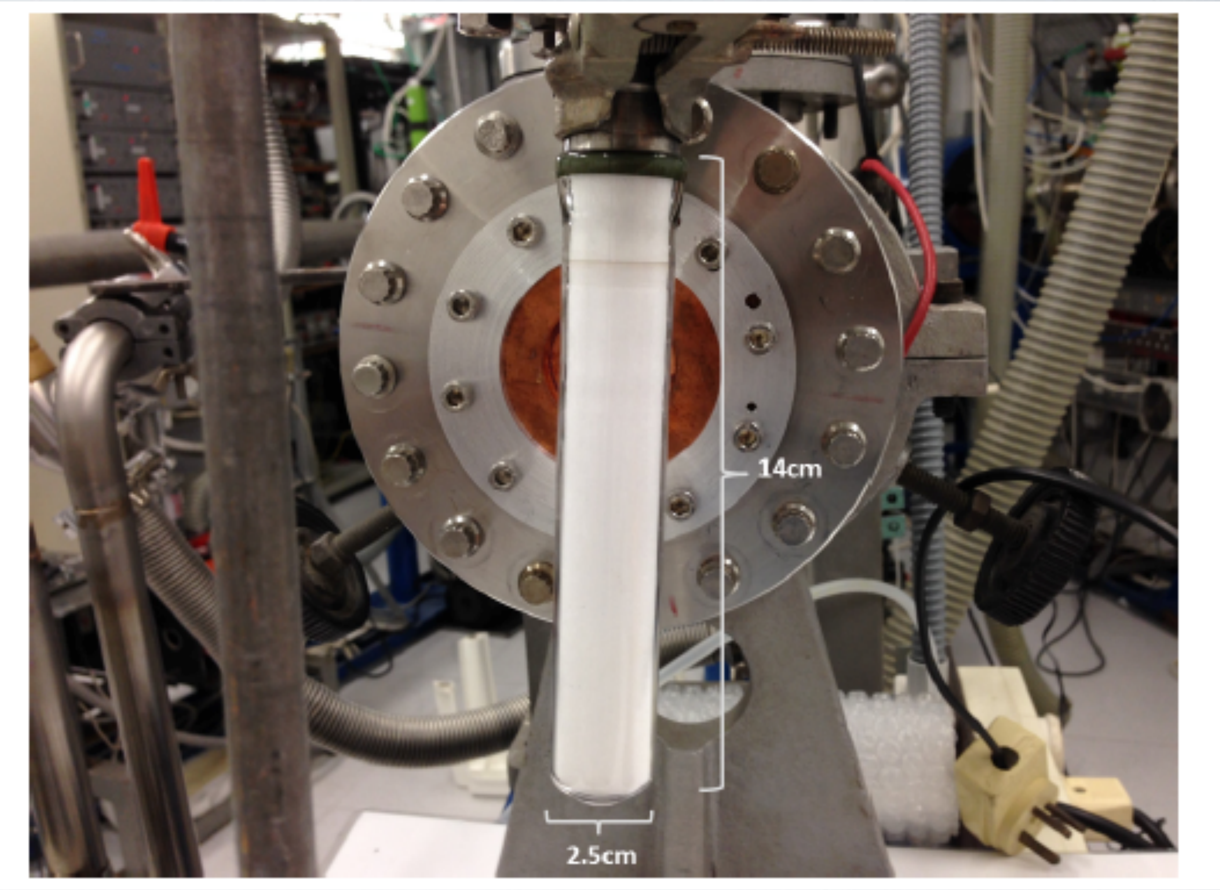

9.77
5.77
1.00, Face of CFF
to Face of Sample
2X Water Cooled
Power Feedthru

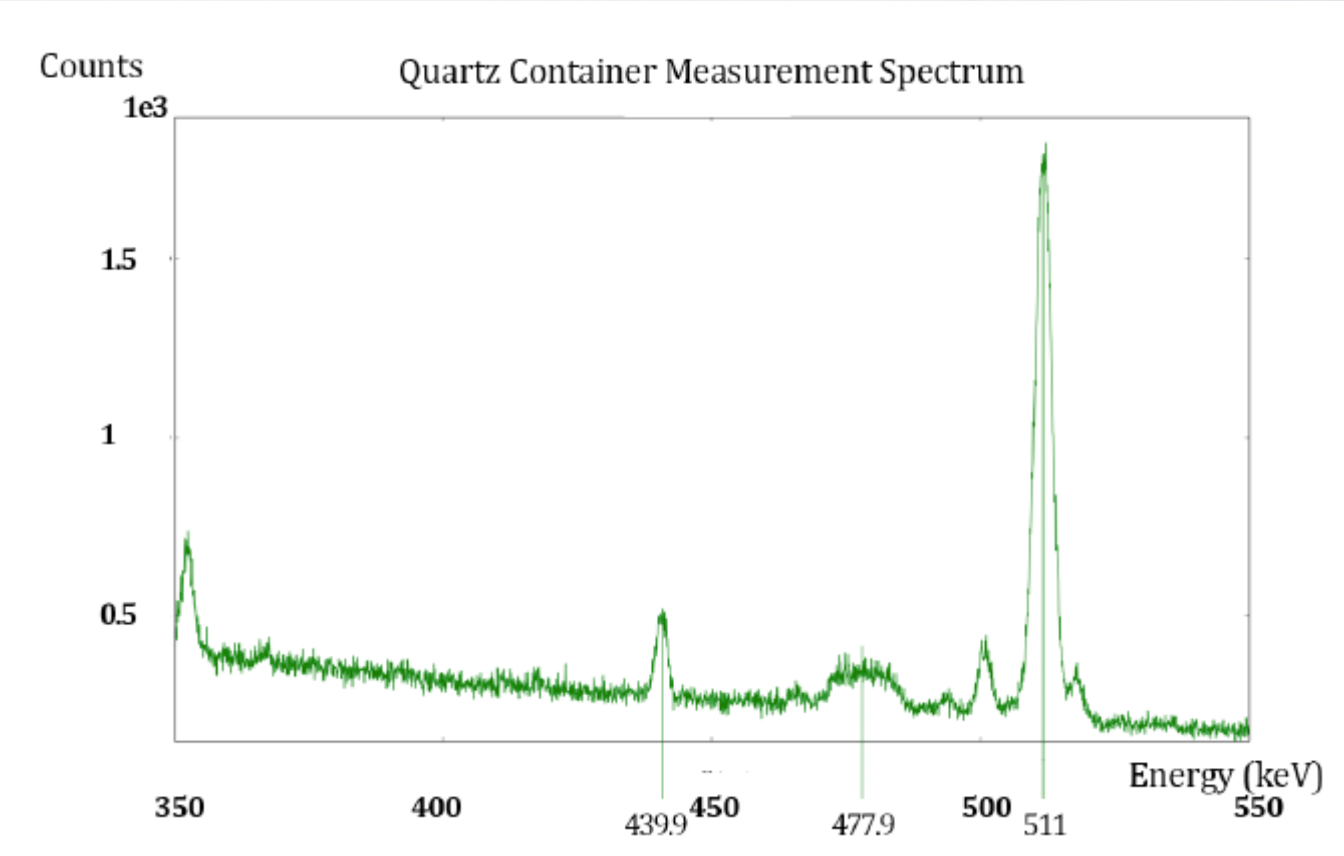




Production Tests – ^{23}Ne







^{23}Ne production and transport demonstrated.

Currently replacing heating element to increase yield.

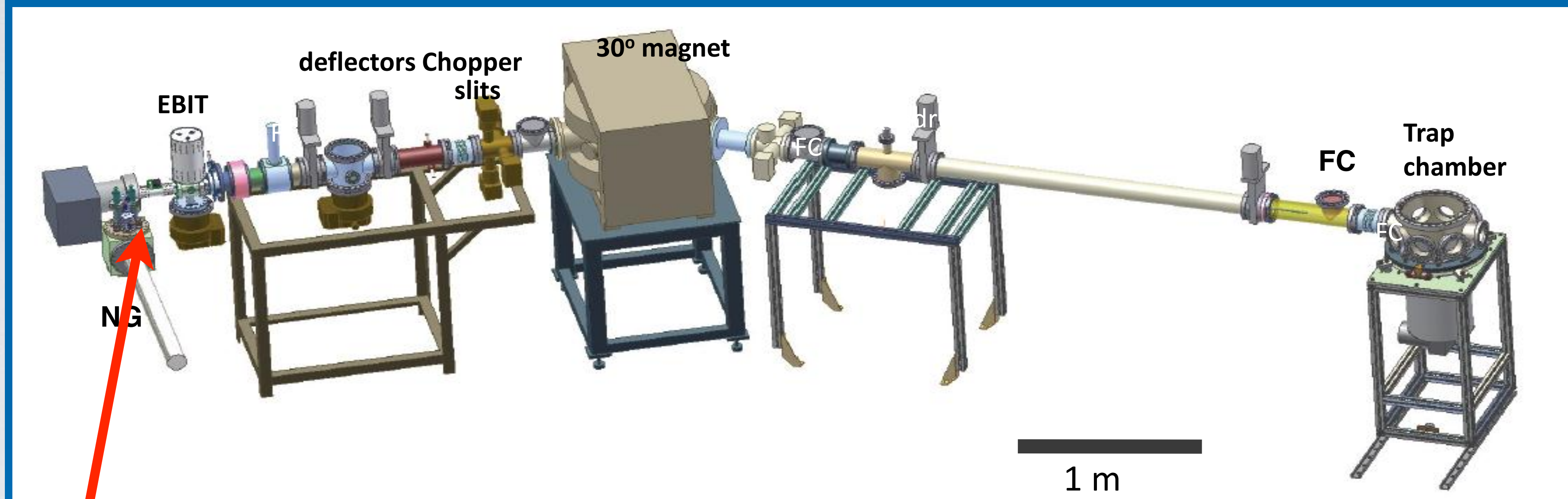
Tom Segal, Yonatan Mishnayot, Micheal Hass, Ist Makul, and GR, In preparation

Furnace + BeO Target

WIRED

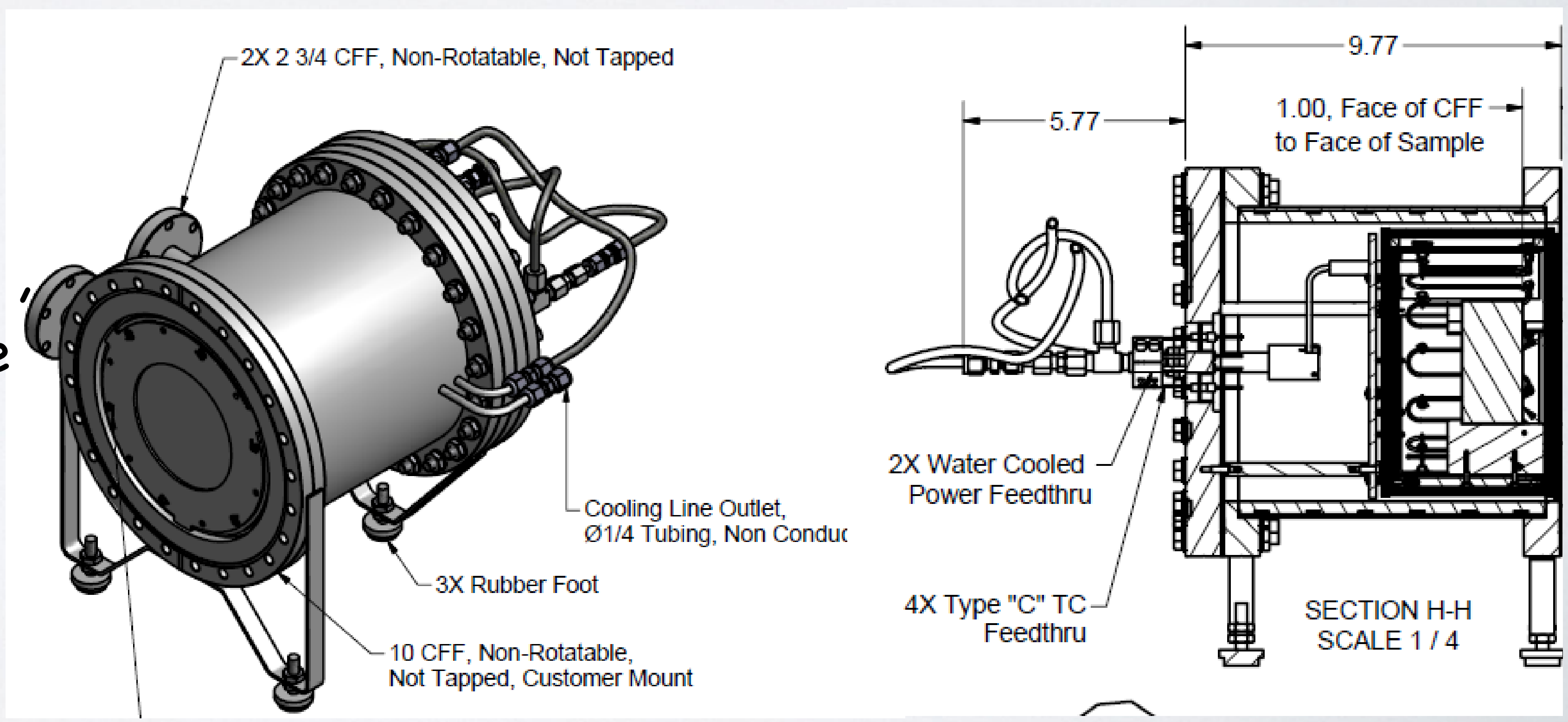
Weizmann Institute Radioactive Electrostatic Device

