An Electrostatic Ion Beam Trap and (some) Possible Applications

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Nuclear Science Division
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Nov. 30, 2010


Booty Way
Black Rock Way
Island
Classical Electrodynamics
Third Edition
John David Jackson
Standard Model of
FUNDAMENTAL PARTICLES AND INTERACTIONS
FERMIONS
BOSONS
PROPERTIES OF THE INTERACTIONS
Eye Patch Inlet
Jewel Coast
Pirate's Booty

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

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Time varying ("Paul trap", MOT) & Magnetic fields ("Penning trap").

Electronic correction.

Diamagnetic materials (aka "Floating Frog").

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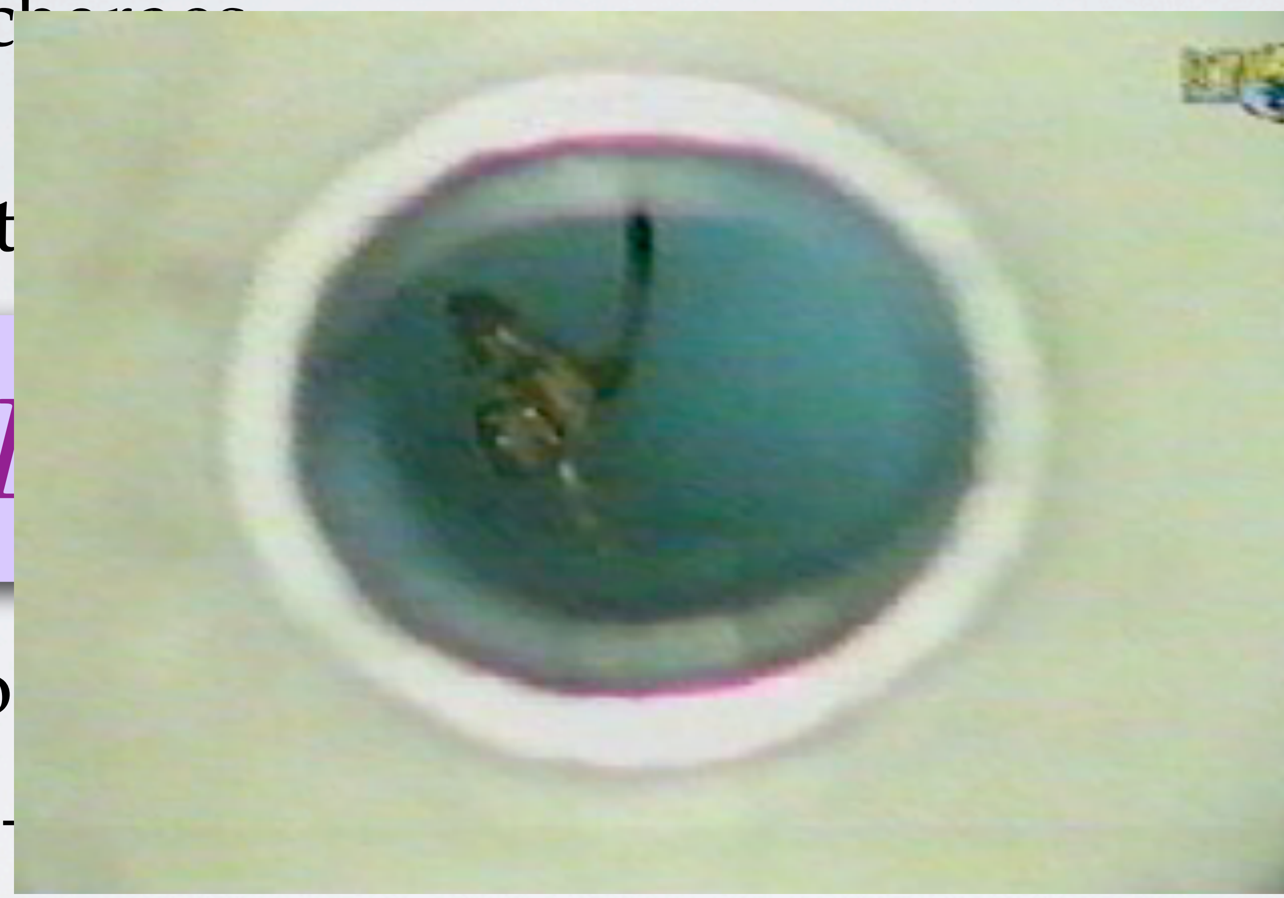

Rest … e)

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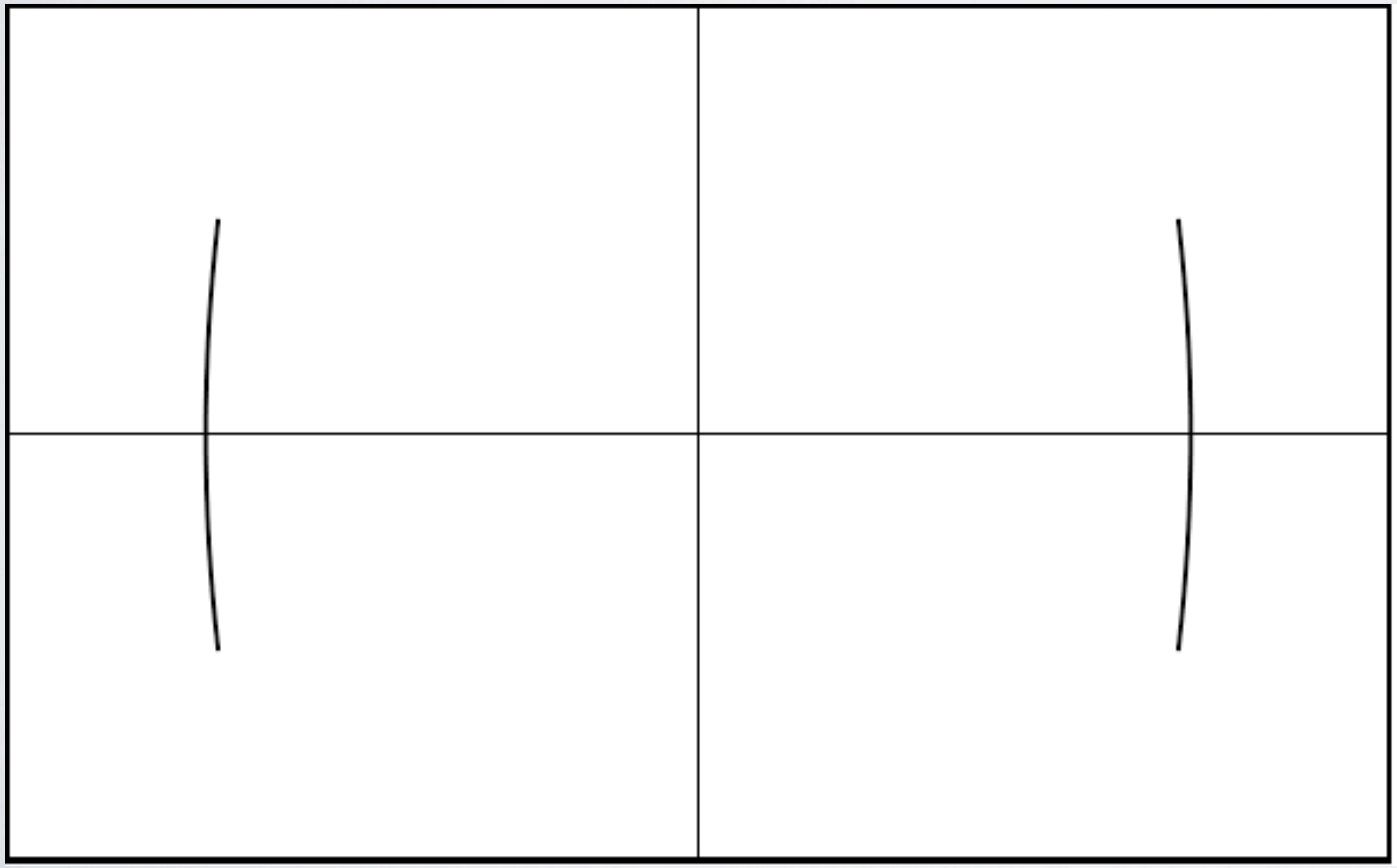

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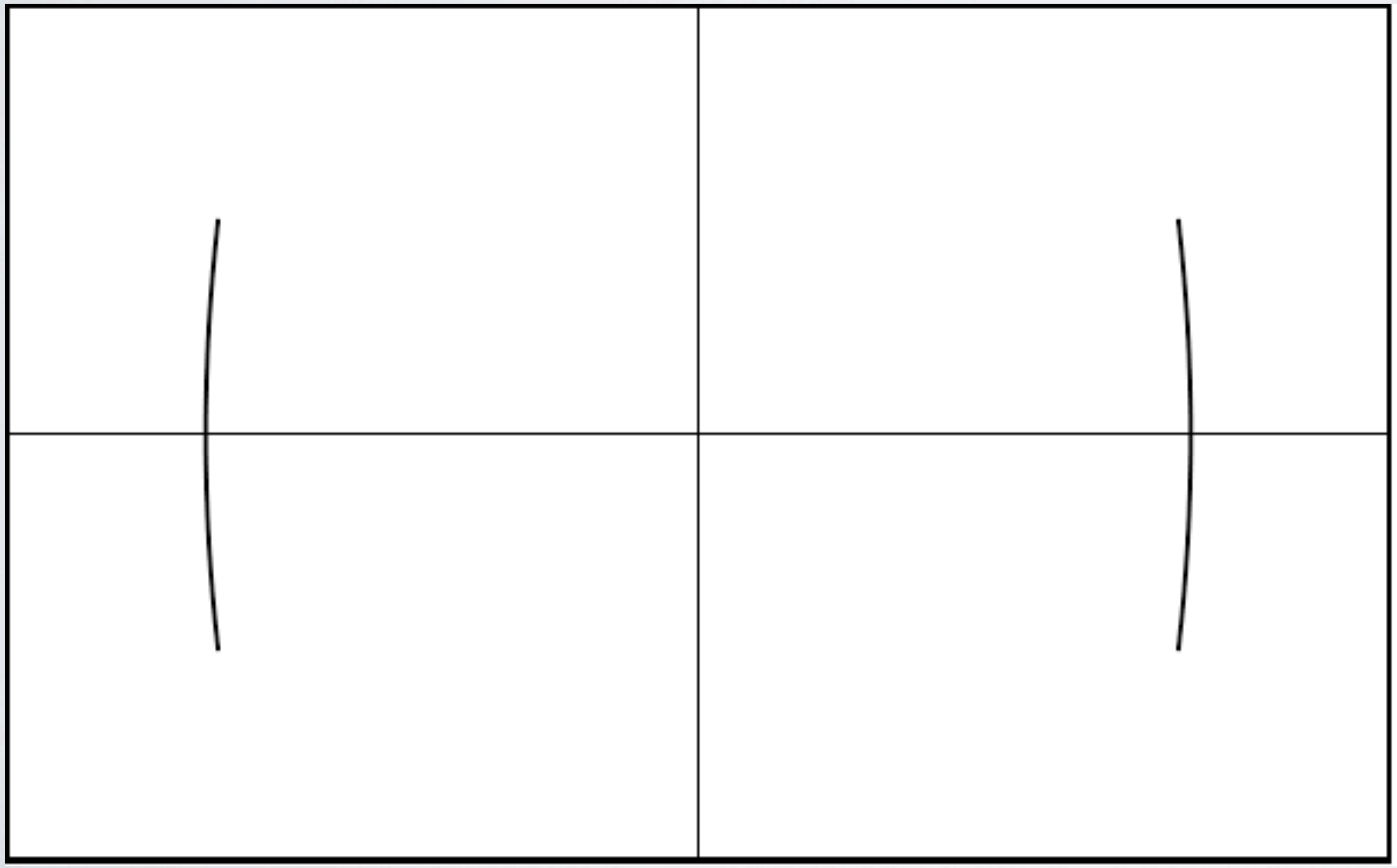

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$$\frac{L}{4} \leq f \leq \infty$$

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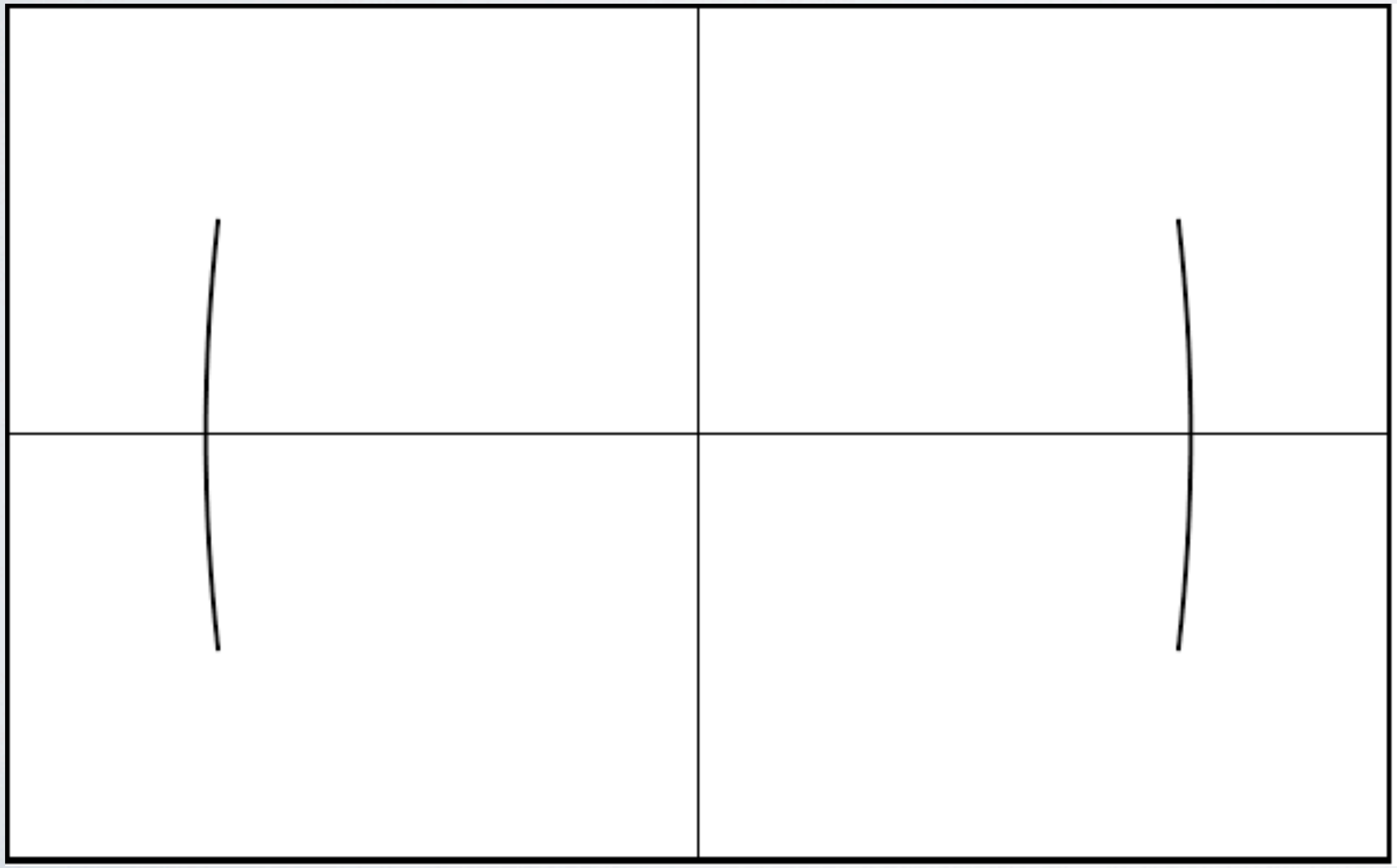