Experimental scheme



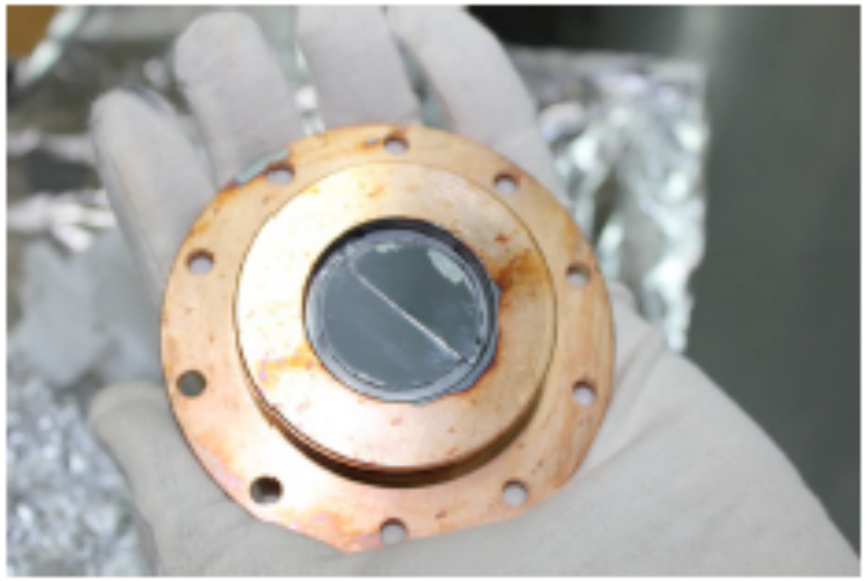
The 14 MeV neutrons hit a hot (1500K) BeO target, as a result, ^{6}He nuclei are produced via the (n,α) reaction.

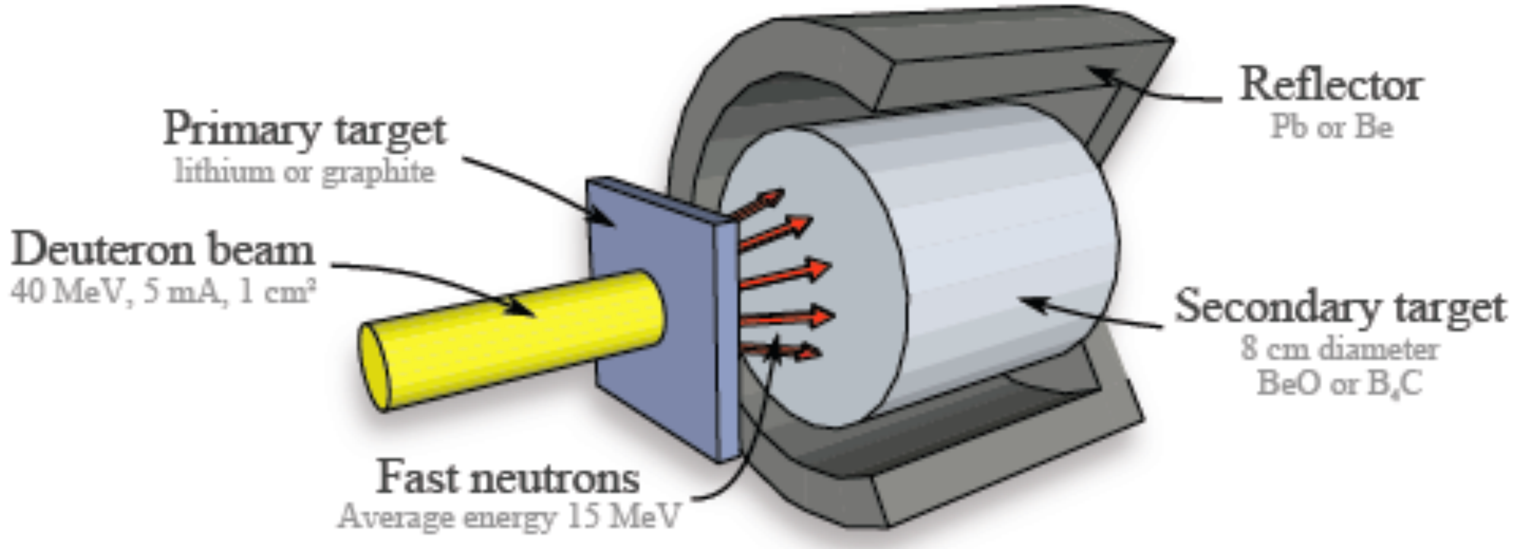
Porous BeO 80 mm x 2 mm discs delivered and stored



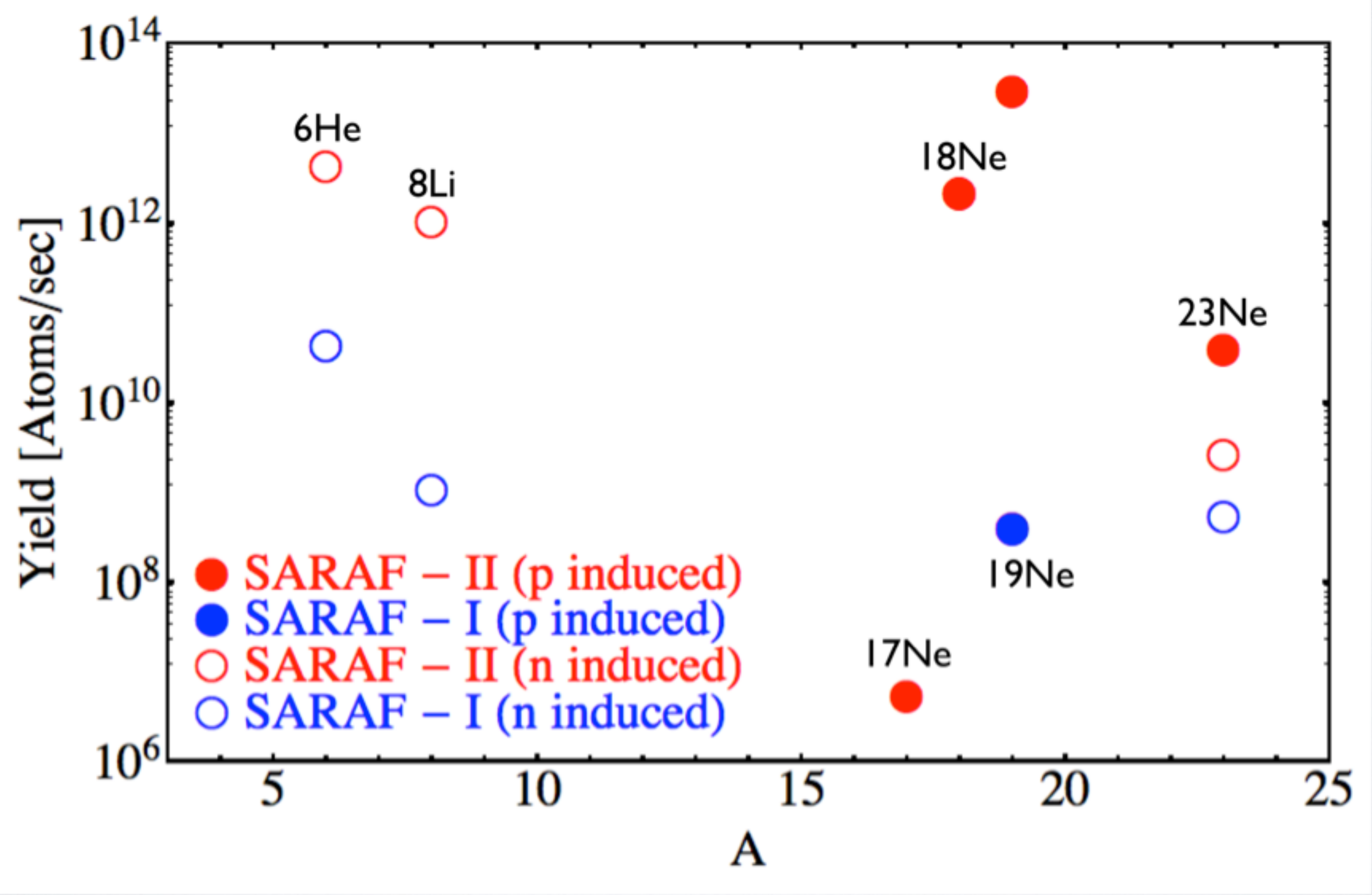
SARAF

* New, (very) high current p/d accelerator (5mA/up to 40MeV) under construction at SOREQ.
* Neutron production also possible with Liquid-Li (for eg., but under construction).
* Currently running d beams on LiF target (SARAF/WI) for neutron beam production (very similar energy to NG).

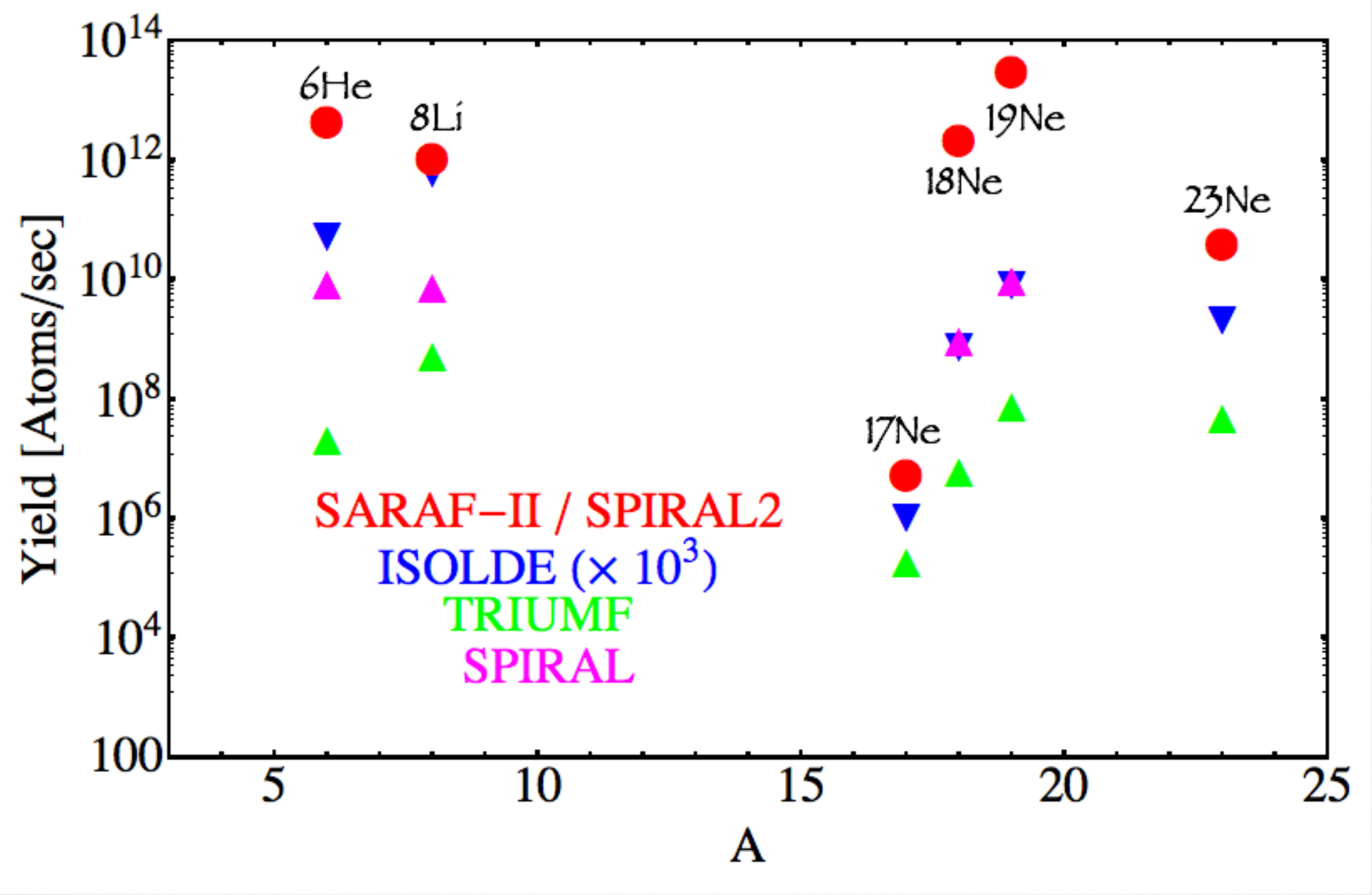


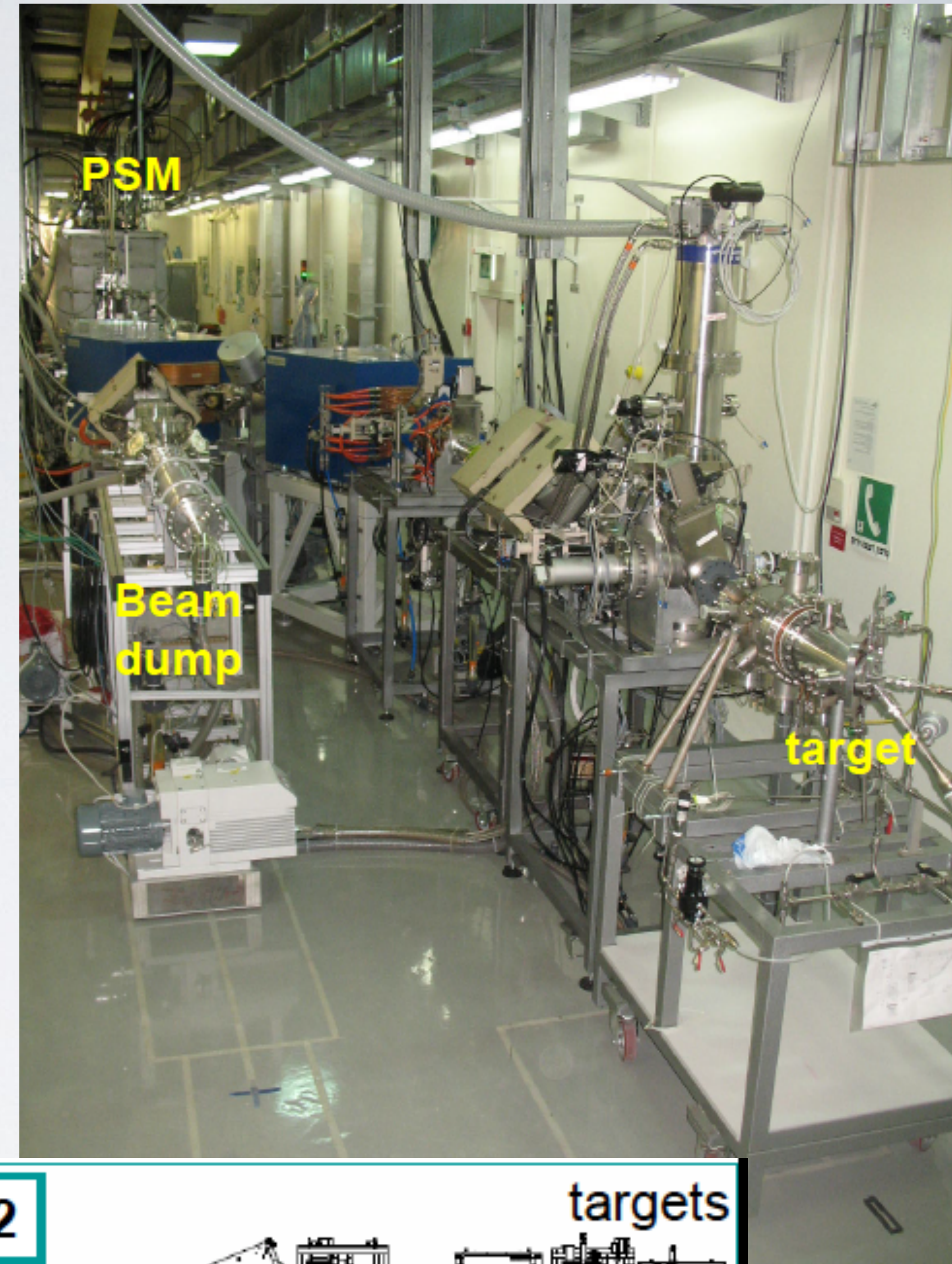


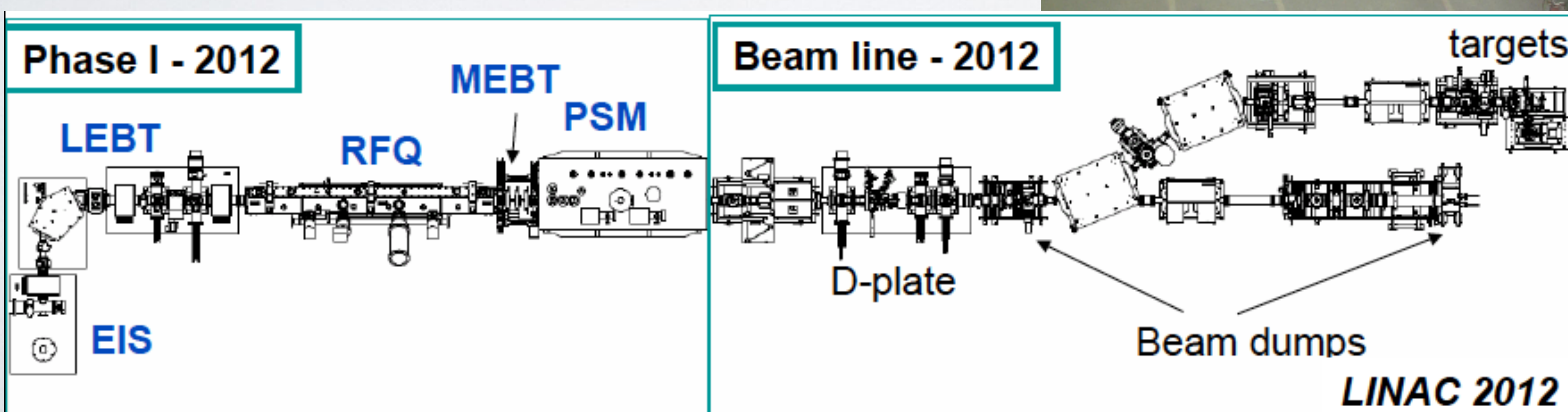
SARAF Projected Yields



SARAF Projected Yields

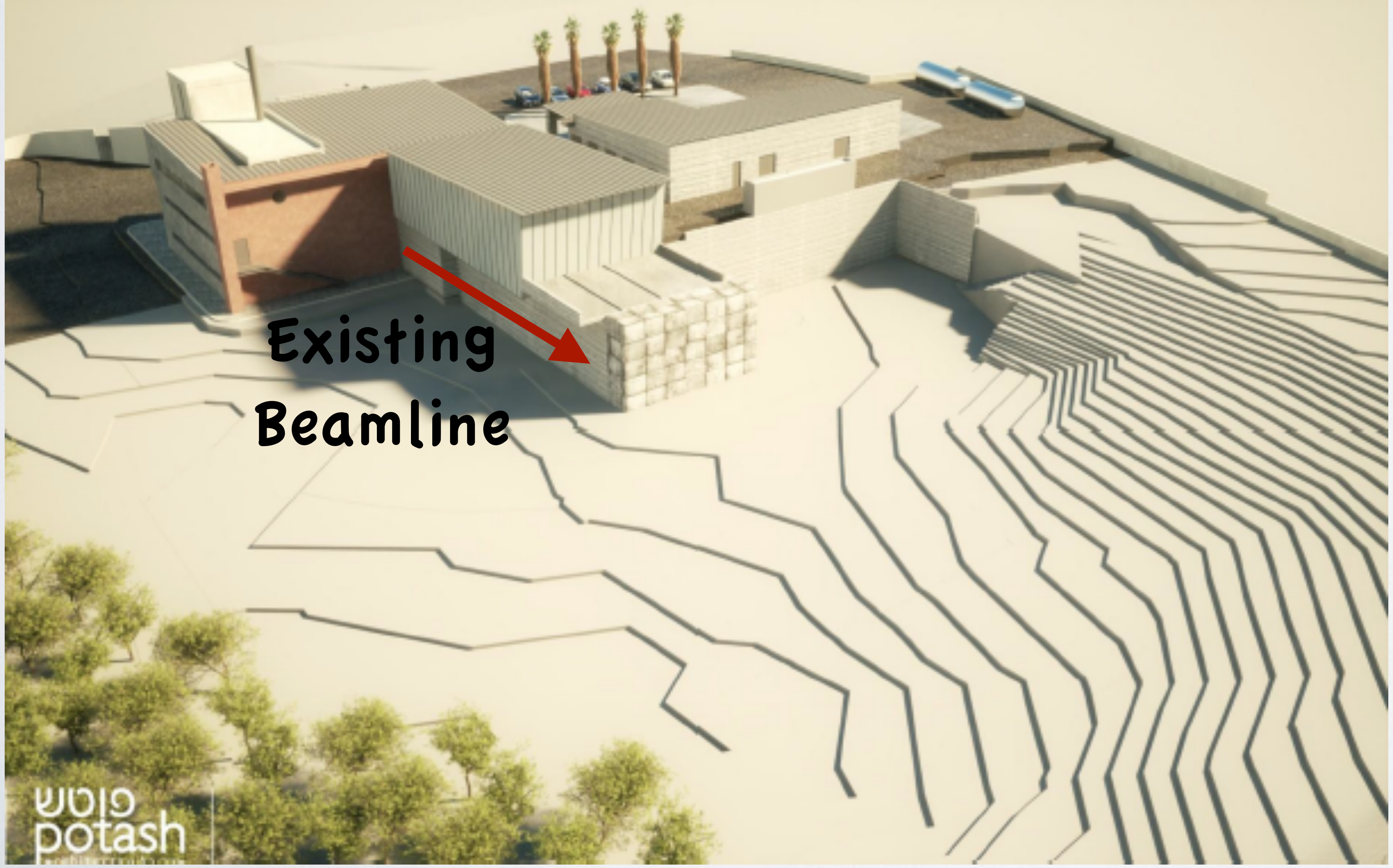



PSM
Beam dump
target


Phase I - 2012
LEBT
RFQ
MEBT
PSM
EIS
Beam line - 2012
targets
D-plate
Beam dumps
LINAC 2012

SARAF Phase-I Target Area

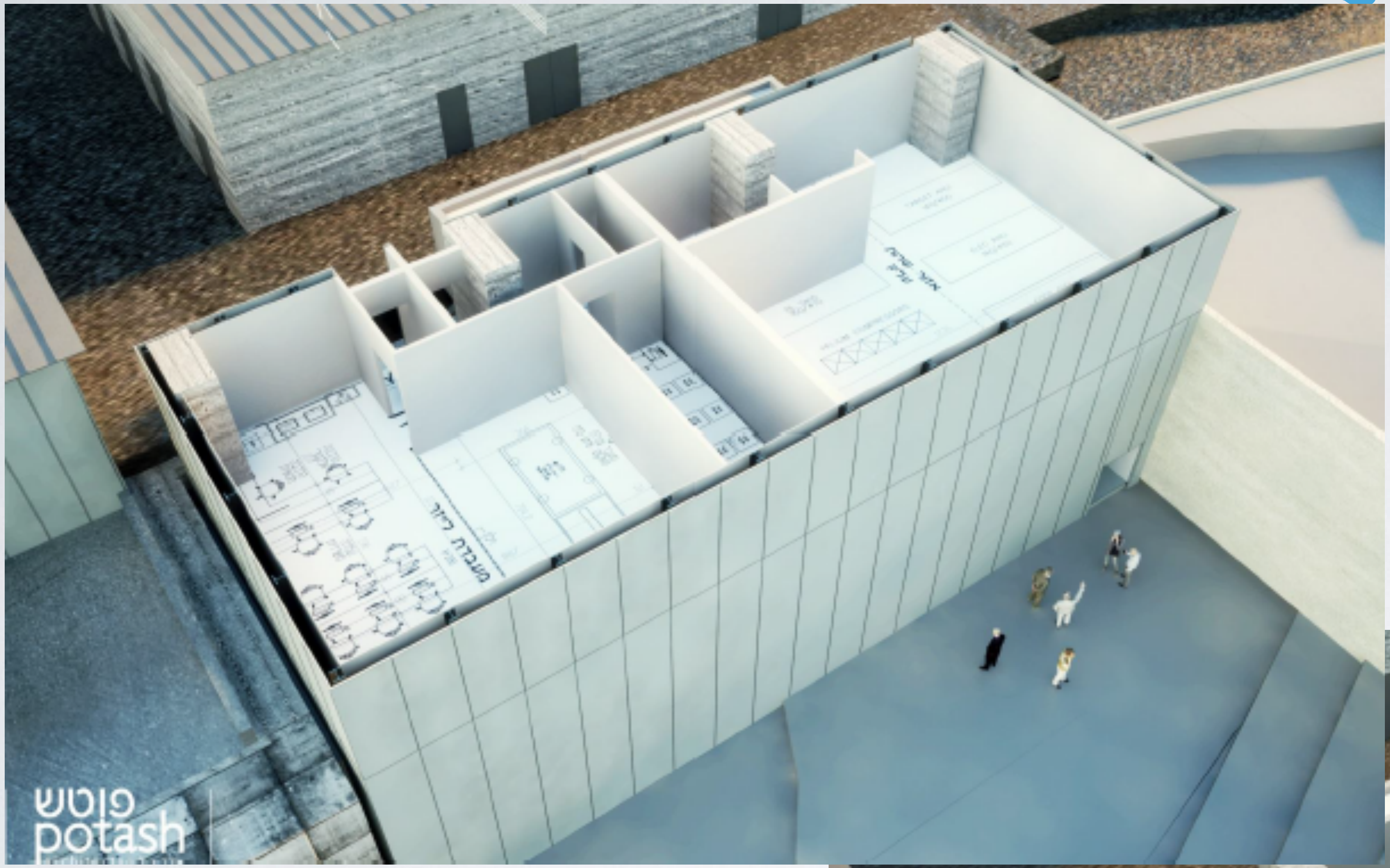
* ~2MEuro project approved by IAEA + Support from Pazy Foundation.
* Construction of dedicated beam line, 2 production targets, and 4 experimental areas.
* Experimental areas for: Laser lab, EIBT, Neutron activation, Positron production.
* Target date - labs open mid 2017.