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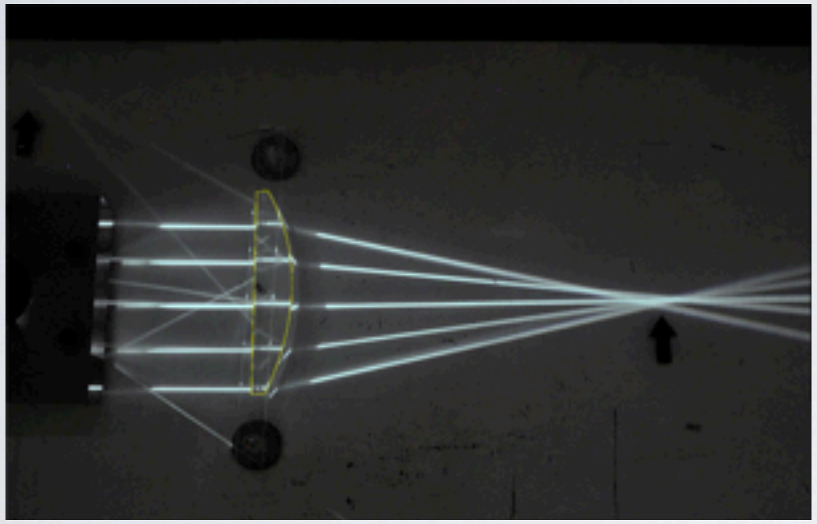
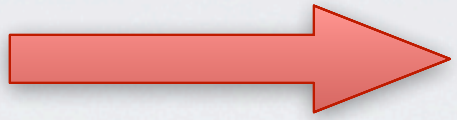
Confining Potential Maximum

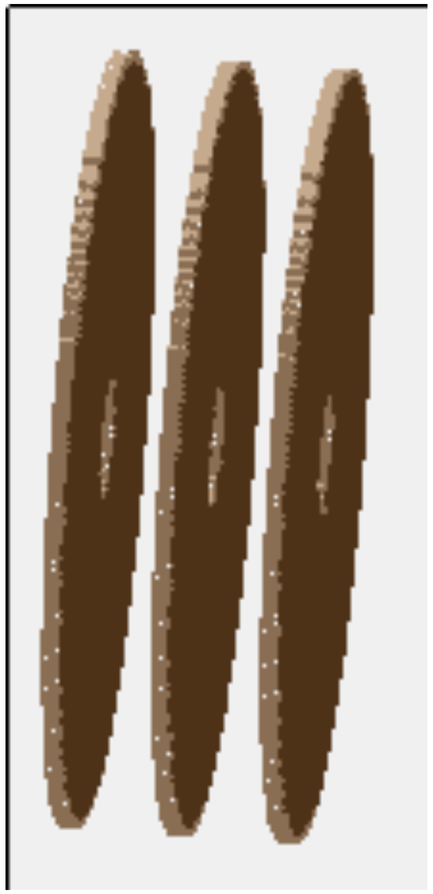
$$q\,e\,V_s > E_k$$

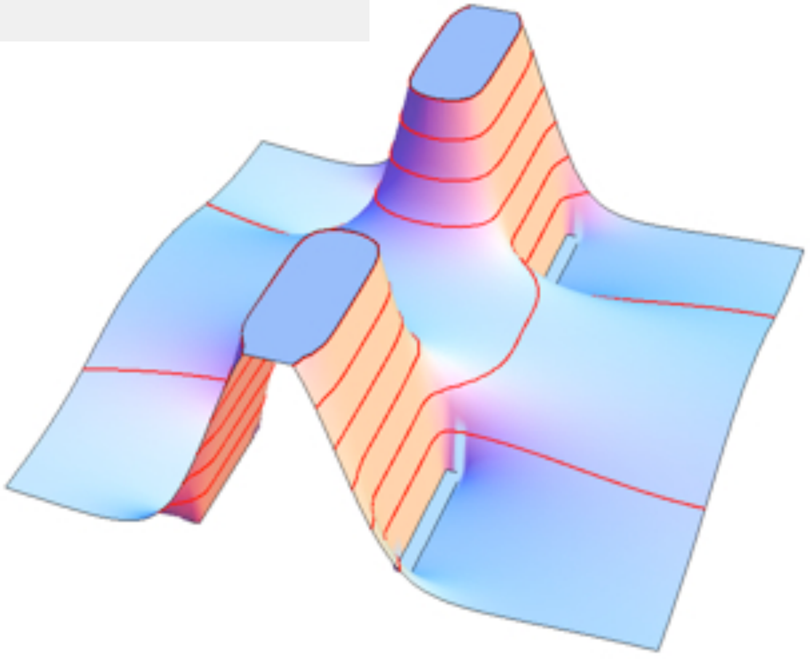
Optics & Ion Optics

Converging/Einzel Lens









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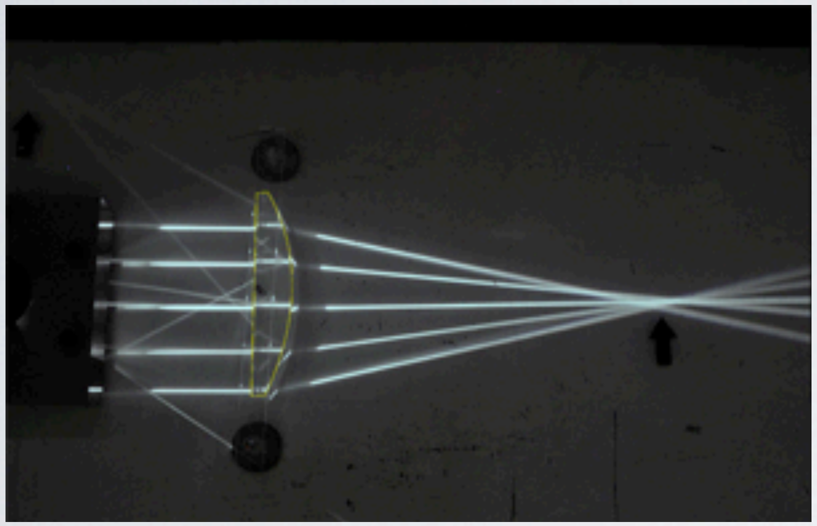