SARAF Phase-I Target Area

* ~2MEuro project approved by IAEA + Support from Pazy Foundation.
* Construction of dedicated beam line, 2 production targets, and 4 experimental areas.
* Experimental areas for: Laser lab, EIBT, Neutron activation, Positron production.
* Target date - labs open mid 2017.

SARAF Phase-I Target Area



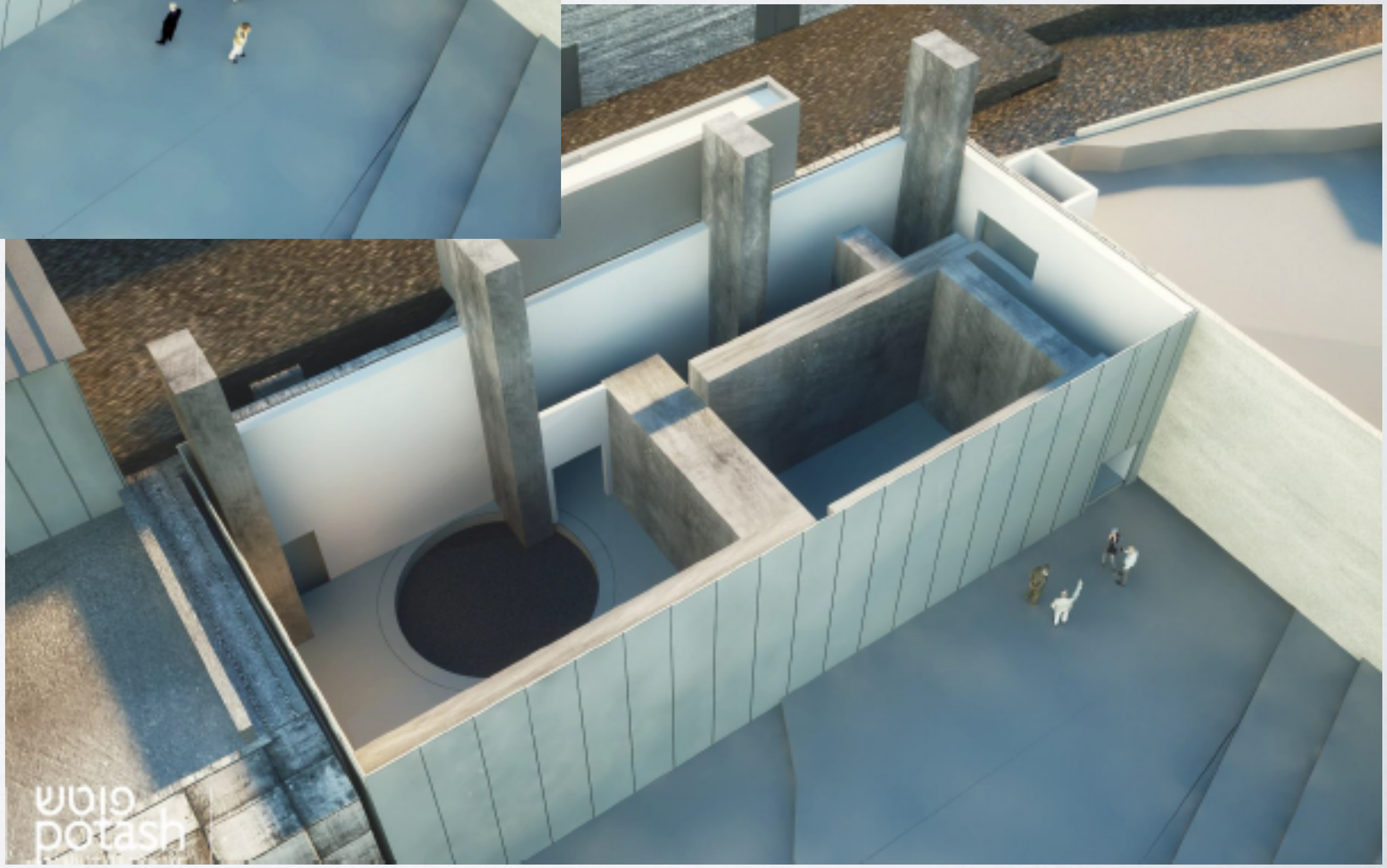
Lab Areas:

Electrostatic trap

MOT Trap

Activation measurements

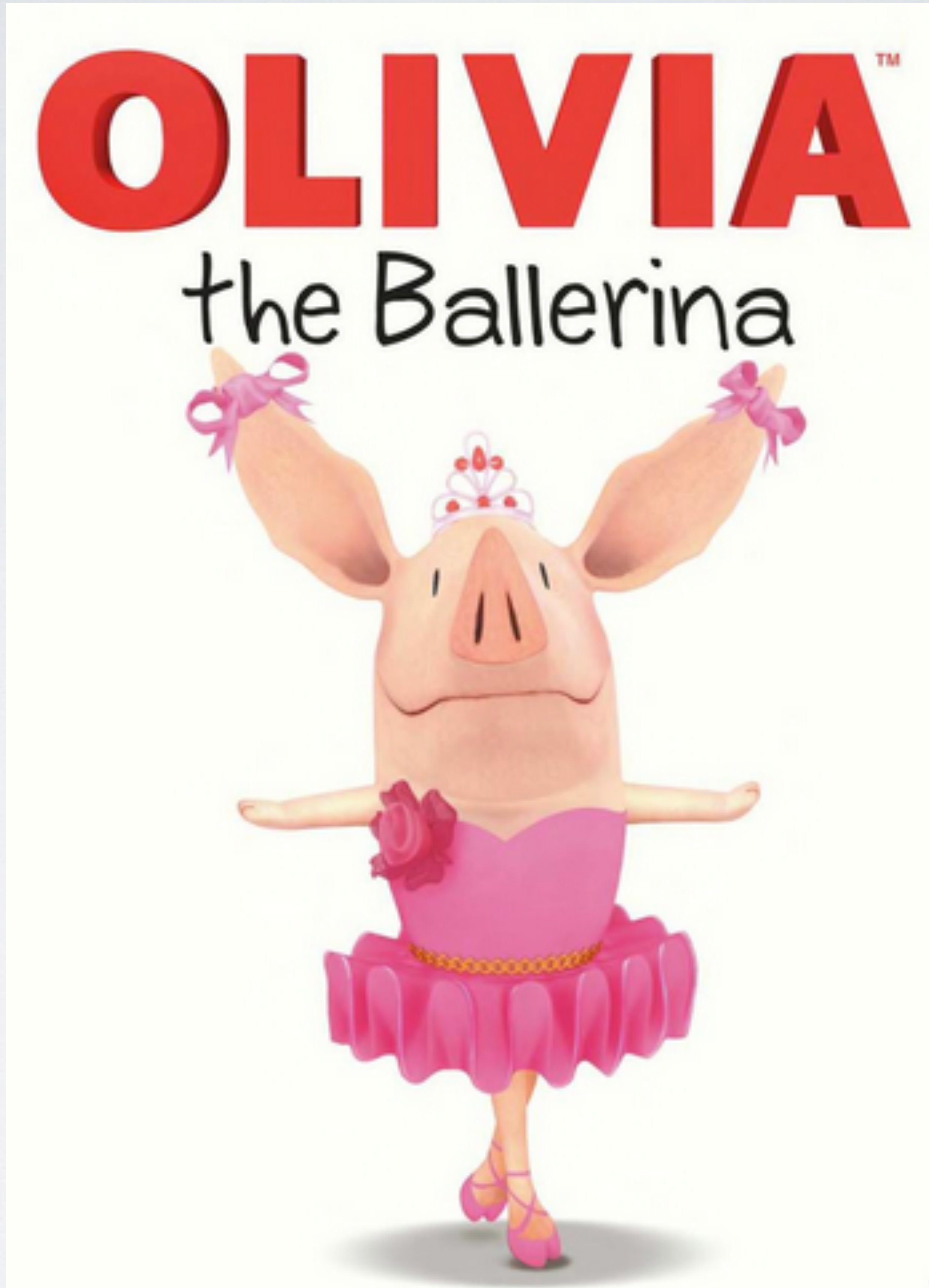
Slow positron beam



Production area:

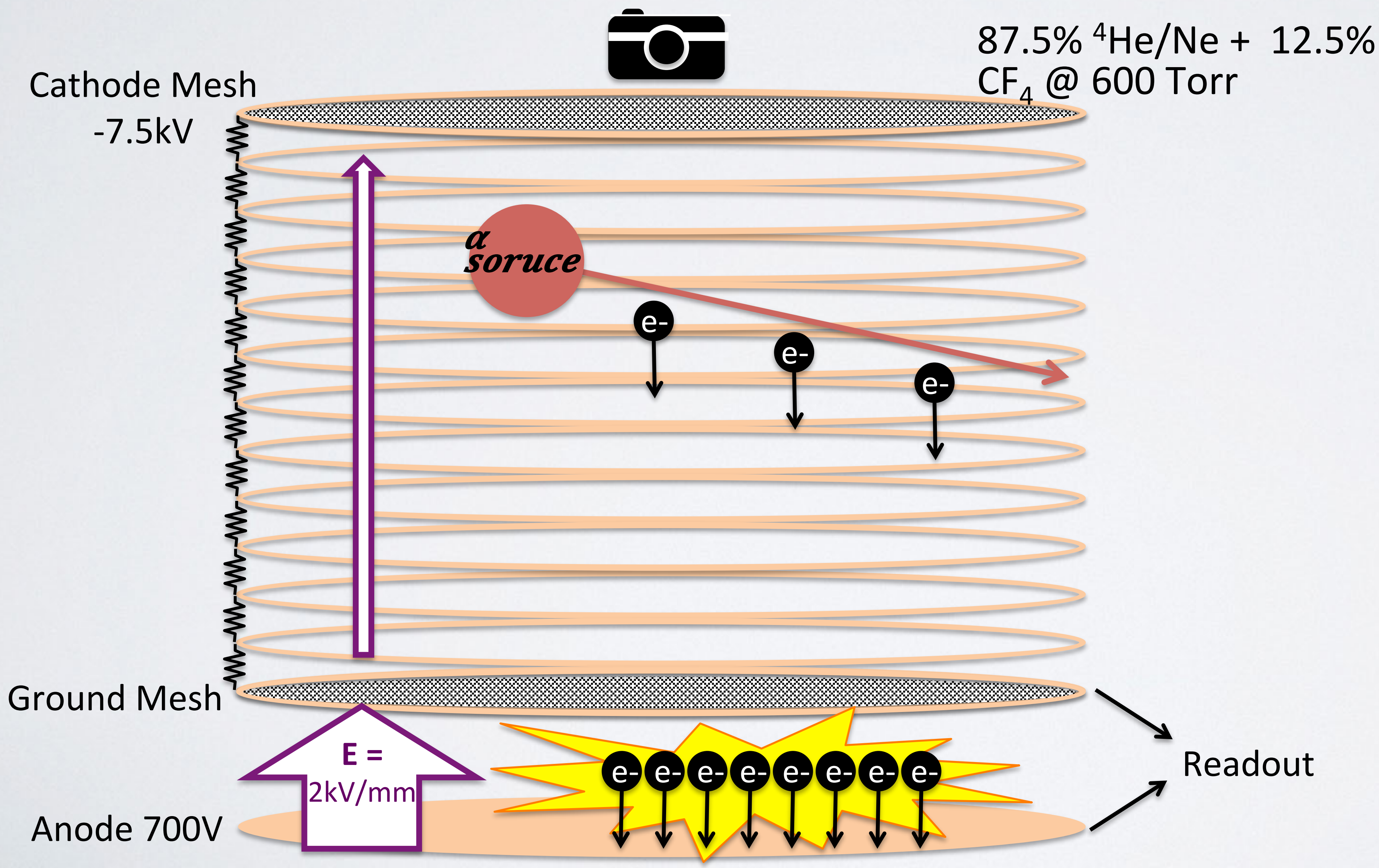
2 production targets

(LiLiT + Replaceable)