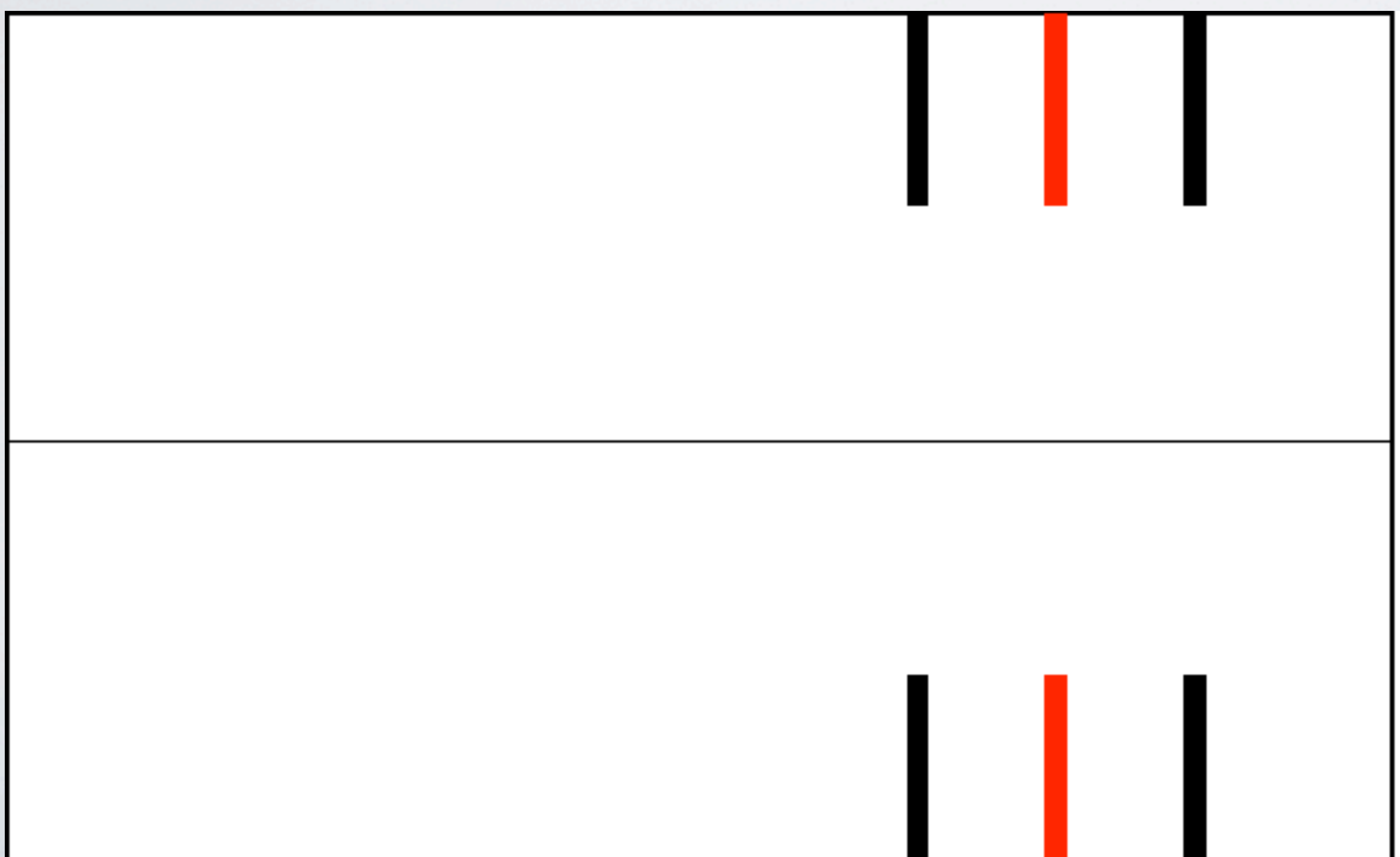

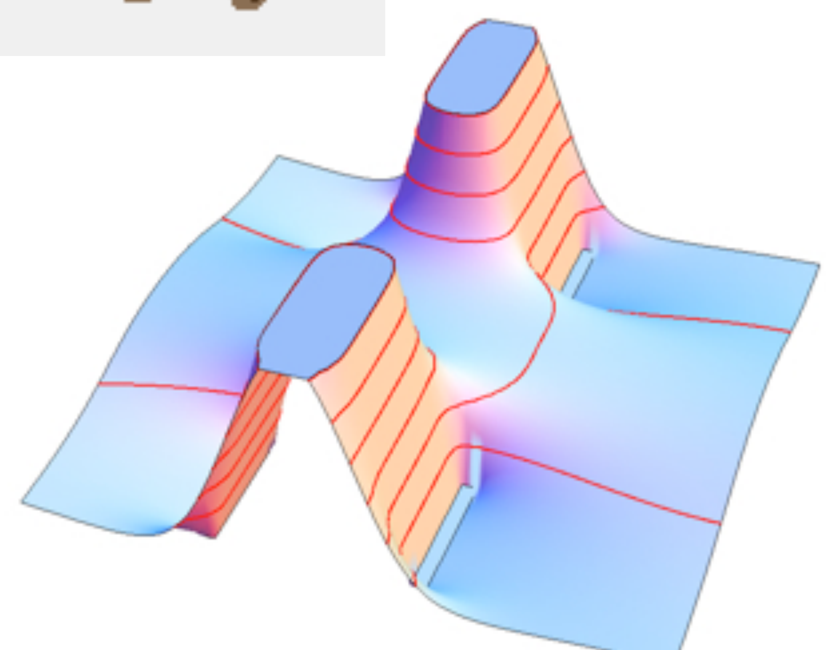

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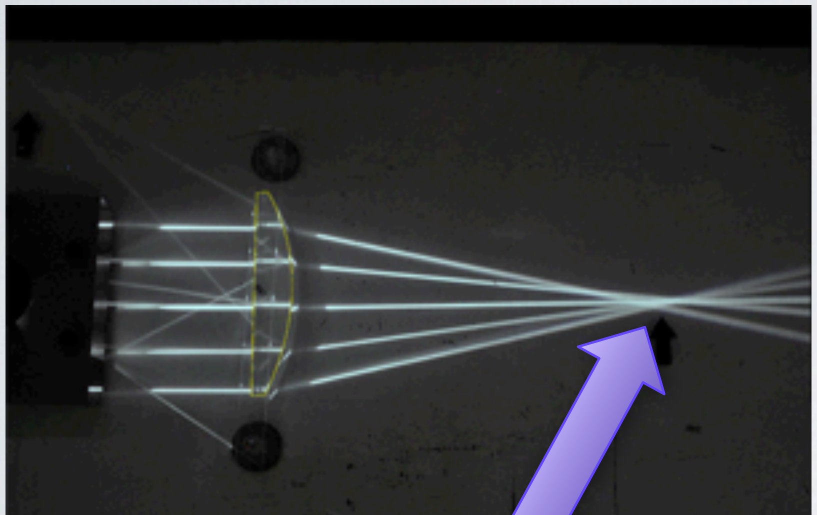
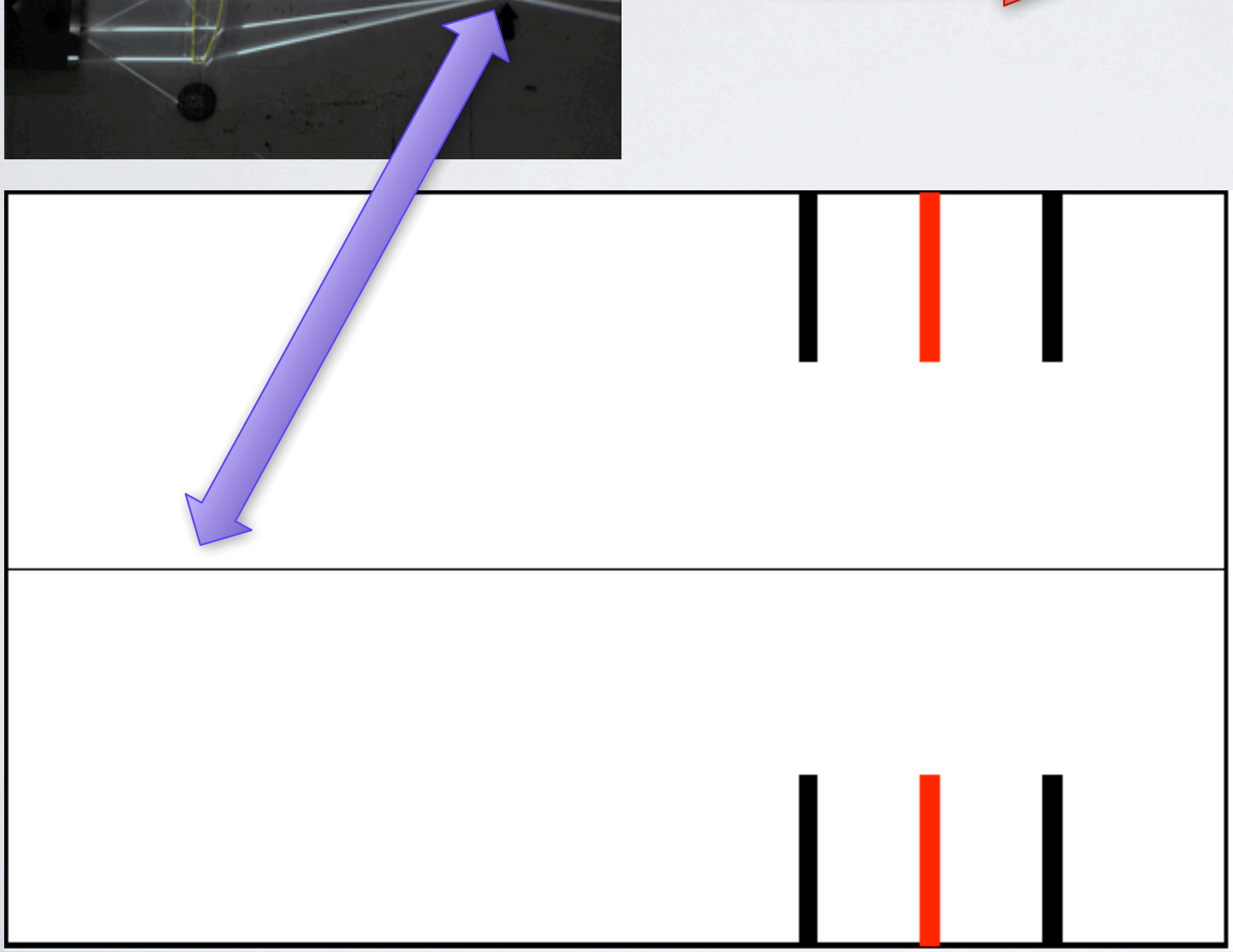
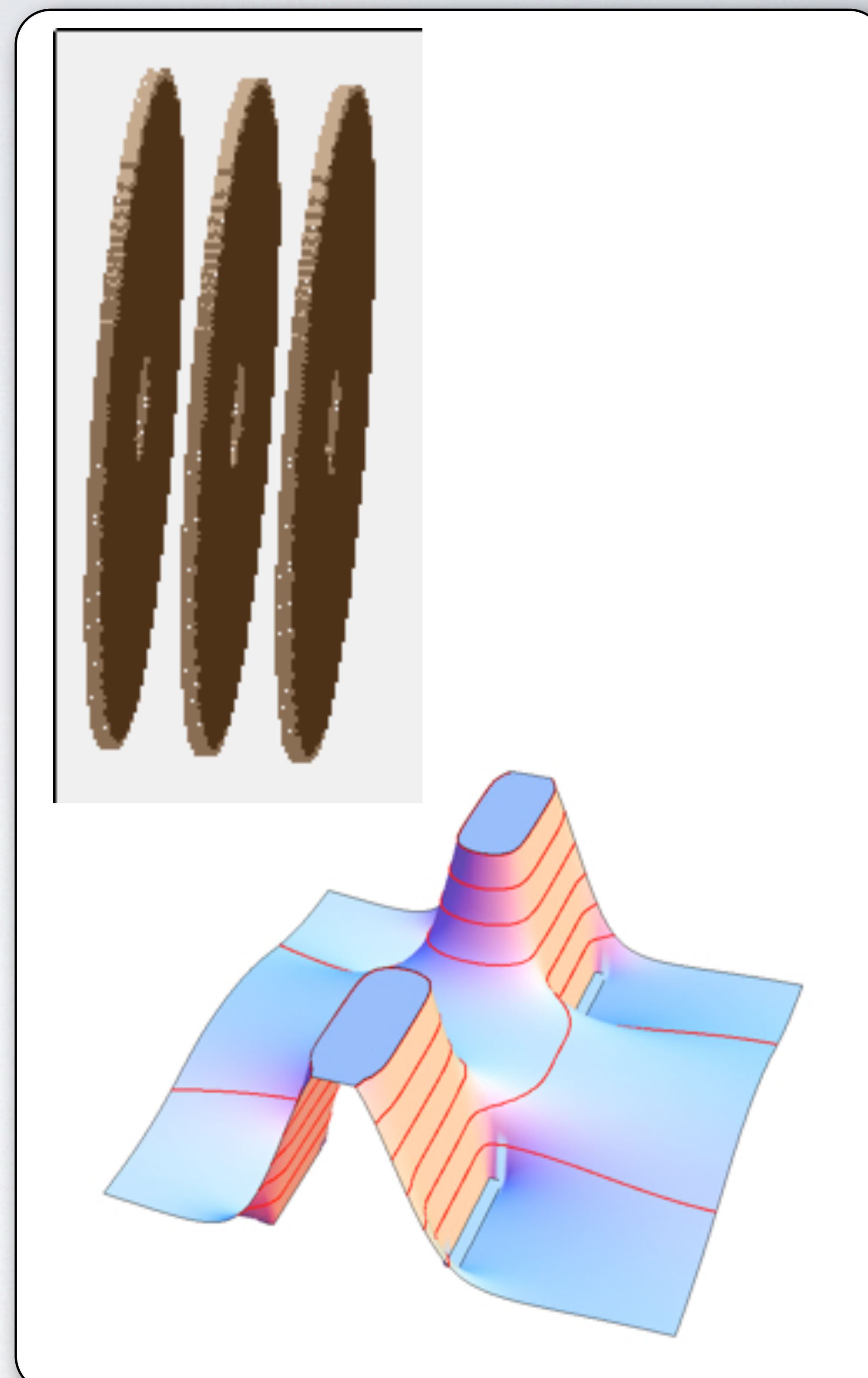
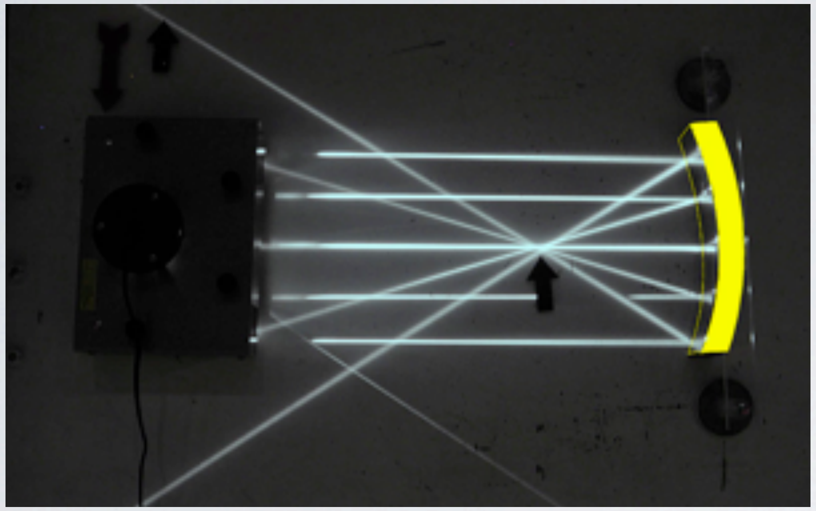


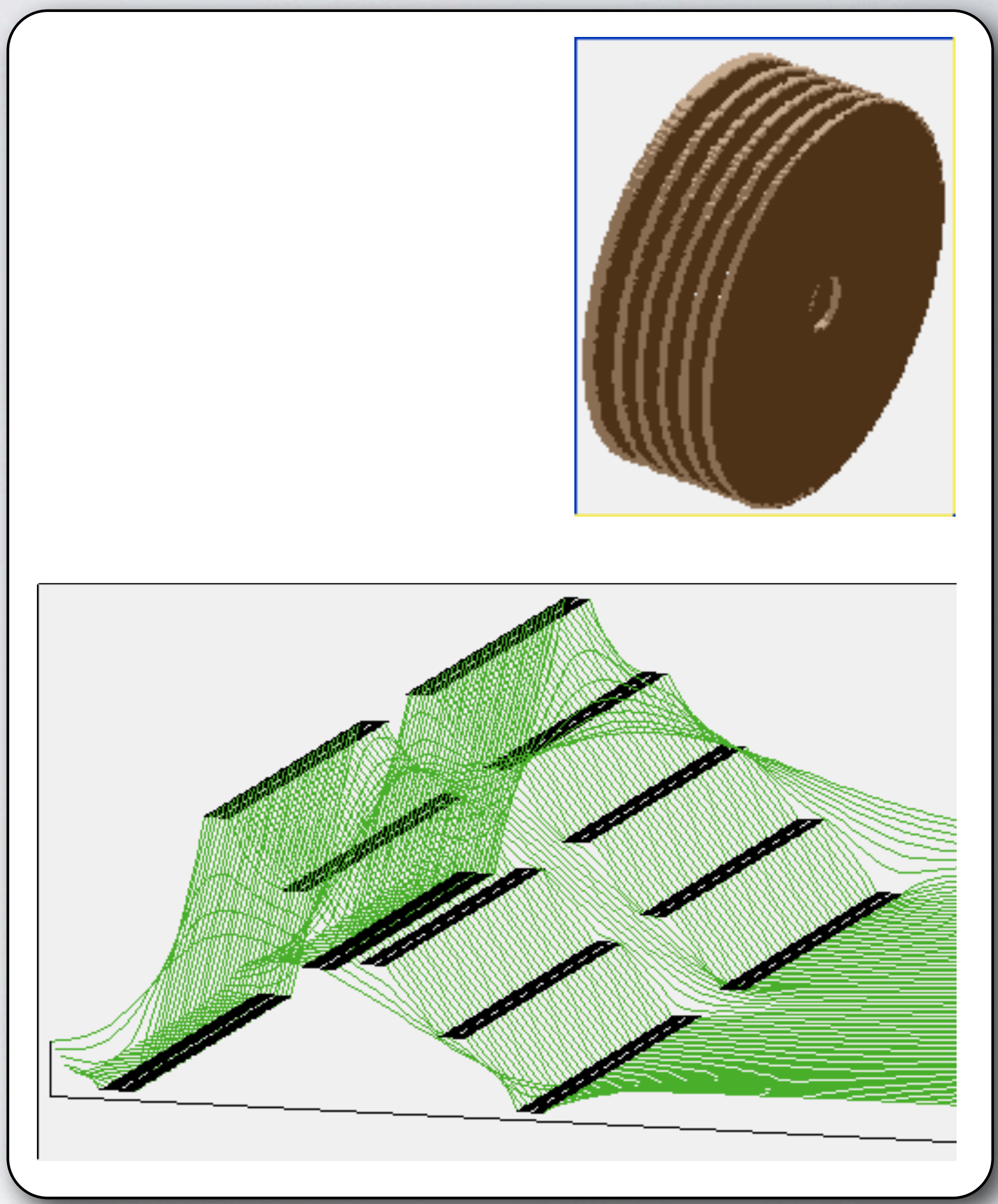




Optics & Ion Optics

Mirrors





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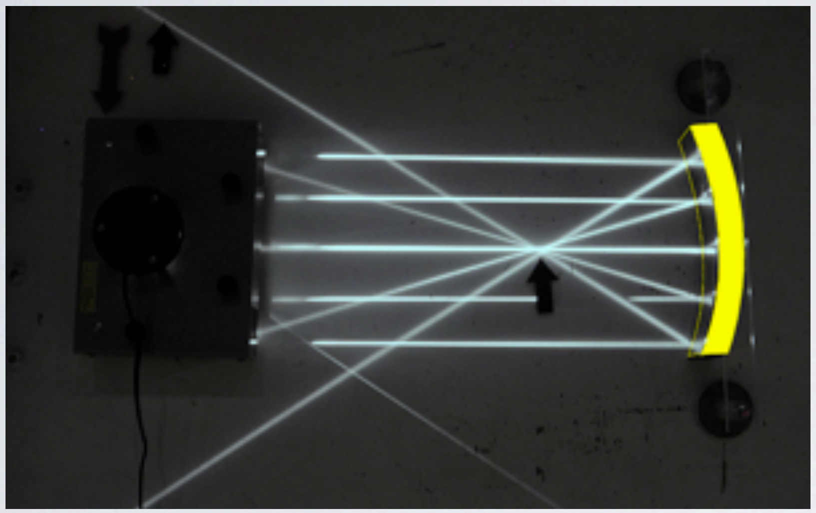

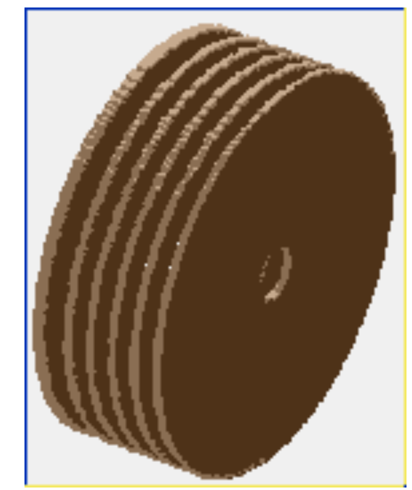

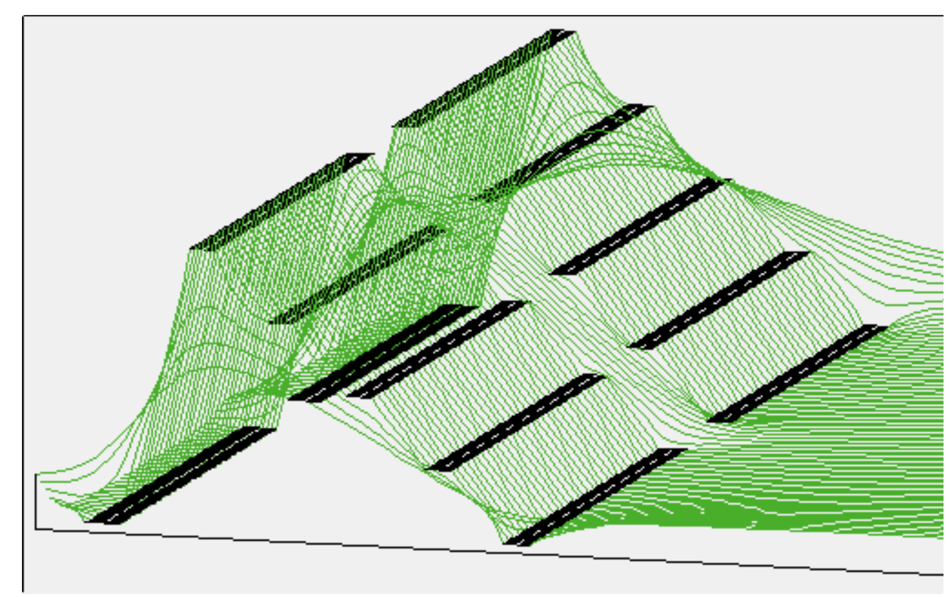

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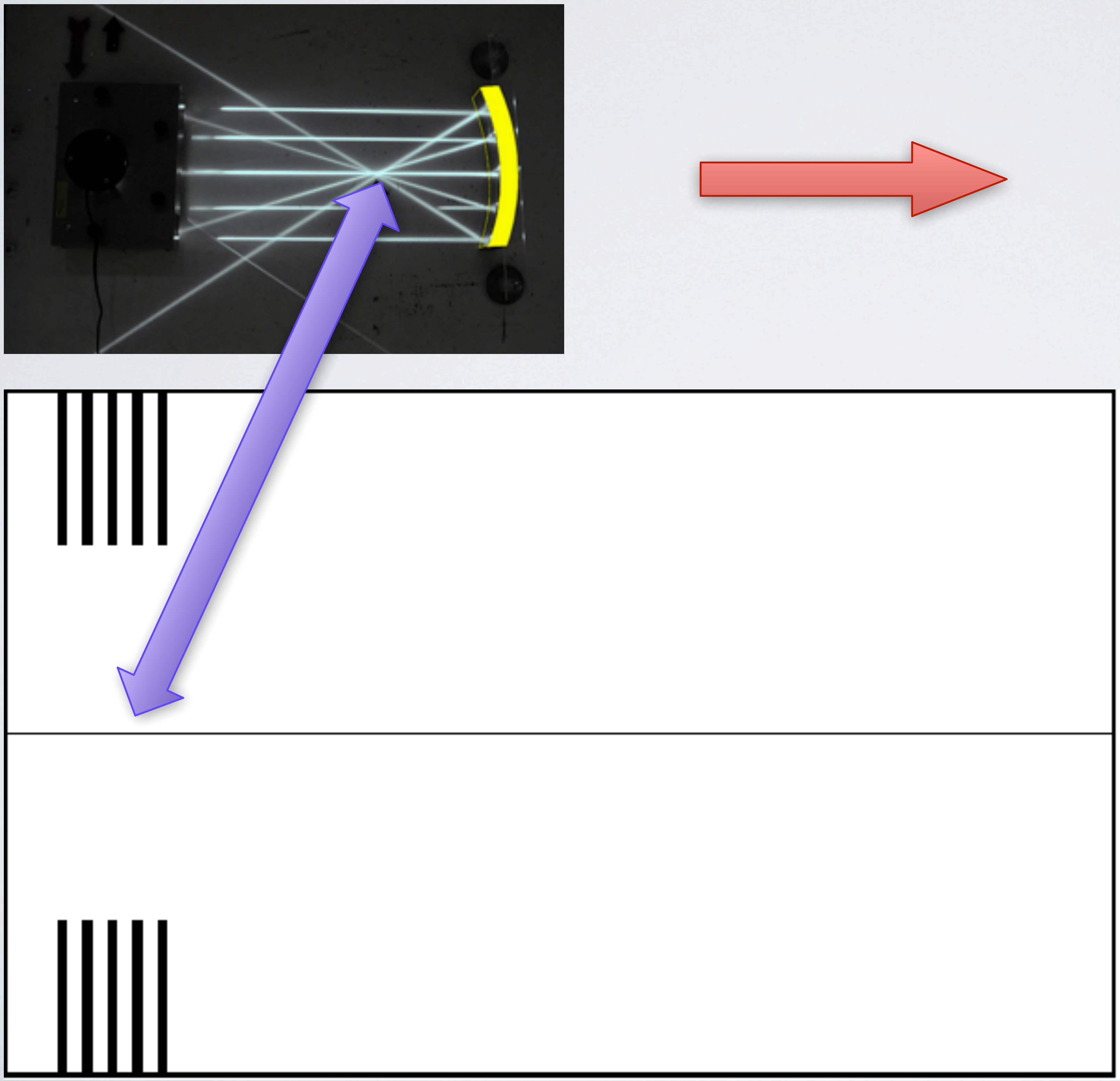
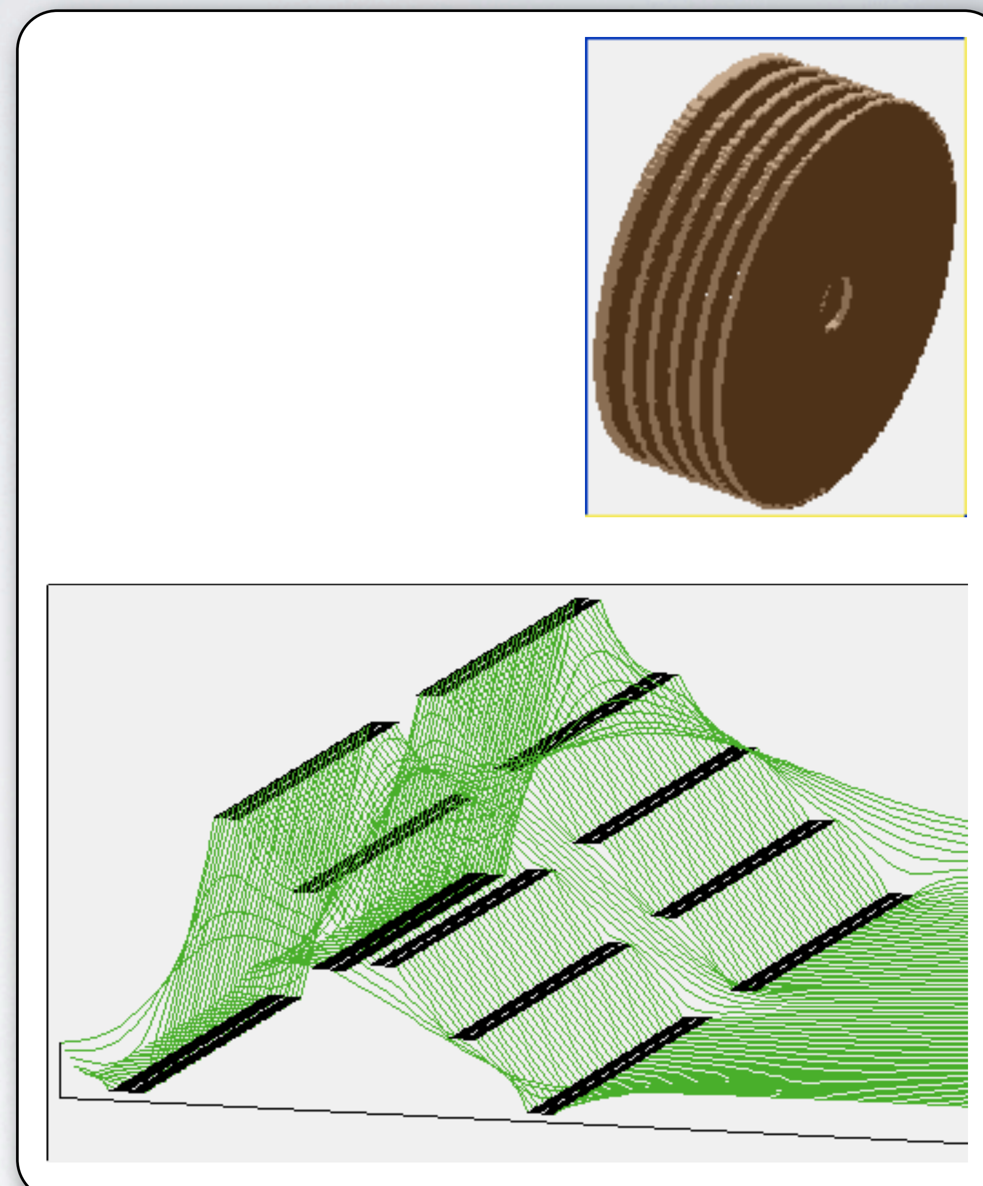
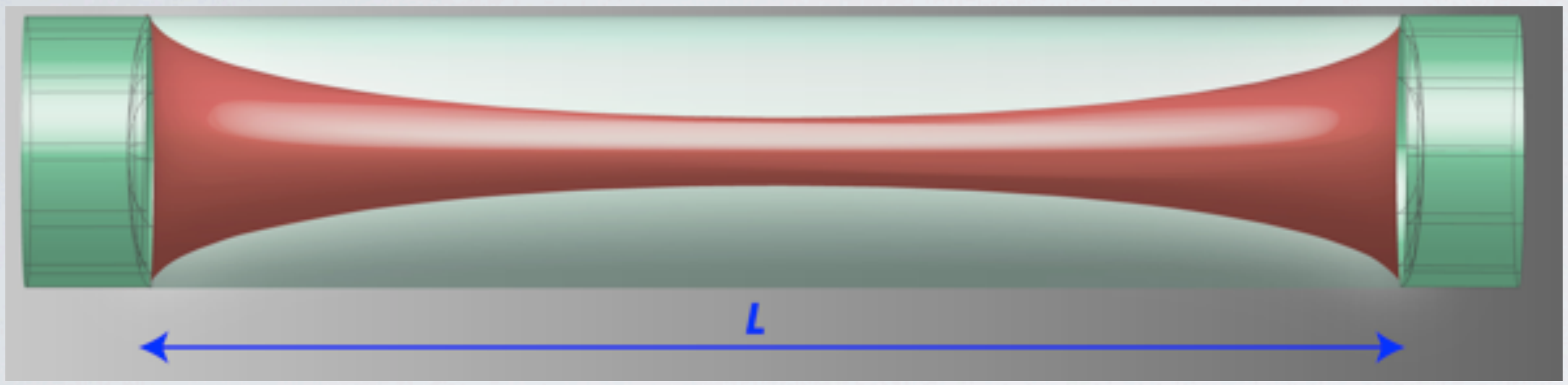
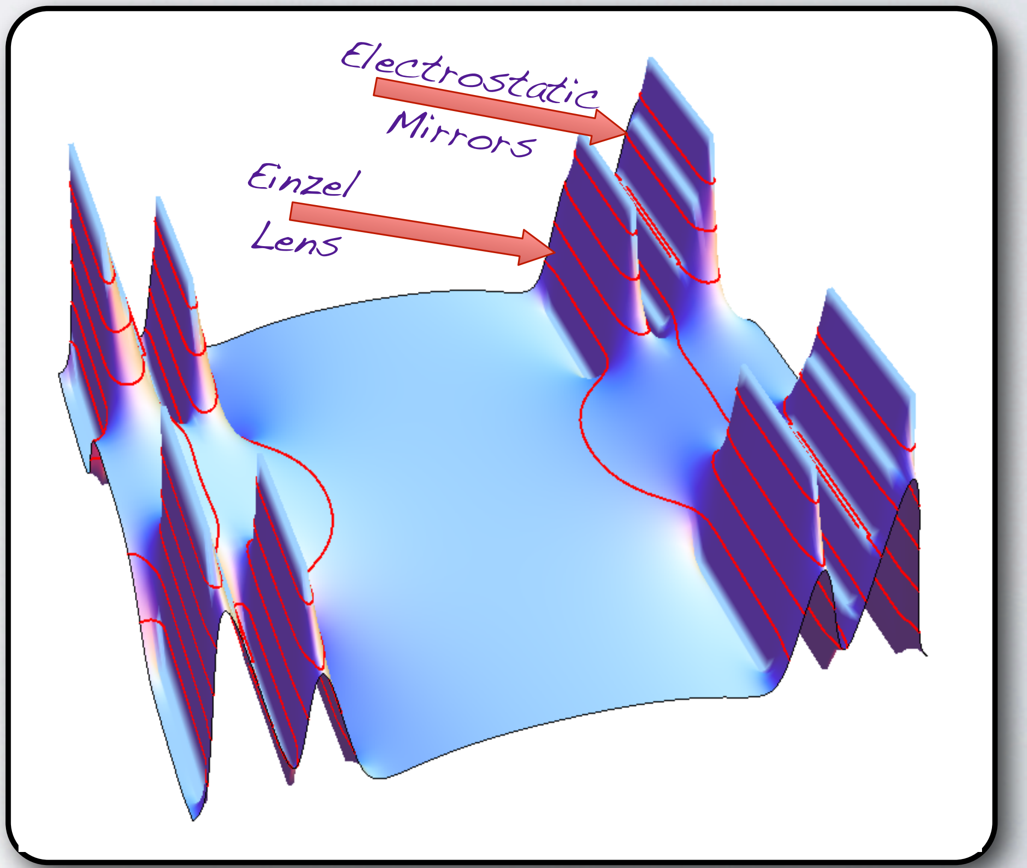