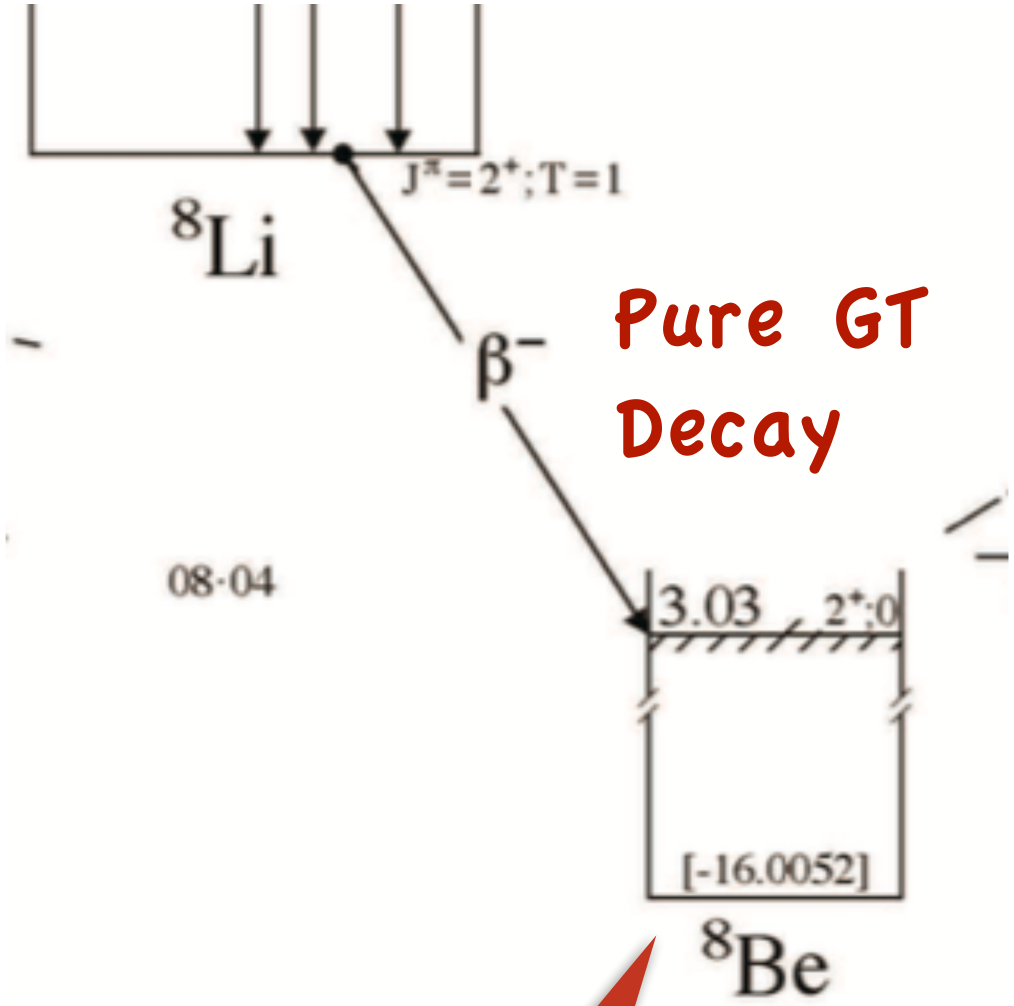

OLIVIA™
the Ballerina

Newest Idea - OLIVIA (MIT/MSU/HUJI)

High precision measurement of the ^{8}Li beta decay.
Use Time Projection Chamber instead of trap.
Full 3D reconstruction of kinematics.

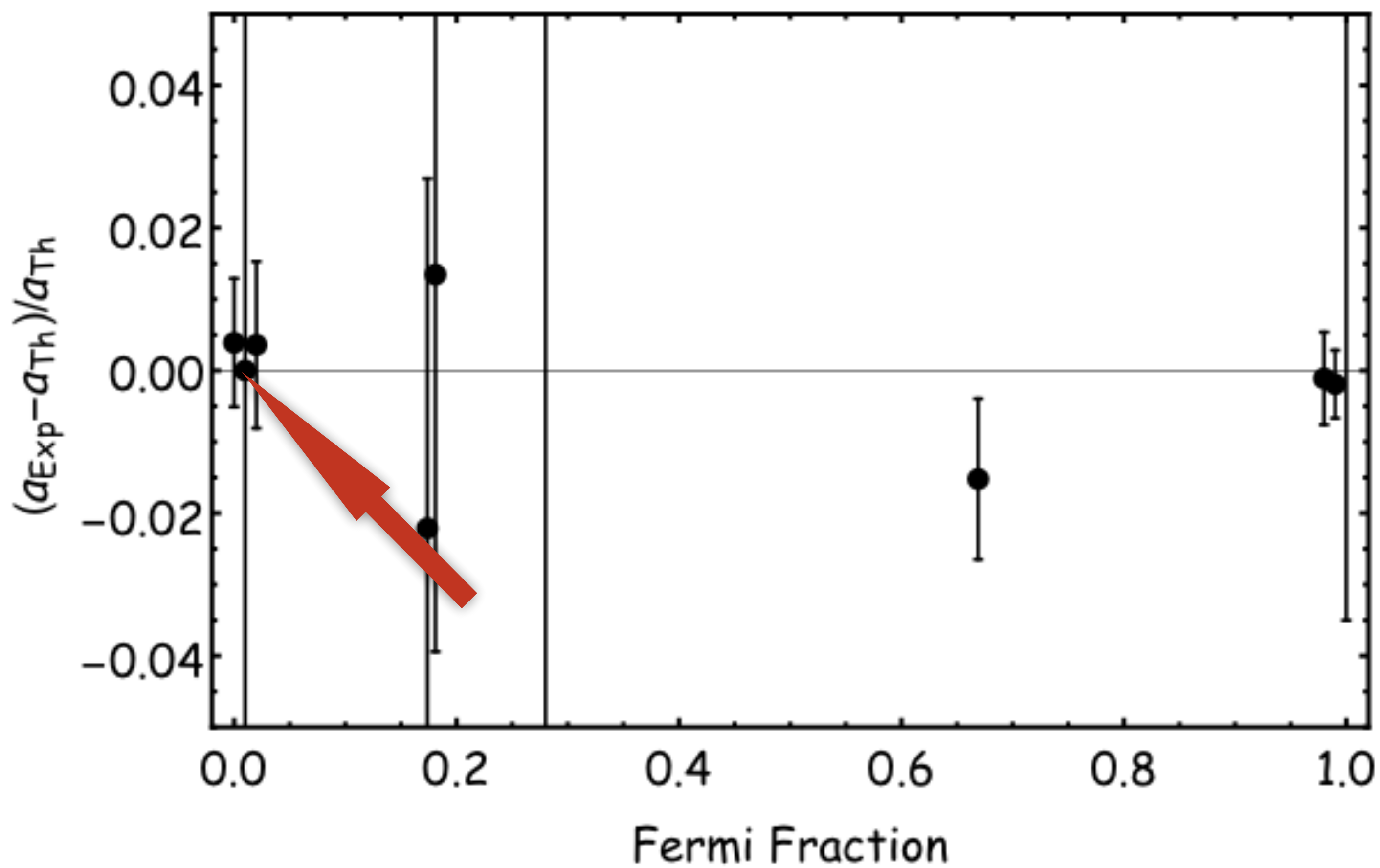


Why ^{8}Li?