Putting It Together

An Ion Resonator





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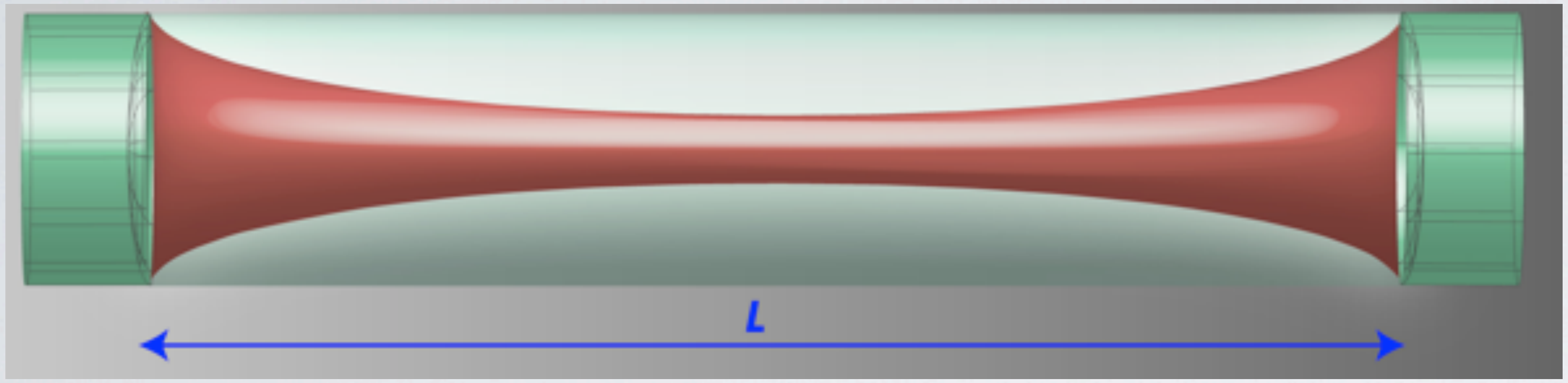
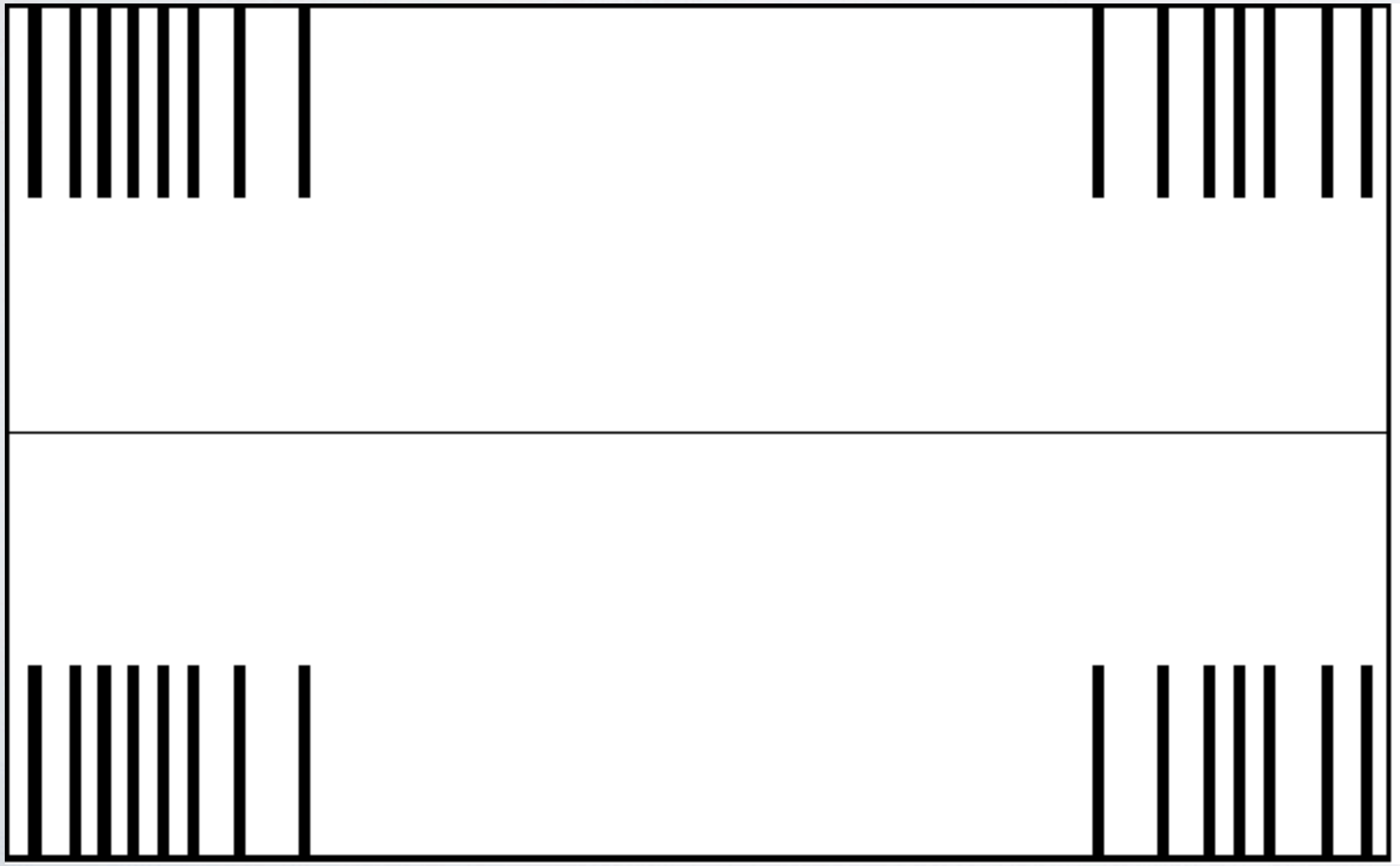
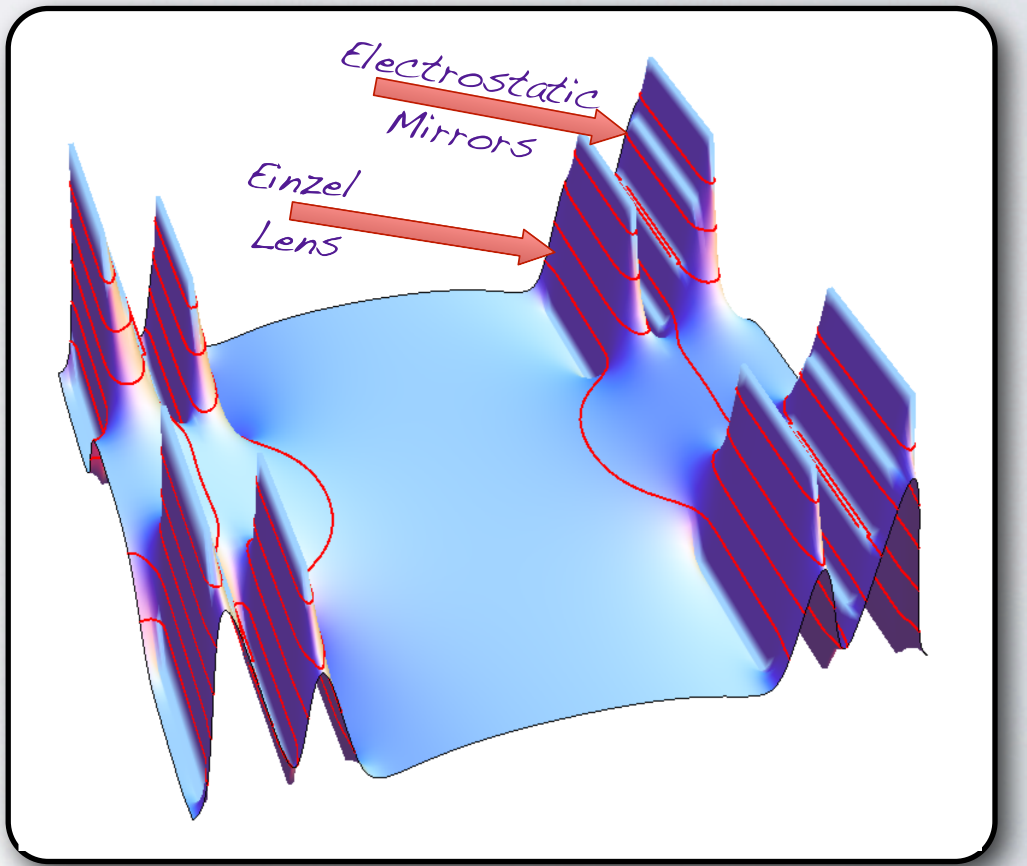
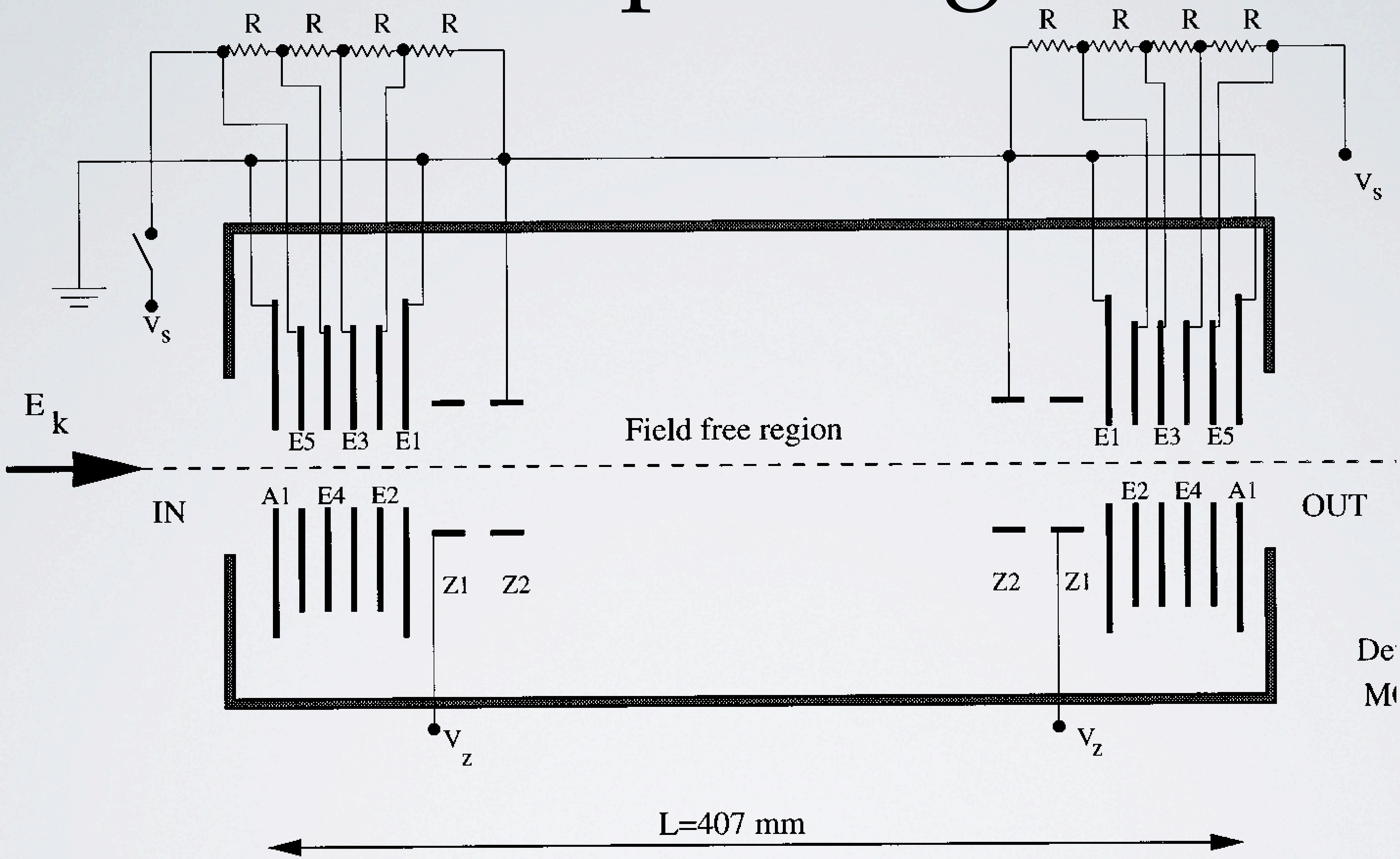


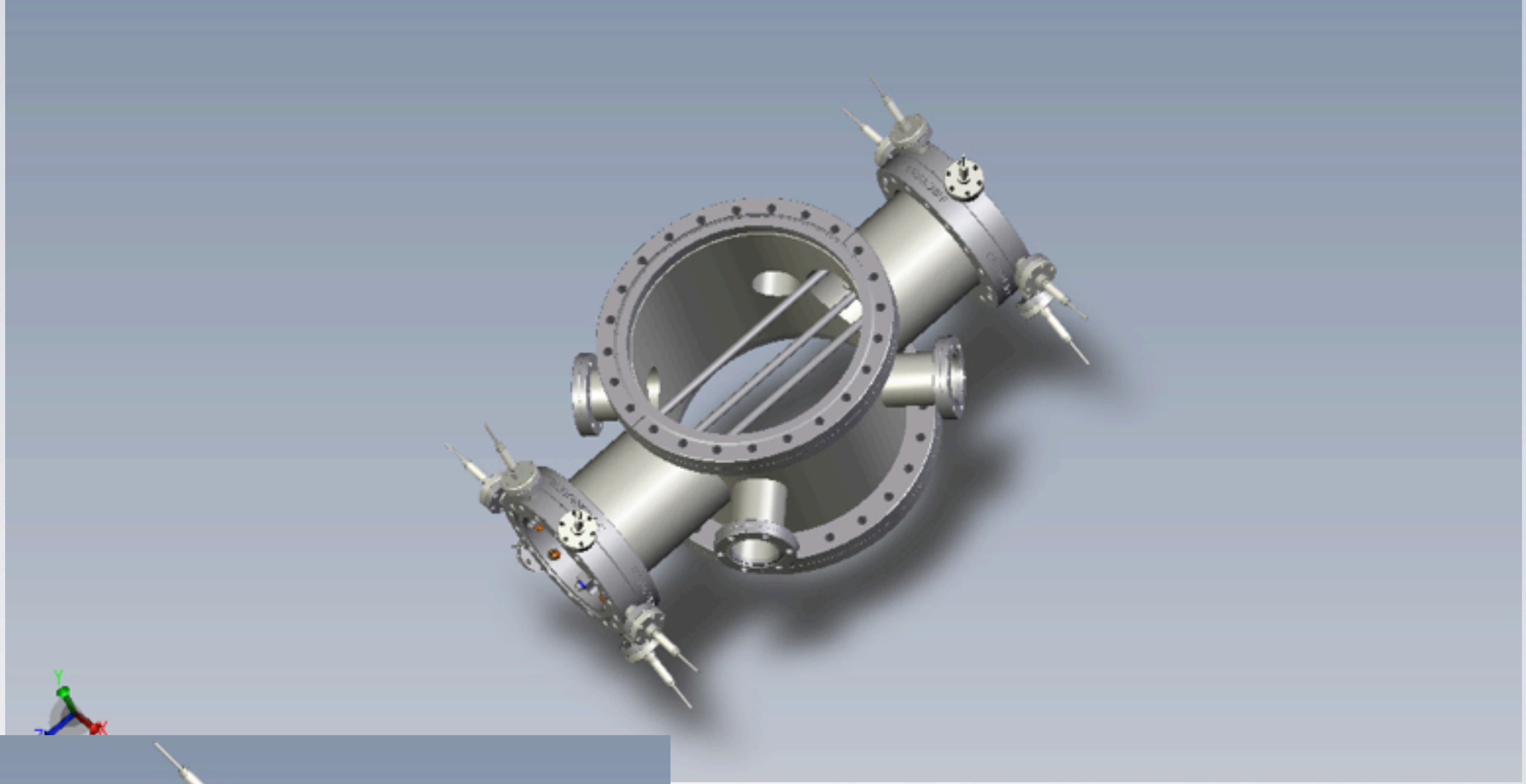


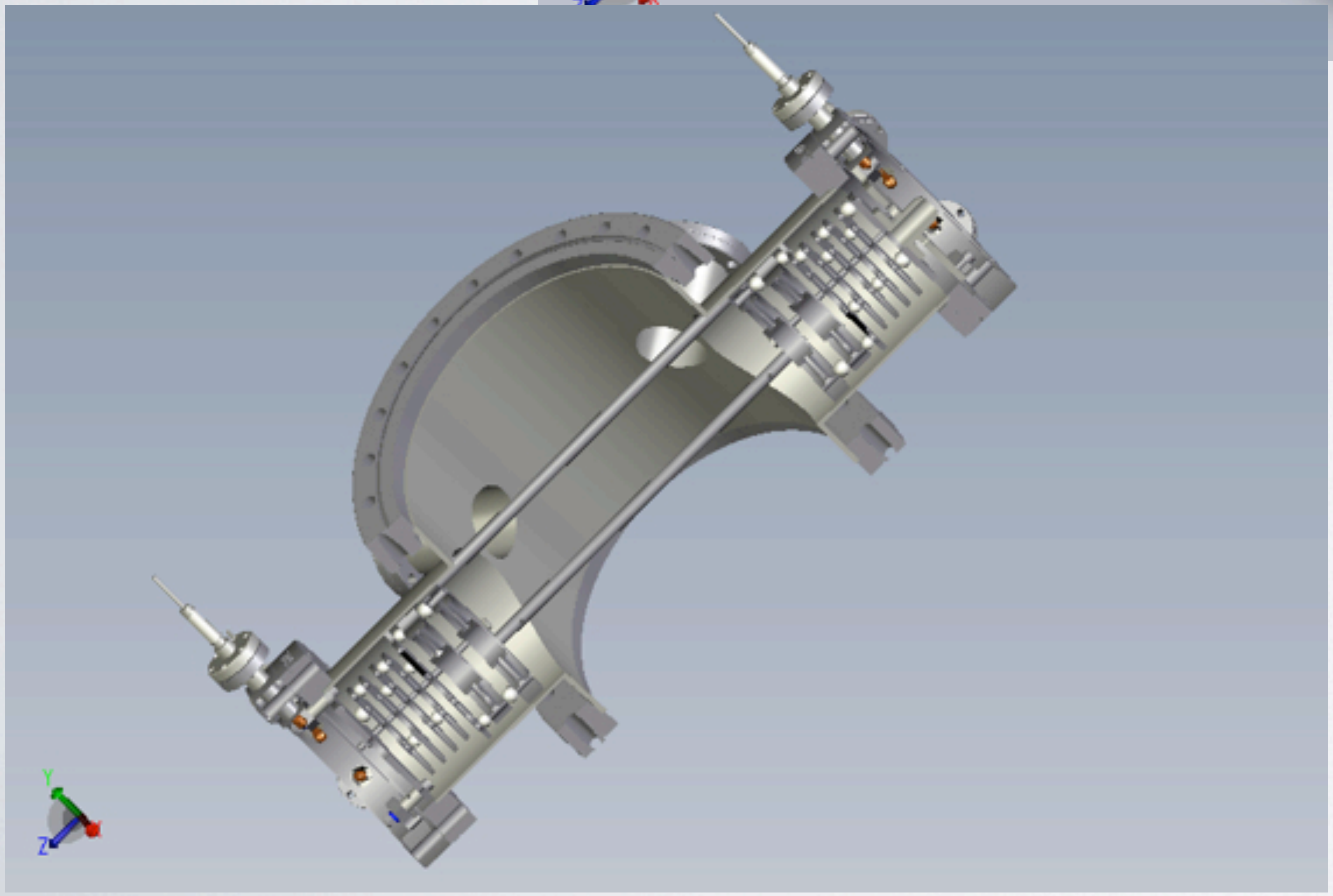


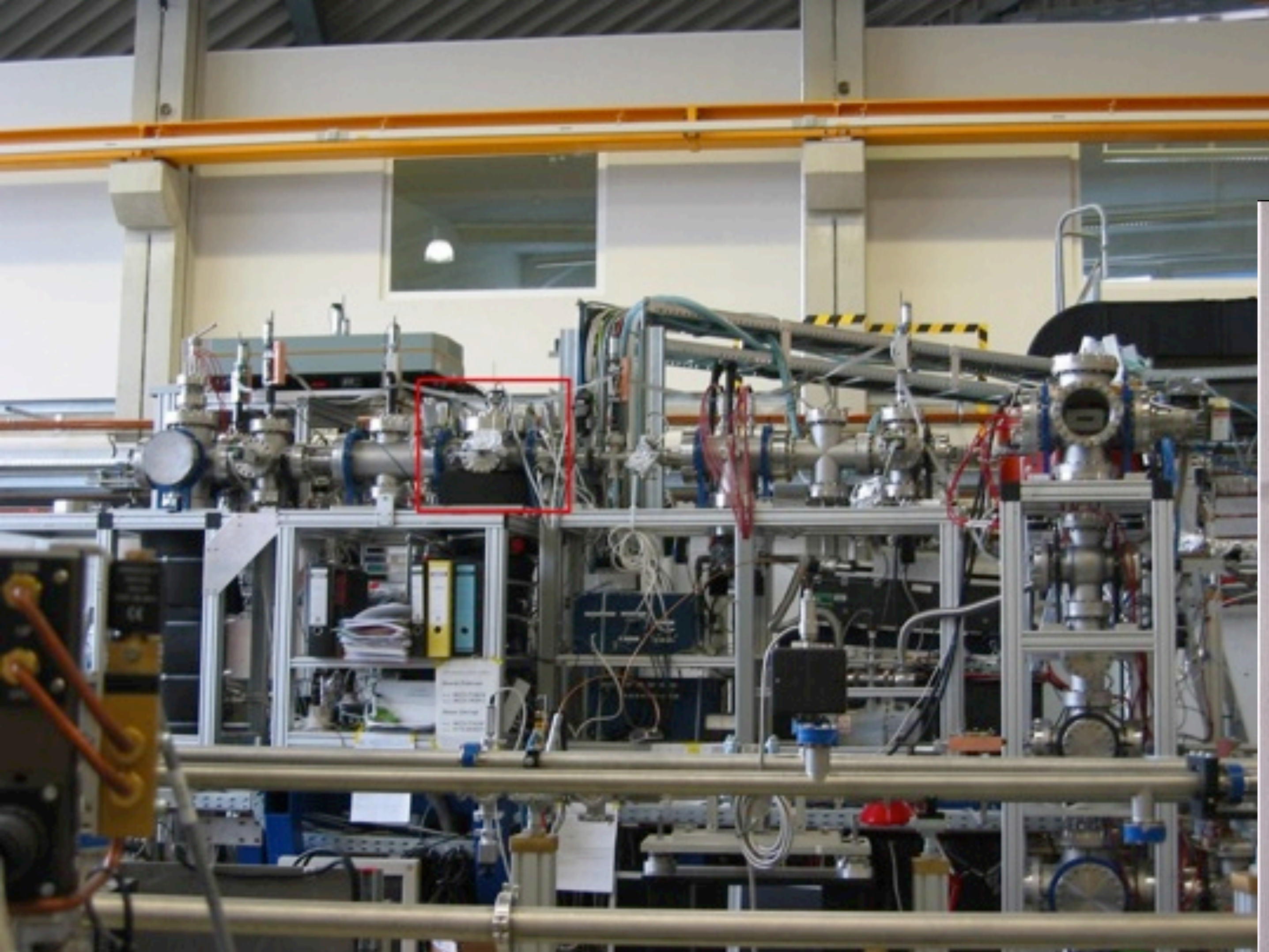
Trap Design



Realized at the Weizmann Institute (Israel). Also used in a cryogenic setup in Heidelberg. And being built at LBL.