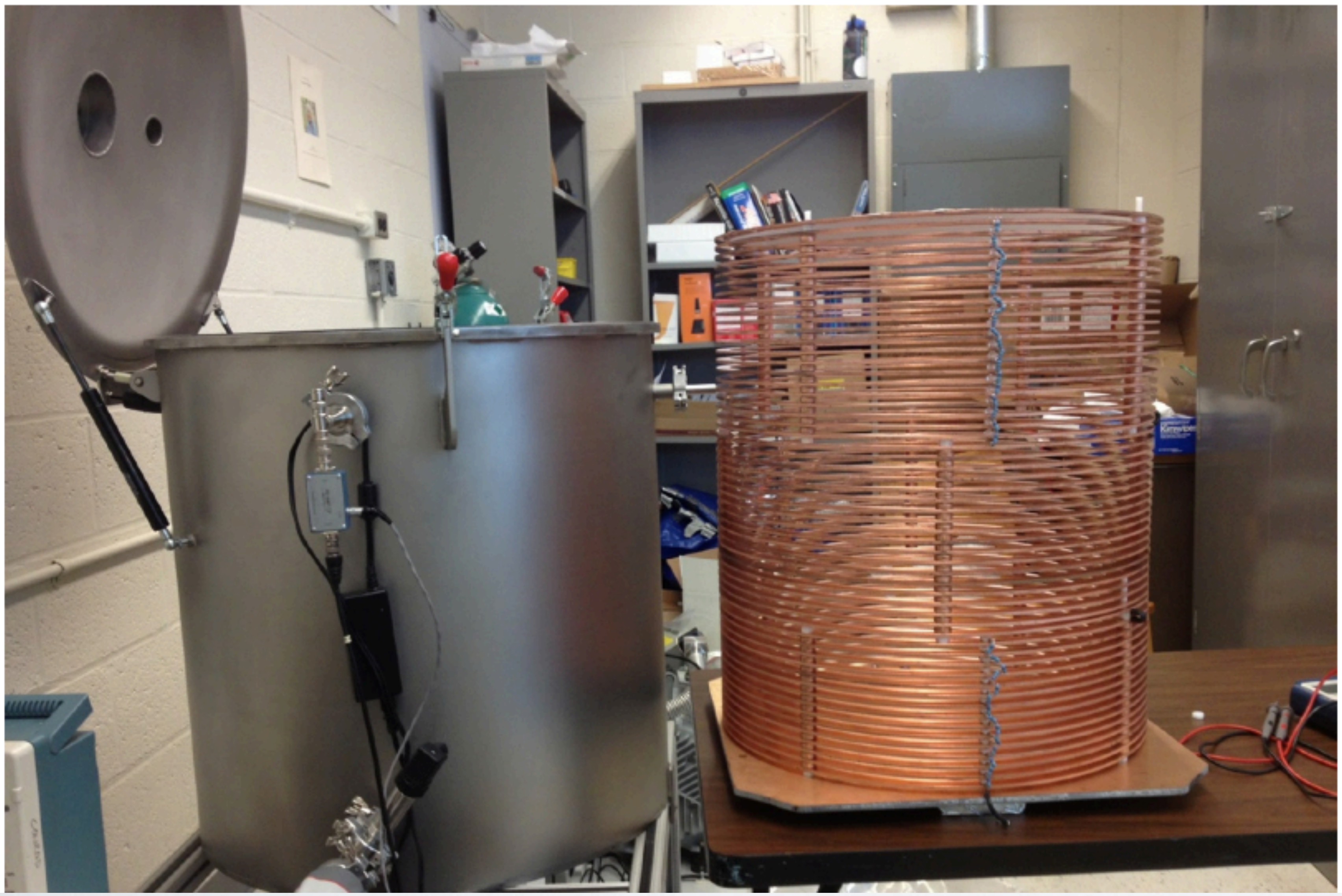


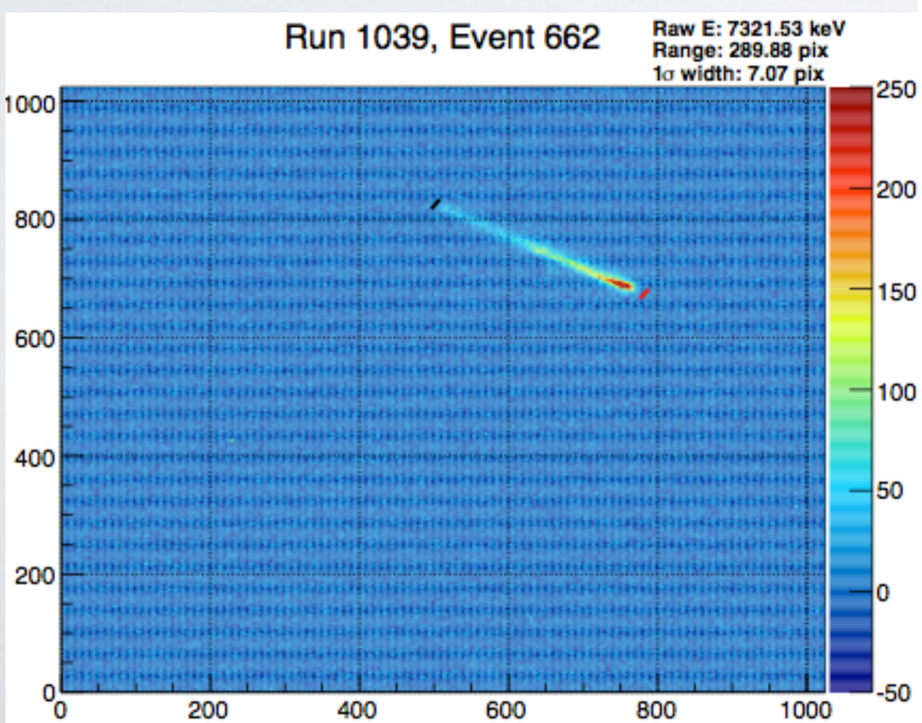
Pure GT Decay

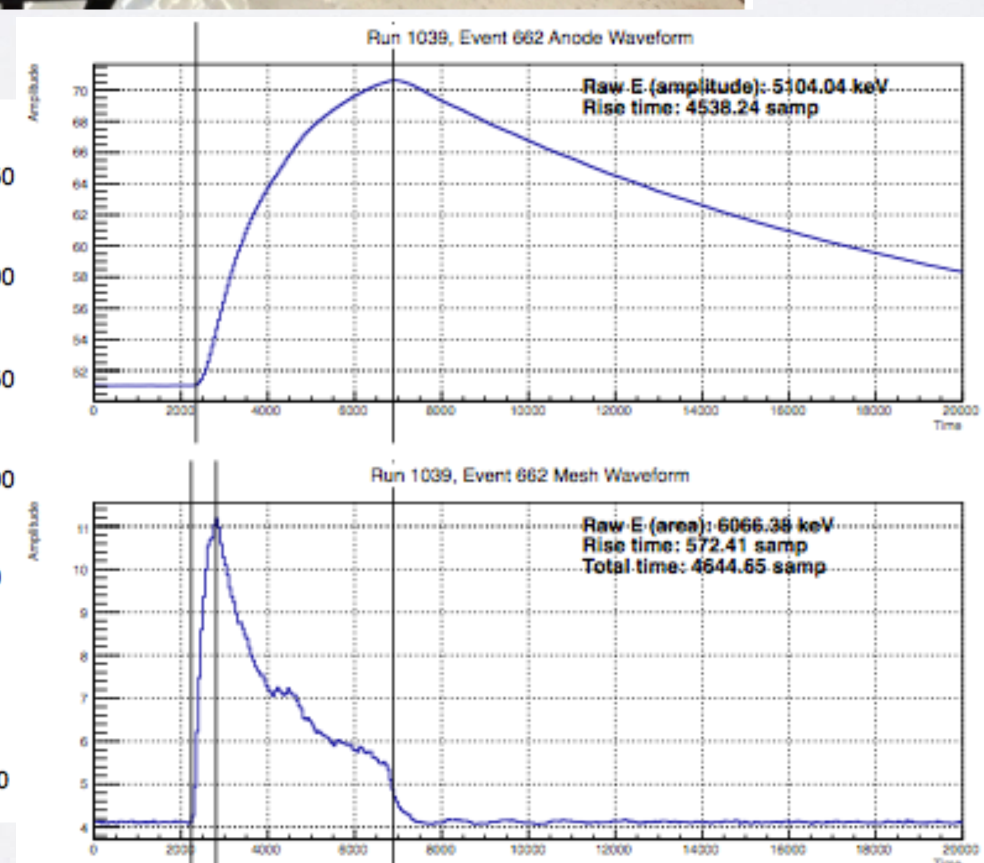
Immediate decay into α+ α (easy to detect)



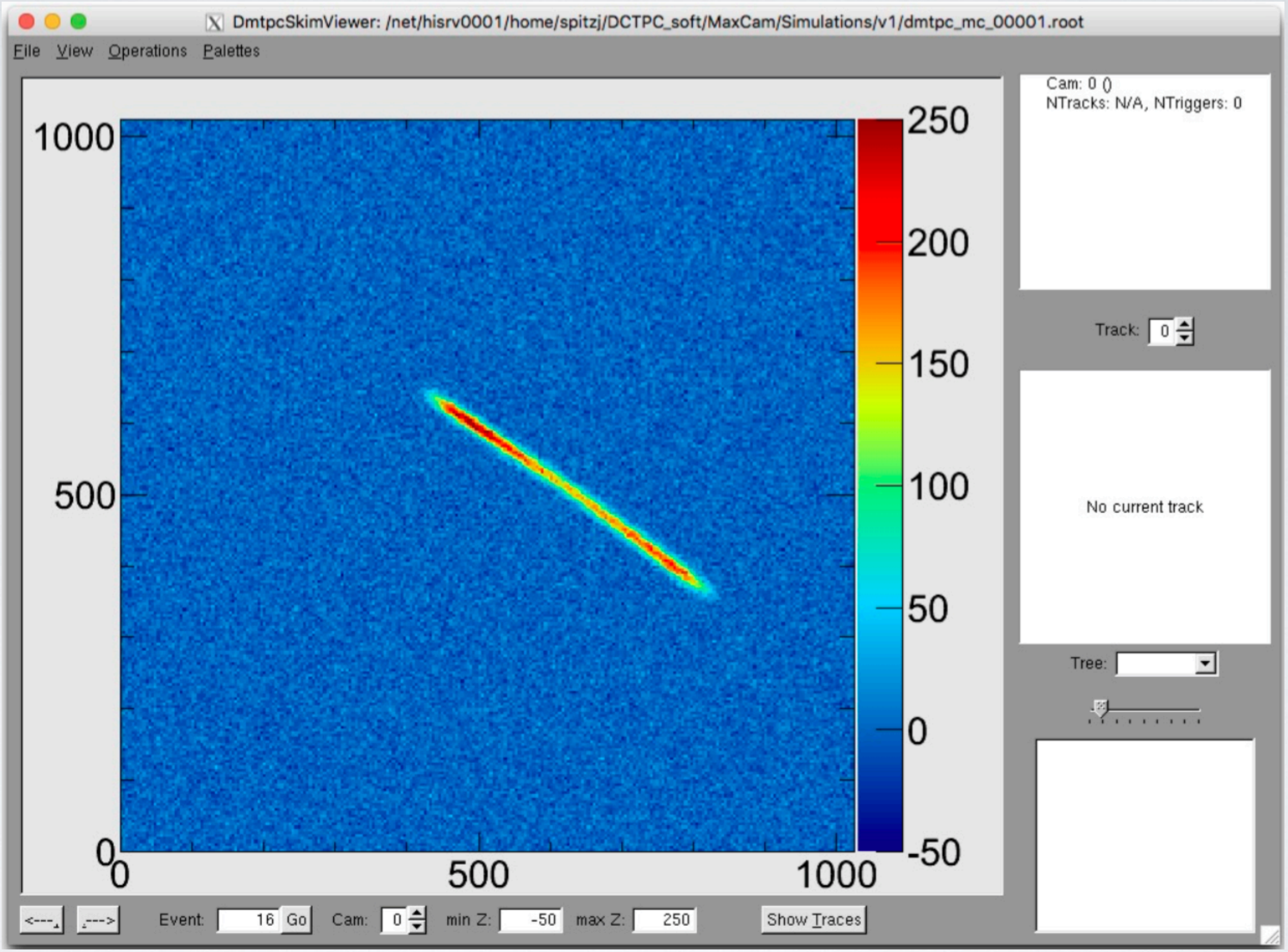
Recoil order corrections well under control




Run 1039, Event 662
Raw E: 7321.53 keV
Range: 289.88 pix
1σ width: 7.07 pix

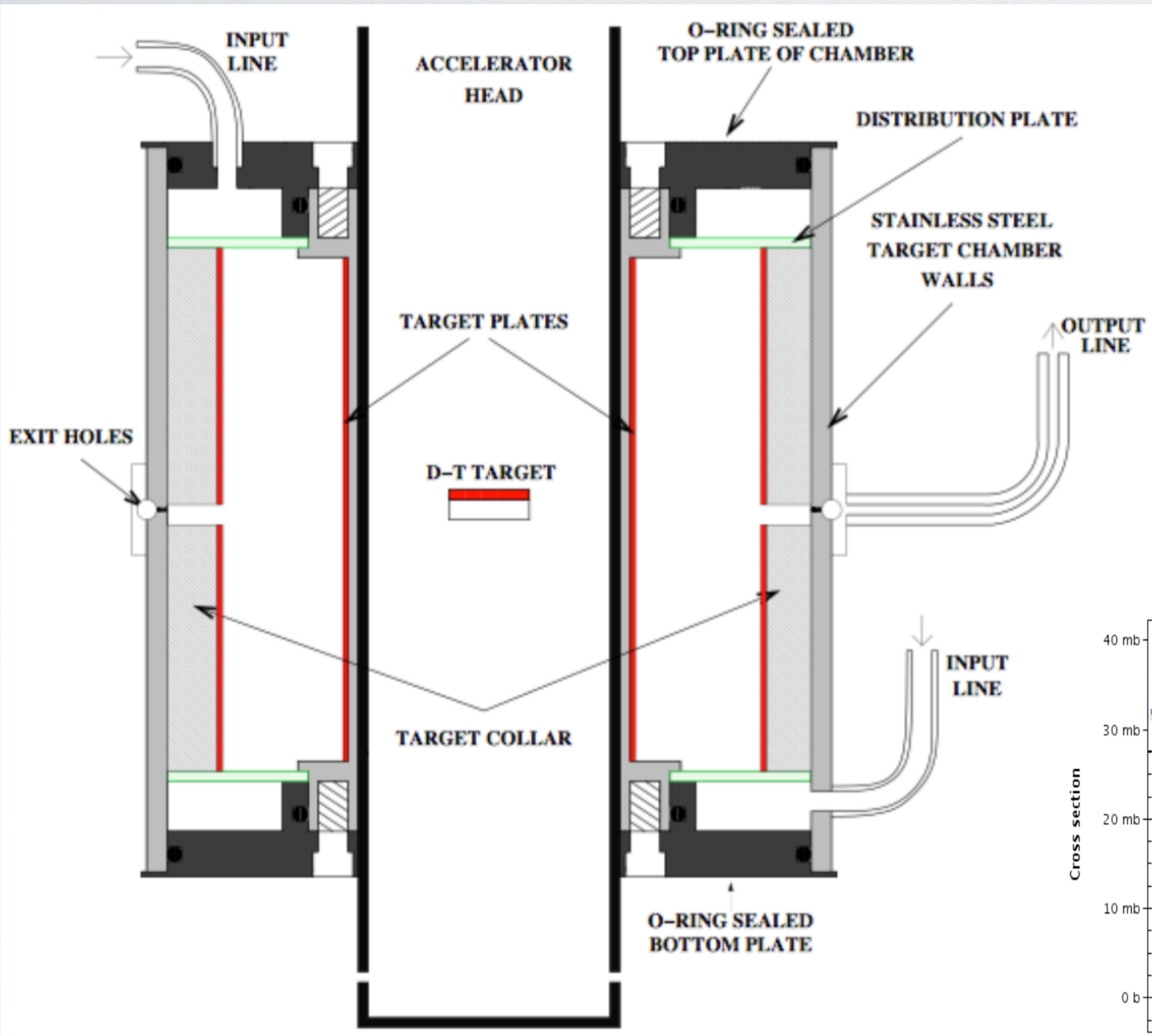

Run 1039, Event 662 Anode Waveform
Raw E (amplitude): 5104.04 keV
Rise time: 4538.24 samp
Run 1039, Event 662 Mesh Waveform
Raw E (area): 6066.38 keV
Rise time: 572.41 samp
Total time: 4644.65 samp

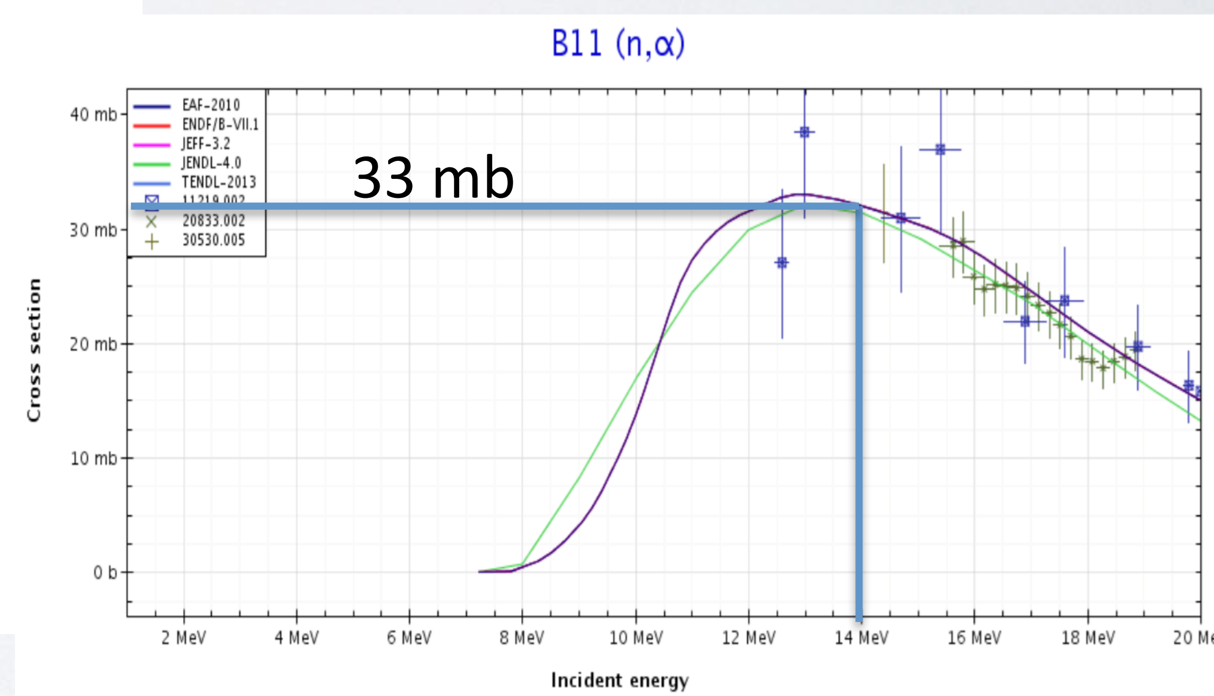
‘Typical’ simulated events @ 200 Torr



^{8}Li Production using a DT generator: ^{11}B(n,α)^{8}Li

+ Transport ^{8}Li to the TPC using a gas flow system



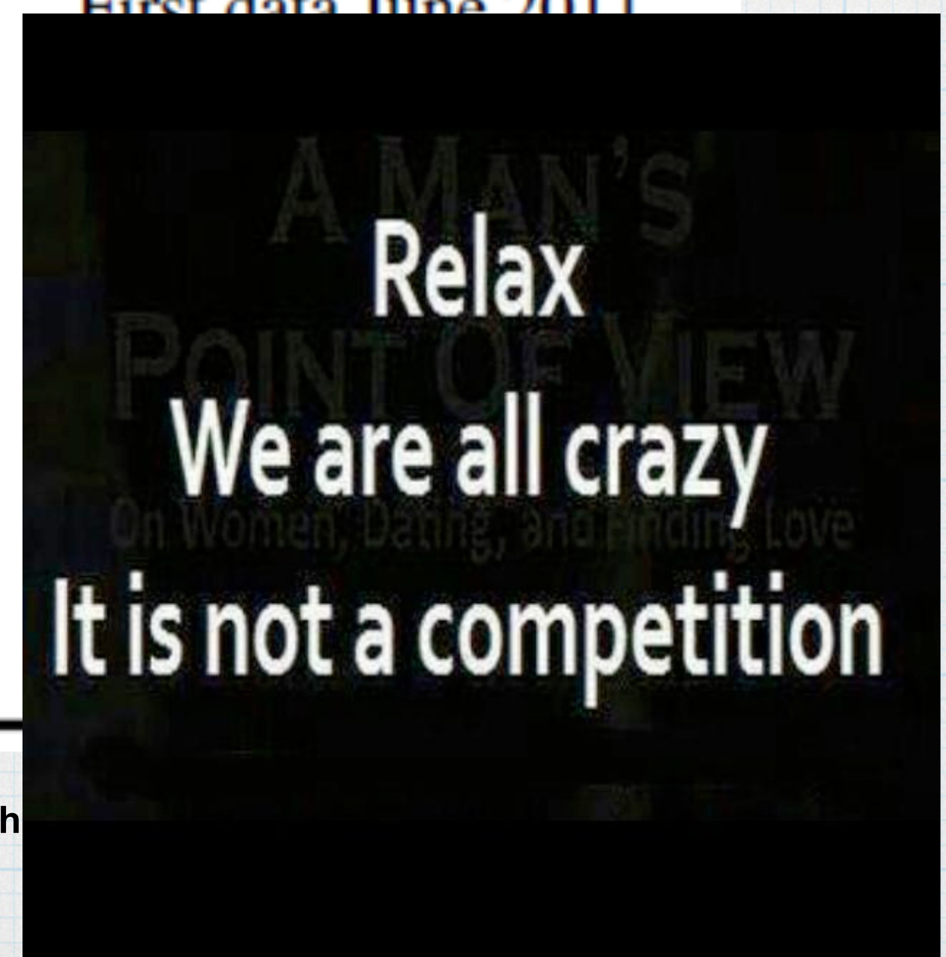


Based on the SNO ^{8}Li calibration system
arXiv: 0202024 (2002)

Beta Decay Studies World Wide

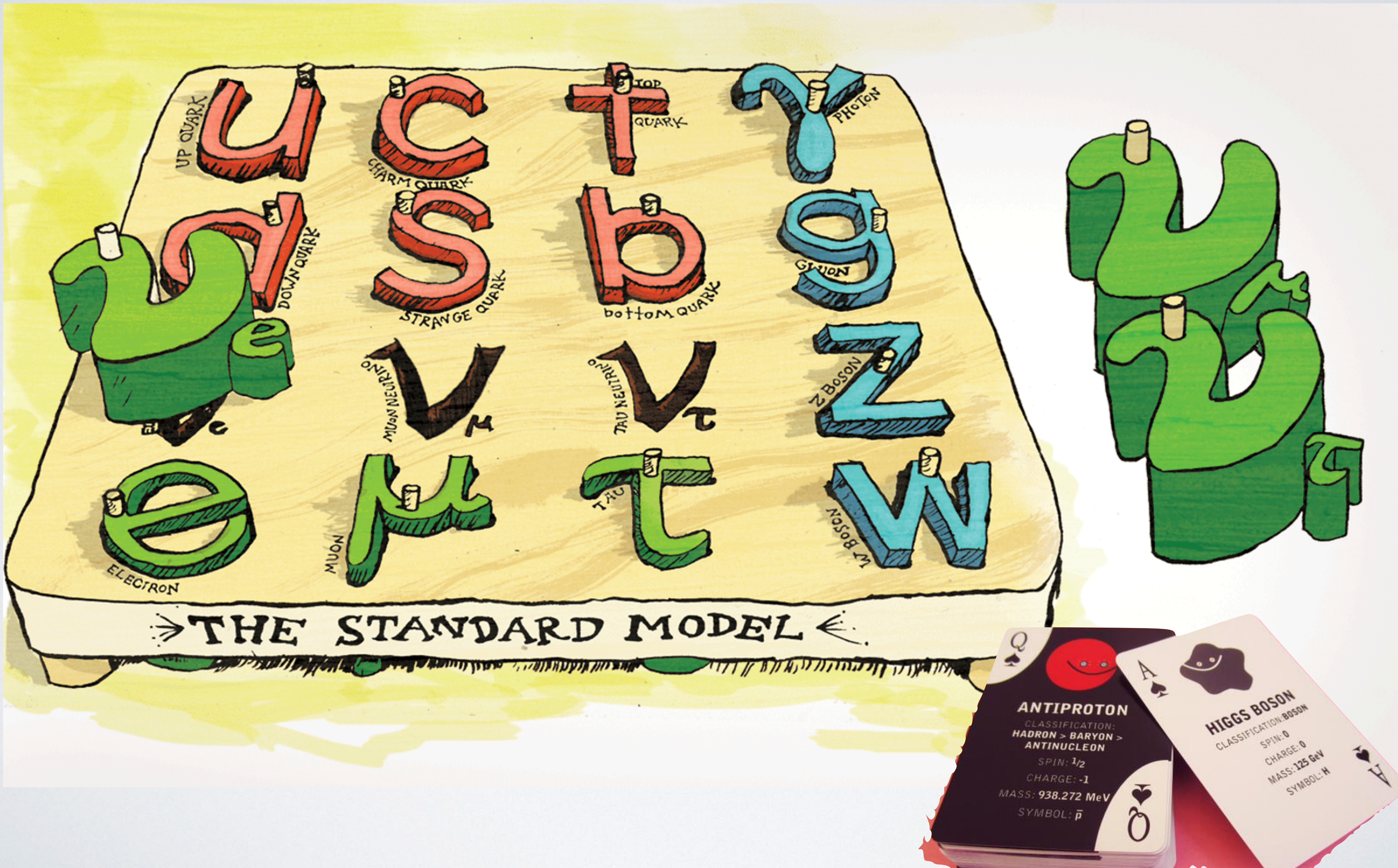
(Partial List)

Parent	Technique	Team, laboratory	Remarks
^{6}He	Spectrometer	ORNL	$a = -0.3308(30)$
^{32}Ar	Foil; p recoil	UW-Seattle, ISOLDE	$\tilde{a} = 0.9989(52)(39)$
^{38m}K	MOT	SFU, TRIUMF	$\tilde{a} = 0.9981(30)(34)$
^{21}Na	MOT	Berkeley, BNL	$a = 0.5502(38)(46)$
^{6}He	Paul trap	LPC-Caen, GANIL	$\tilde{a} = -0.3335(73)(75)$
^{6}He	Paul trap	LPC-Caen, GANIL	Analysis under way
^{8}Li	Paul trap; $\beta\alpha$	ANL	Analysis under way
^{35}Ar	Paul trap	LPC-Caen, GANIL	First data June 2011
^{35}Ar	Penning trap	Leuven, ISOLDE	
^{19}Ne	Paul trap	LPC-Caen, GANIL	
^{6}He	EIBT	Weizmann, SOREQ	
^{6}He	MOT	ANL, CENPA	
Ne	MOT	Huji , SOREQ	
^{21}Na	MOT	KVI-Groningen	
^{32}Ar	Penning trap	Texas A&M	
^{8}He	Foil; $\beta\gamma$	NSCL	