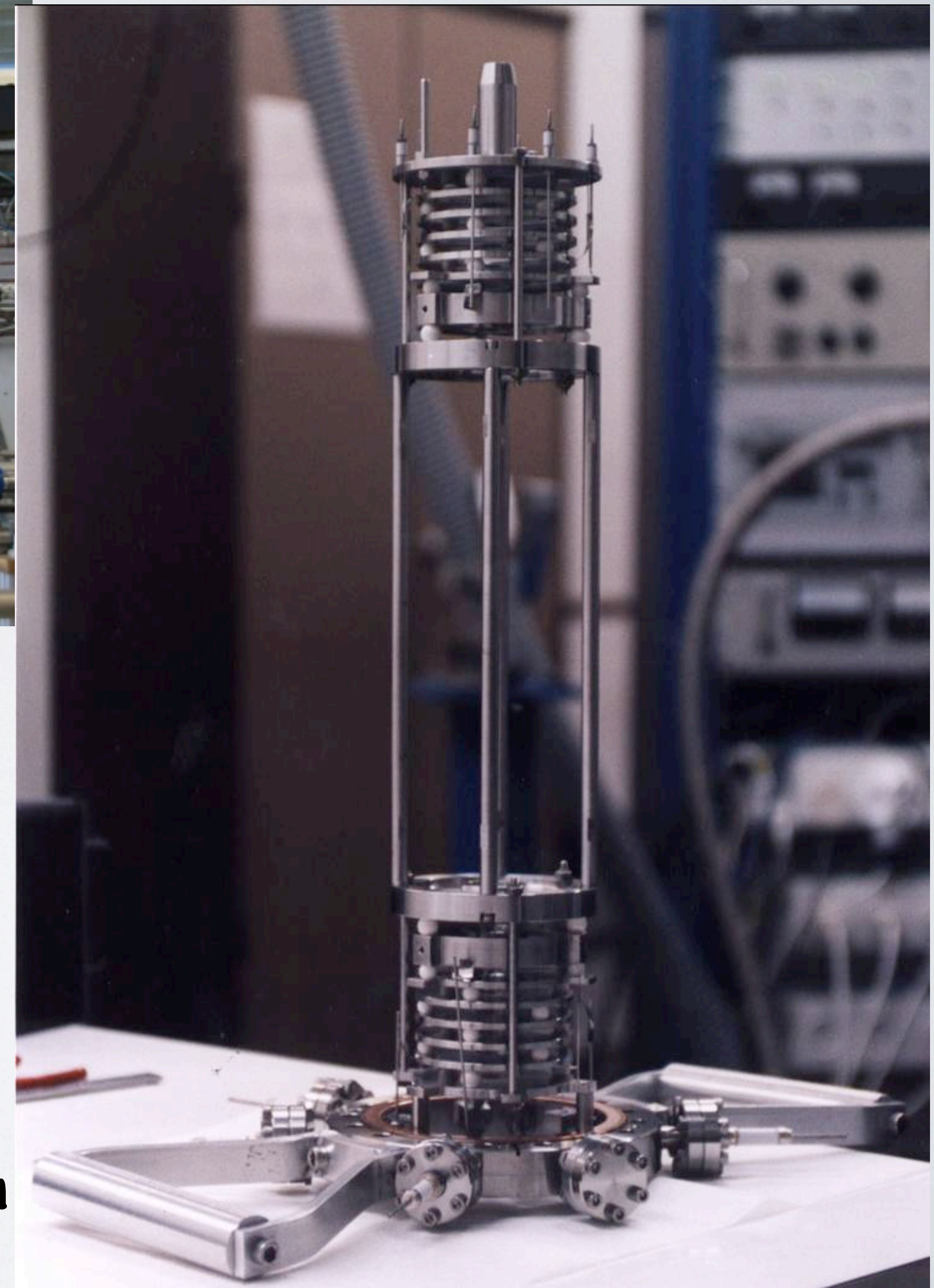




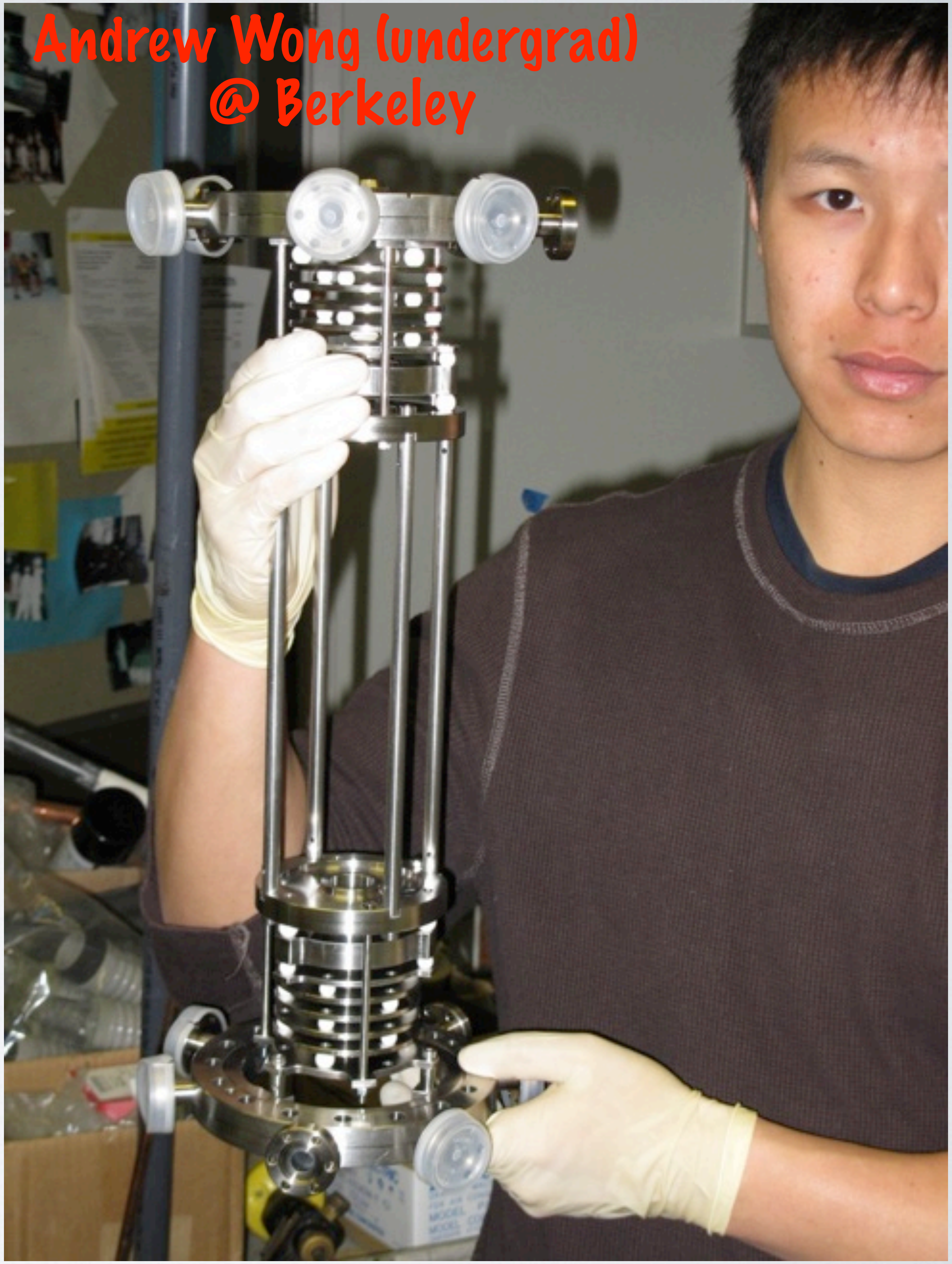


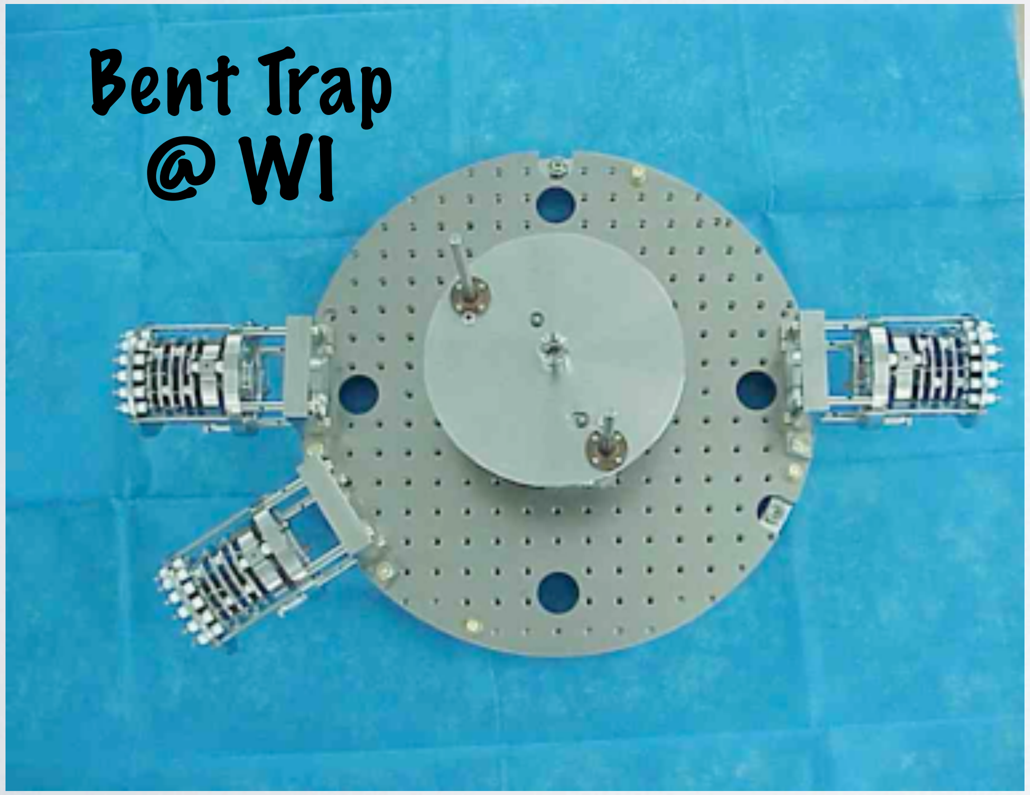
Heidelberg Trap

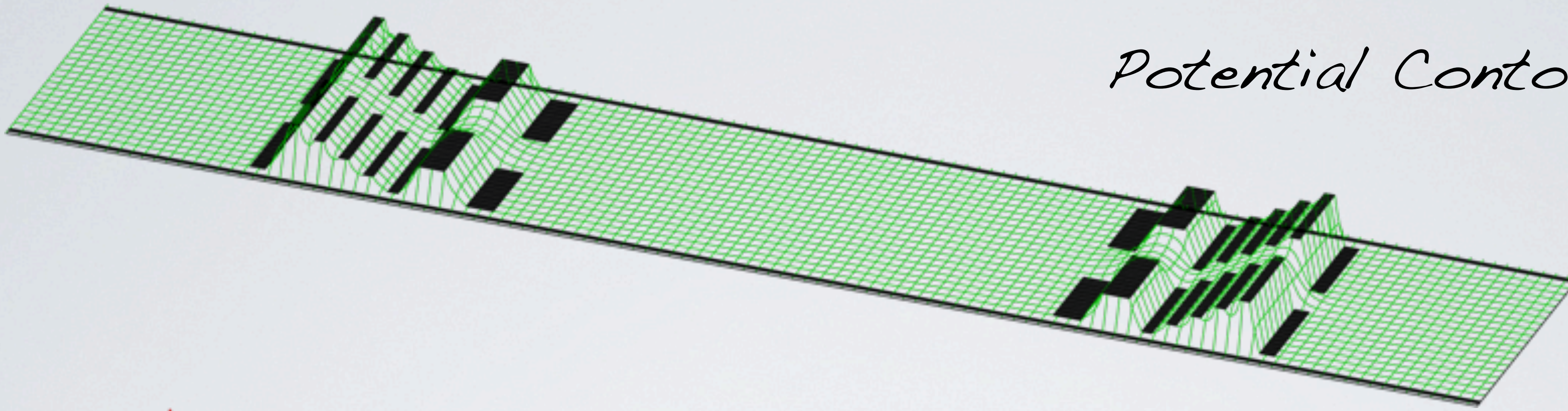
Trap
@
Weizmann
Institue



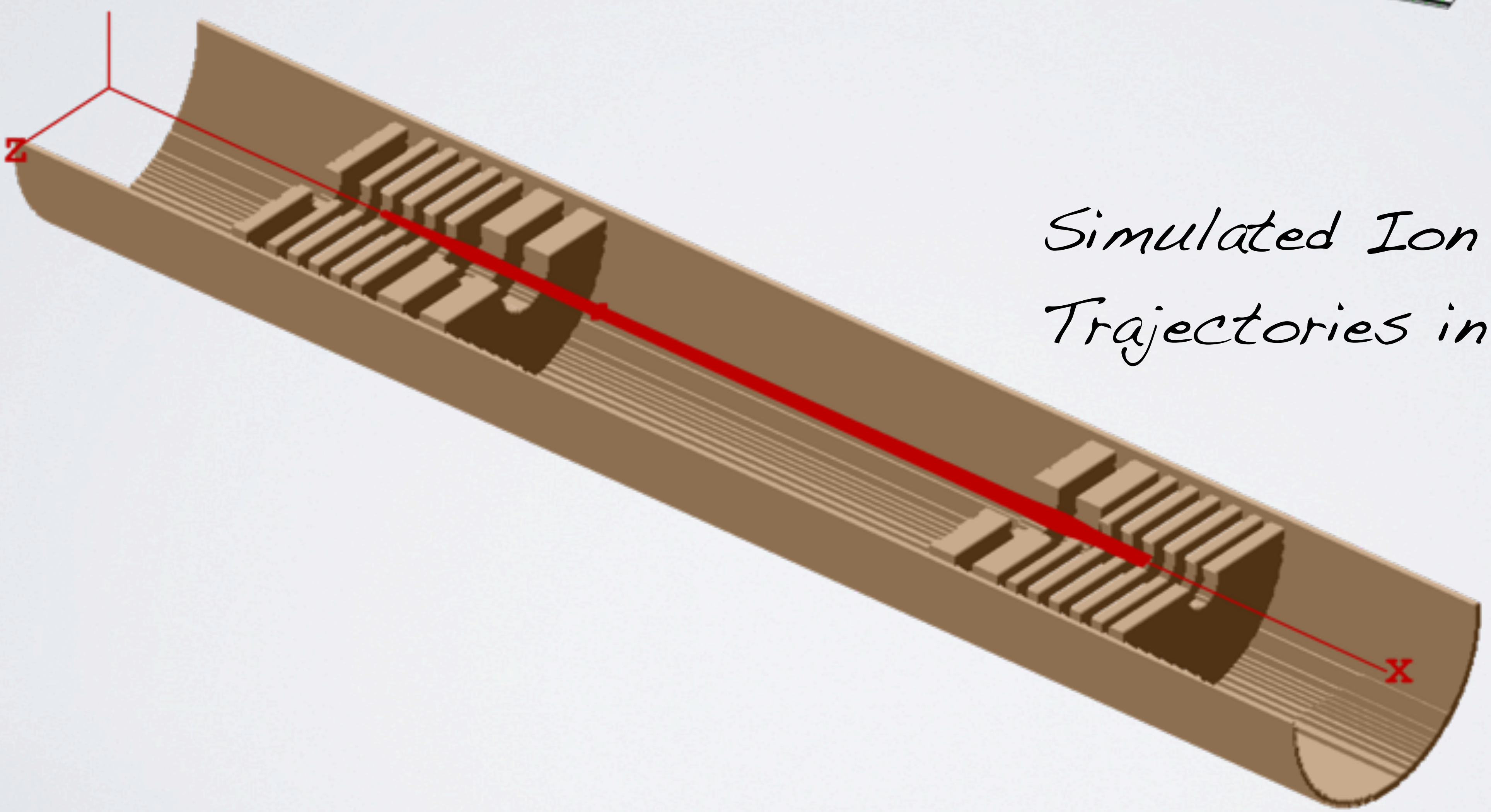

Construction
@ LBL


Andrew Wong (undergrad)
@ Berkeley


Bent Trap
@ WI



Potential Contours

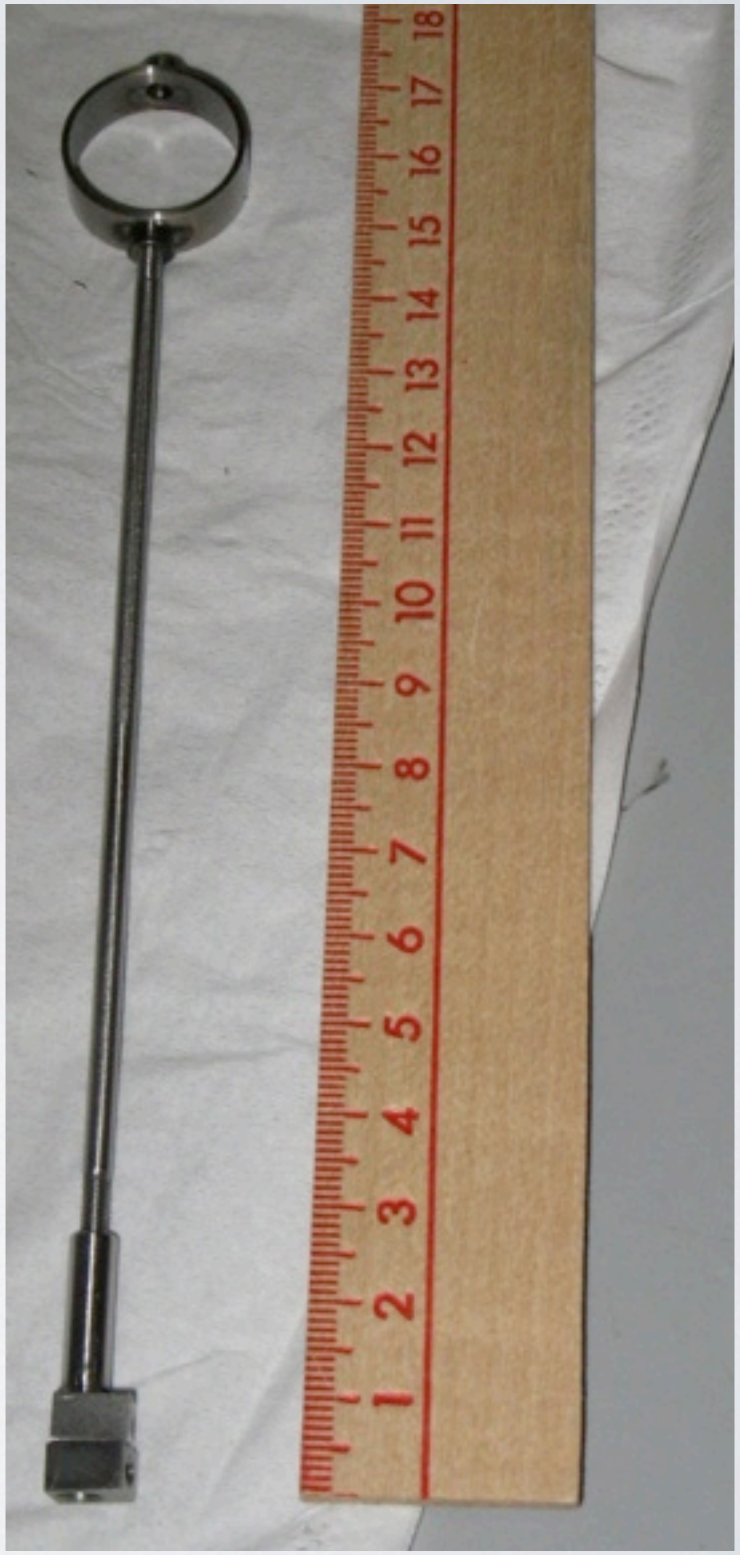


Simulated Ion Trajectories in Trap

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).