Take Home Messages

Take Home Messages



Take Home Messages

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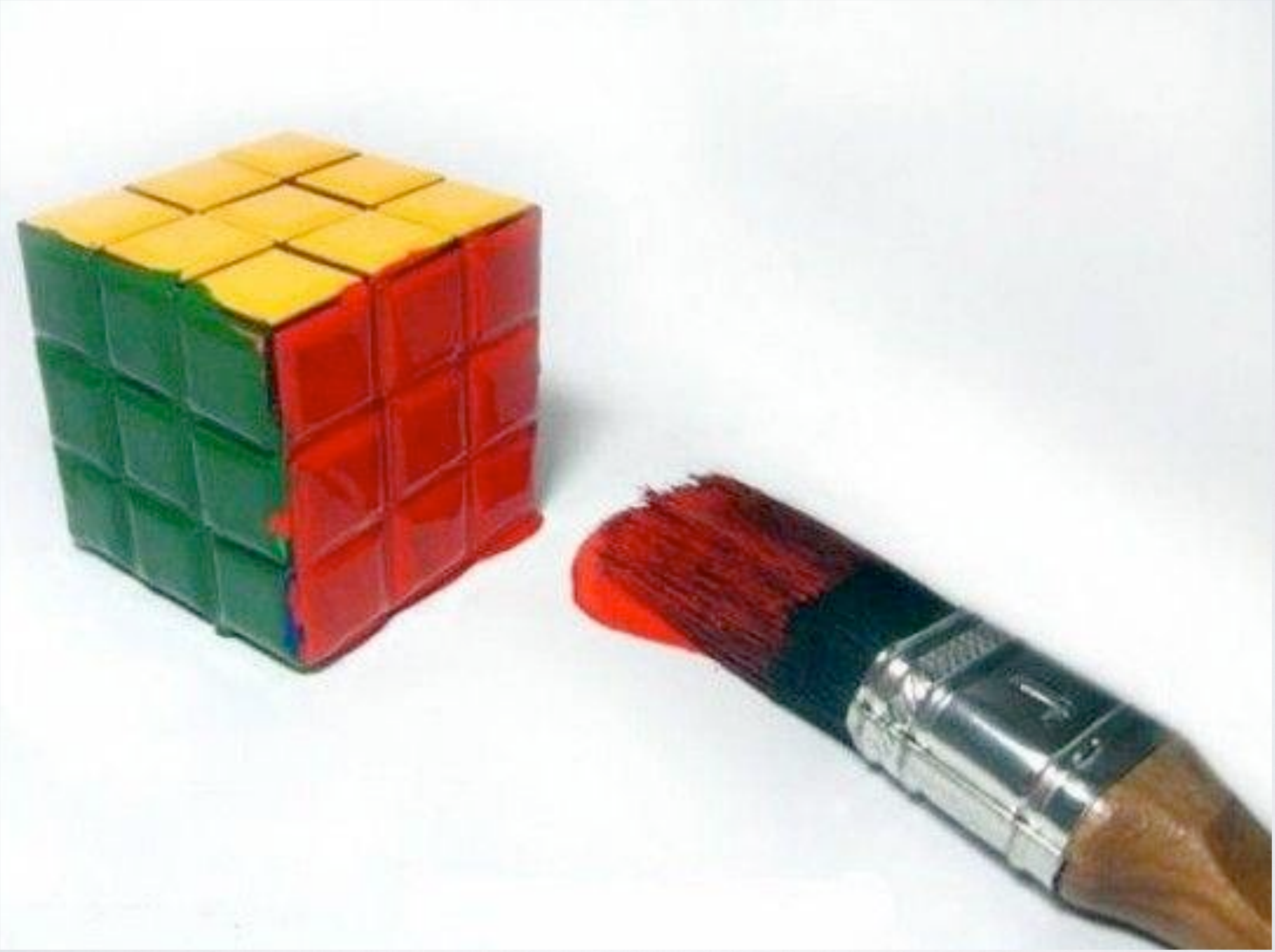
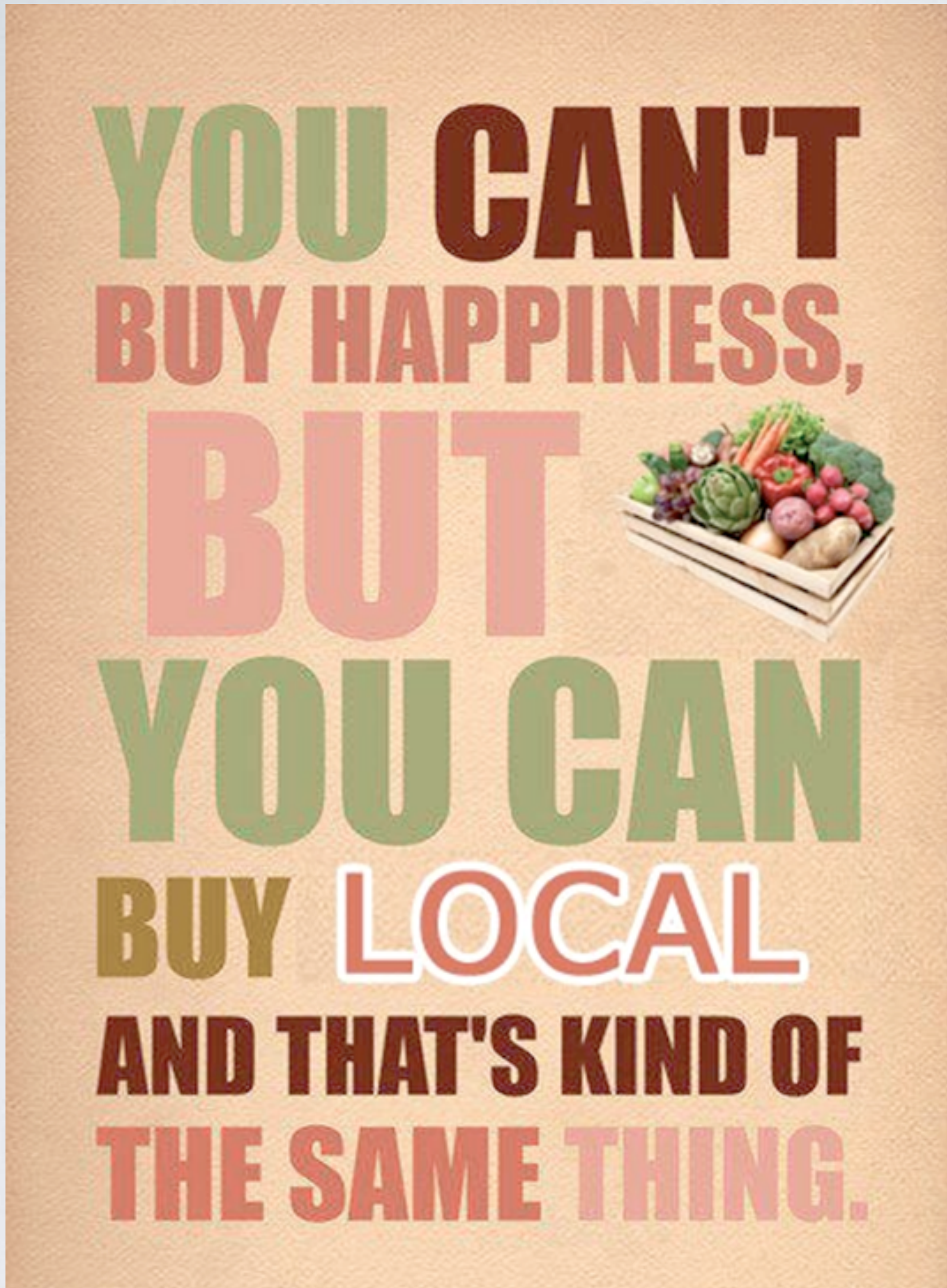
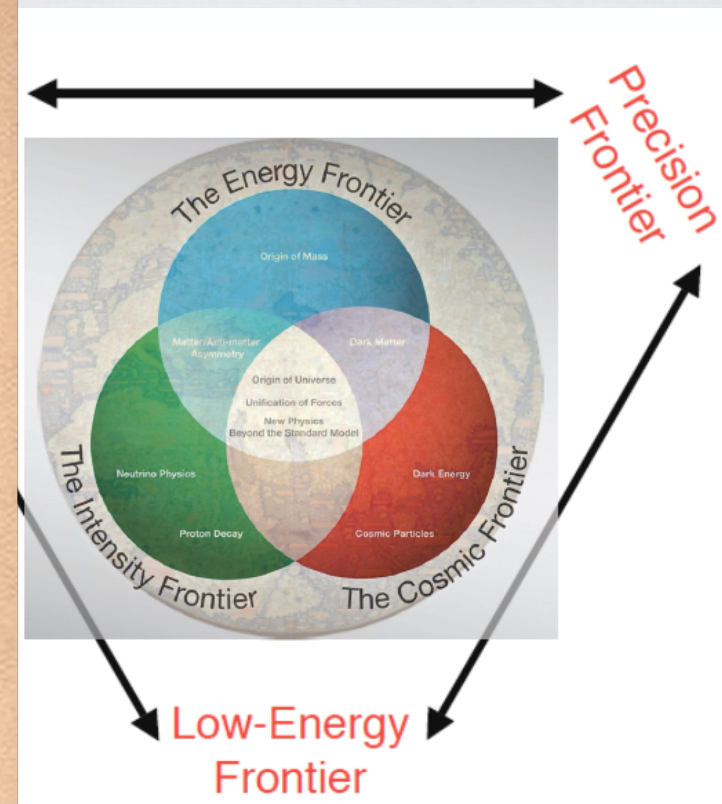
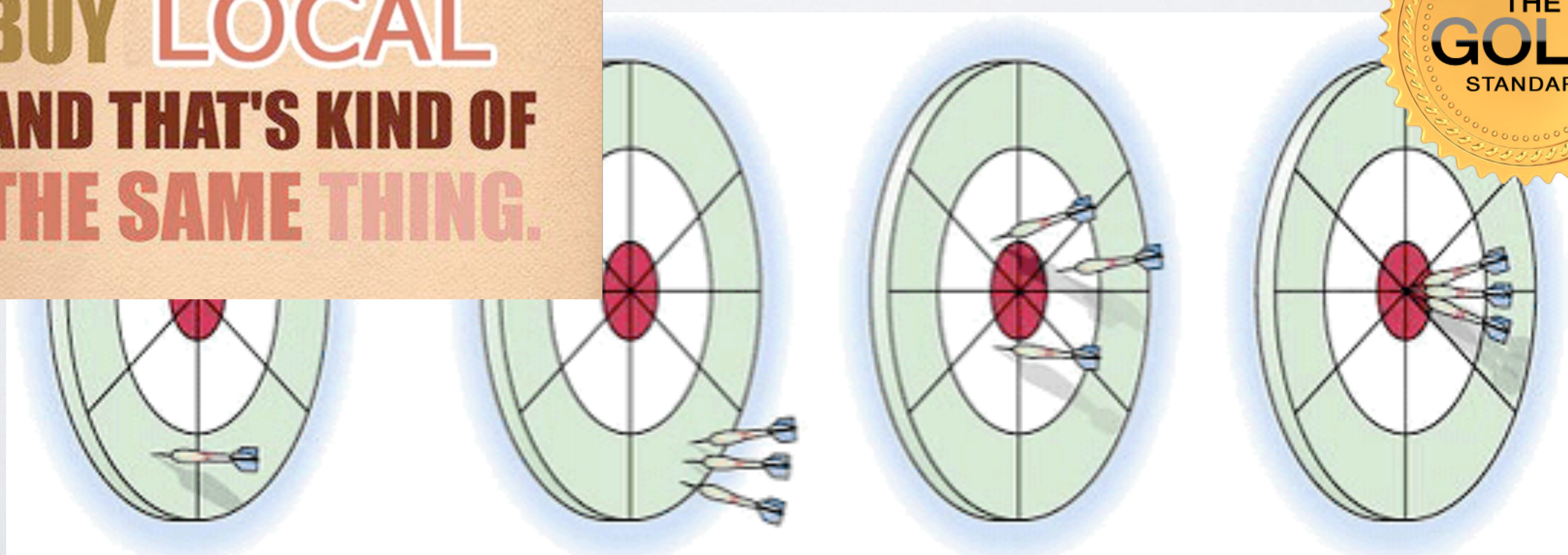


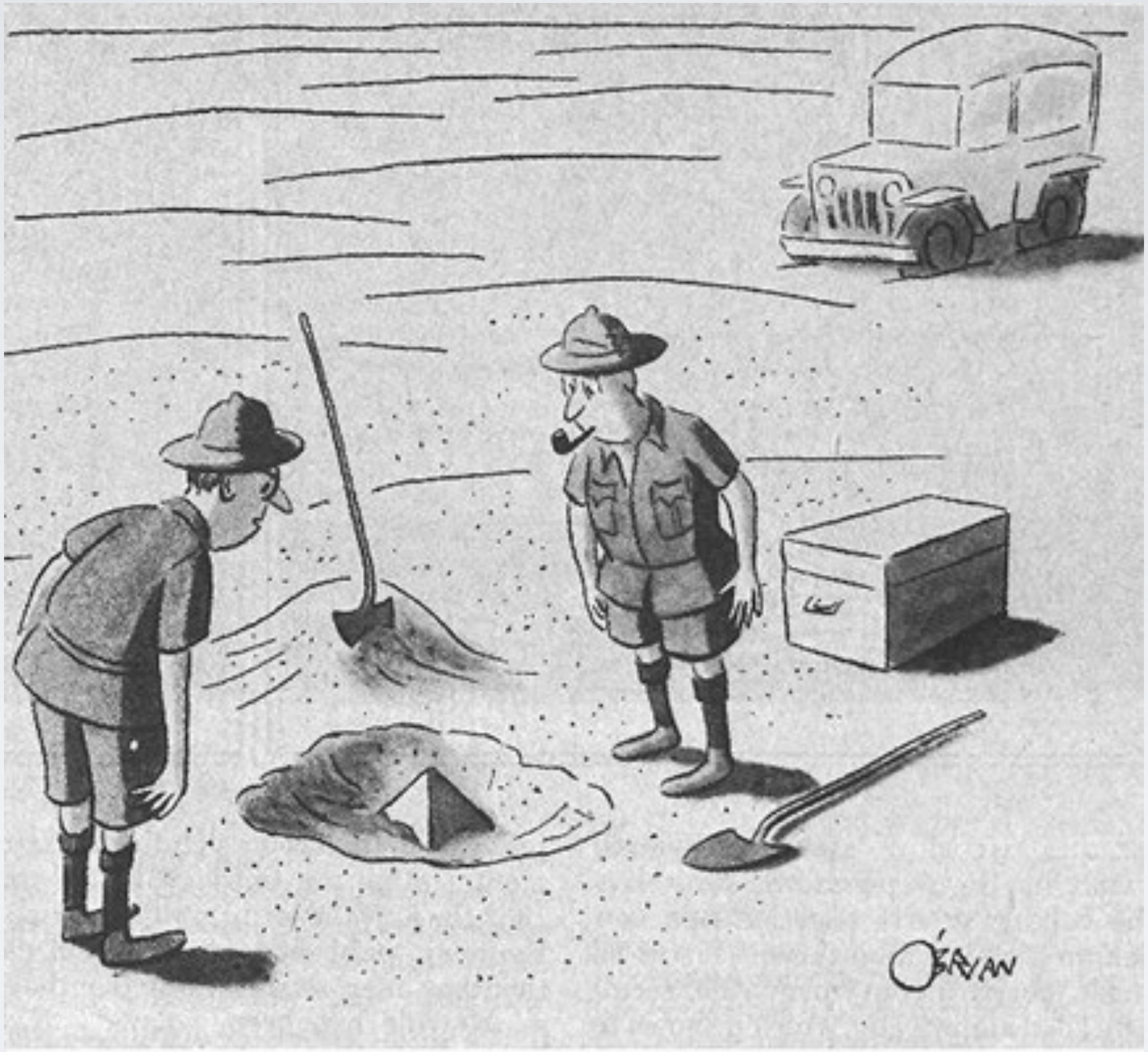
Take Home Messages







Take Home Messages



"This could be the discovery of the century. Depending, of course, on how far down it goes."