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



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

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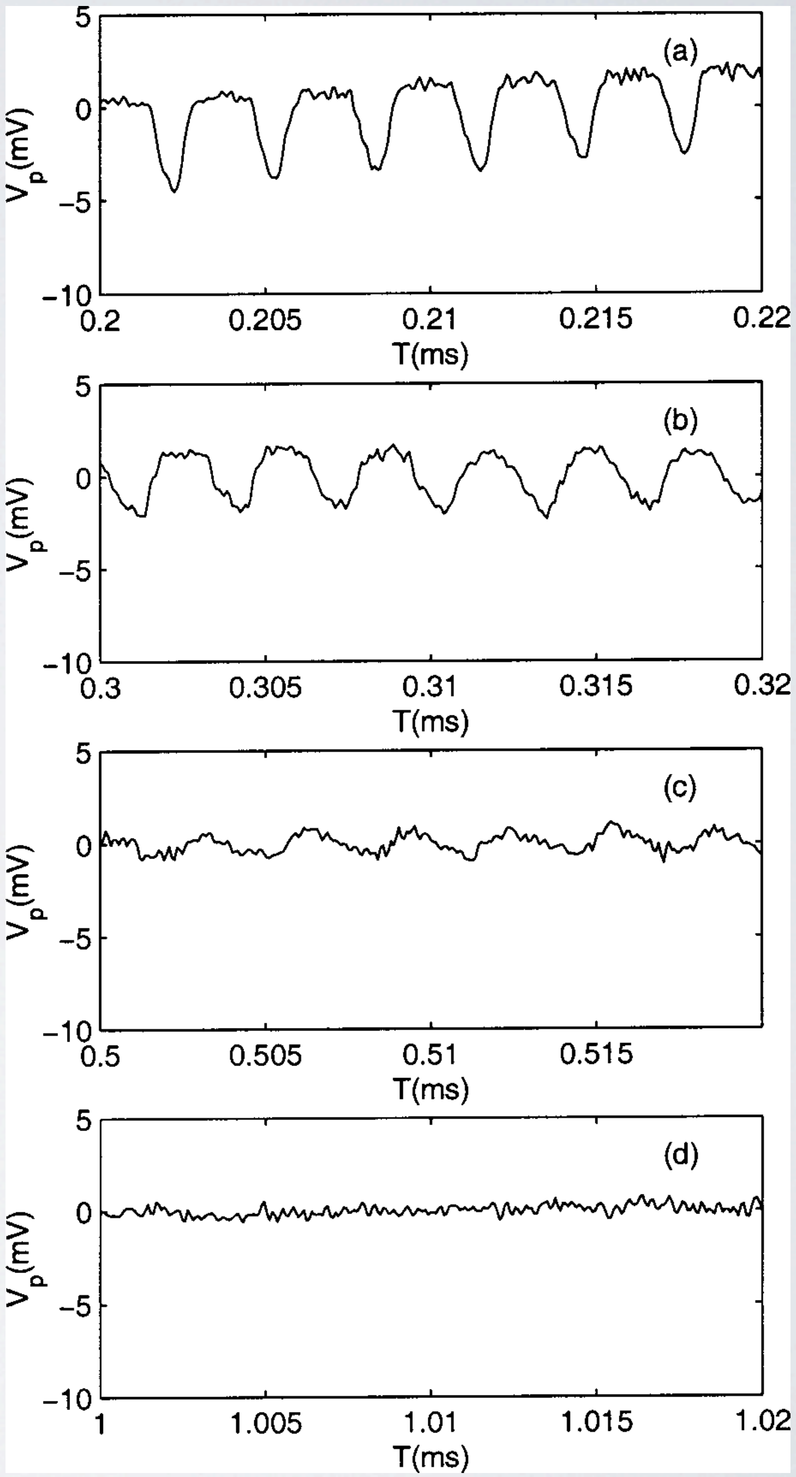
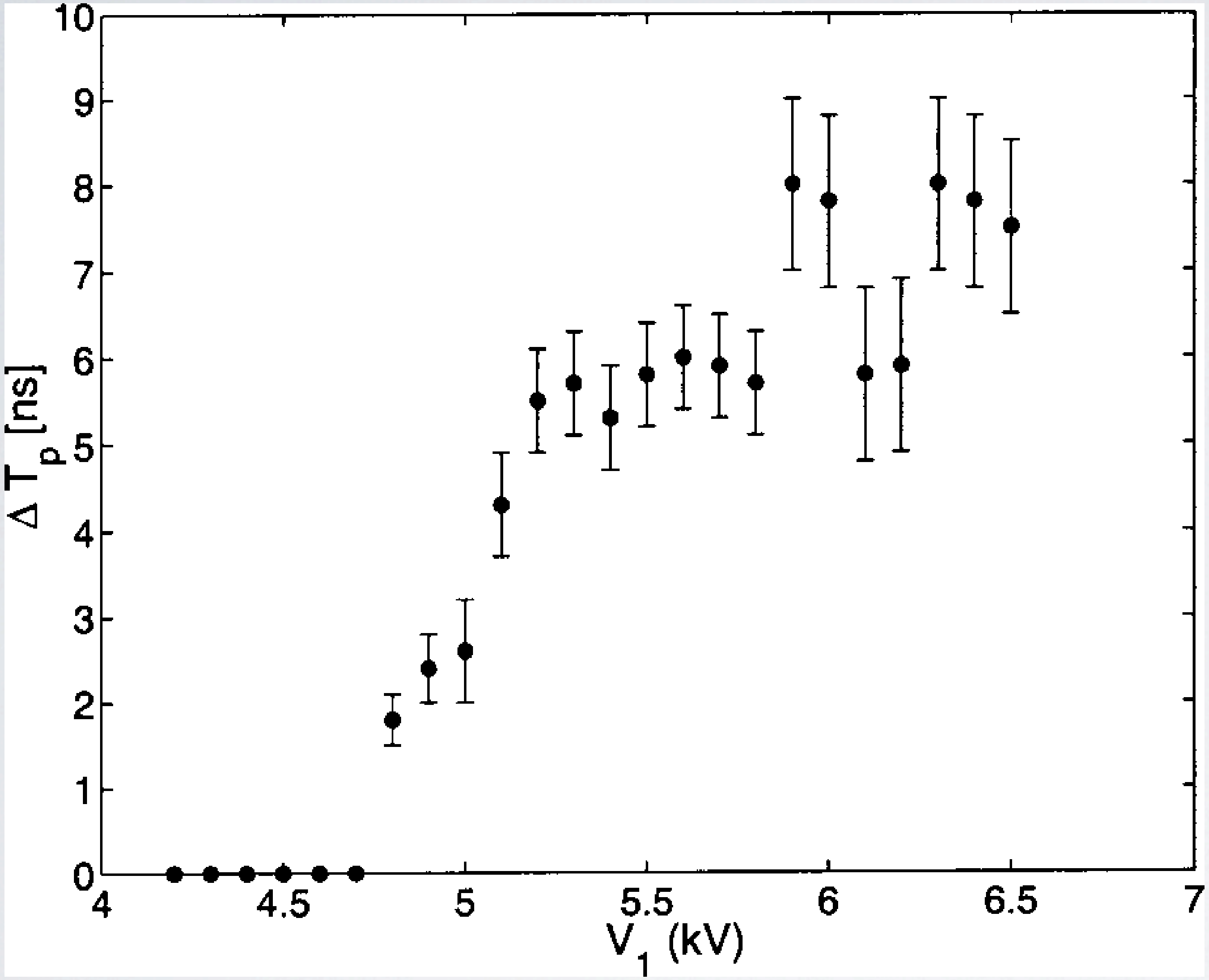
Signal in pickup electrode for different times after injection.



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...



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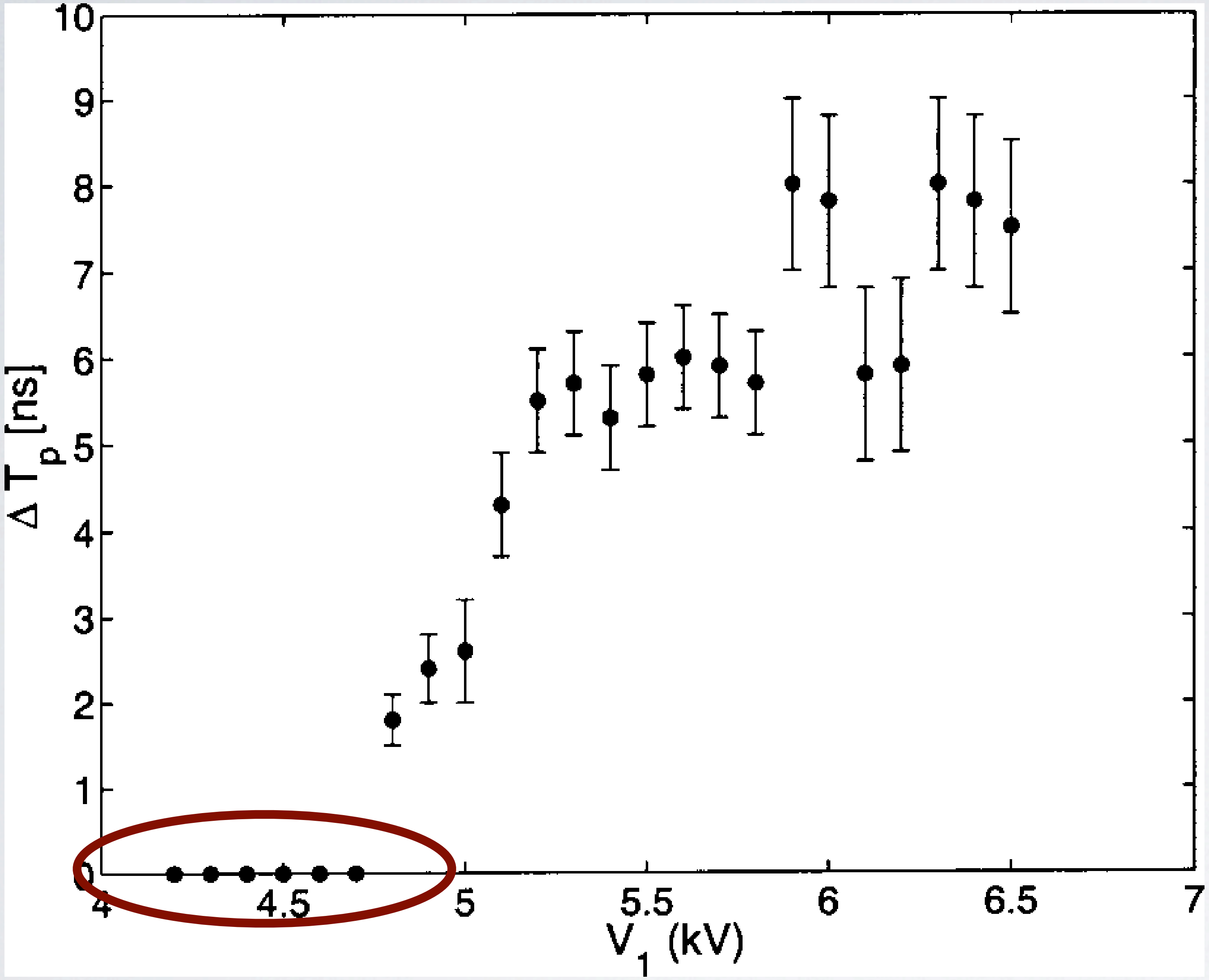

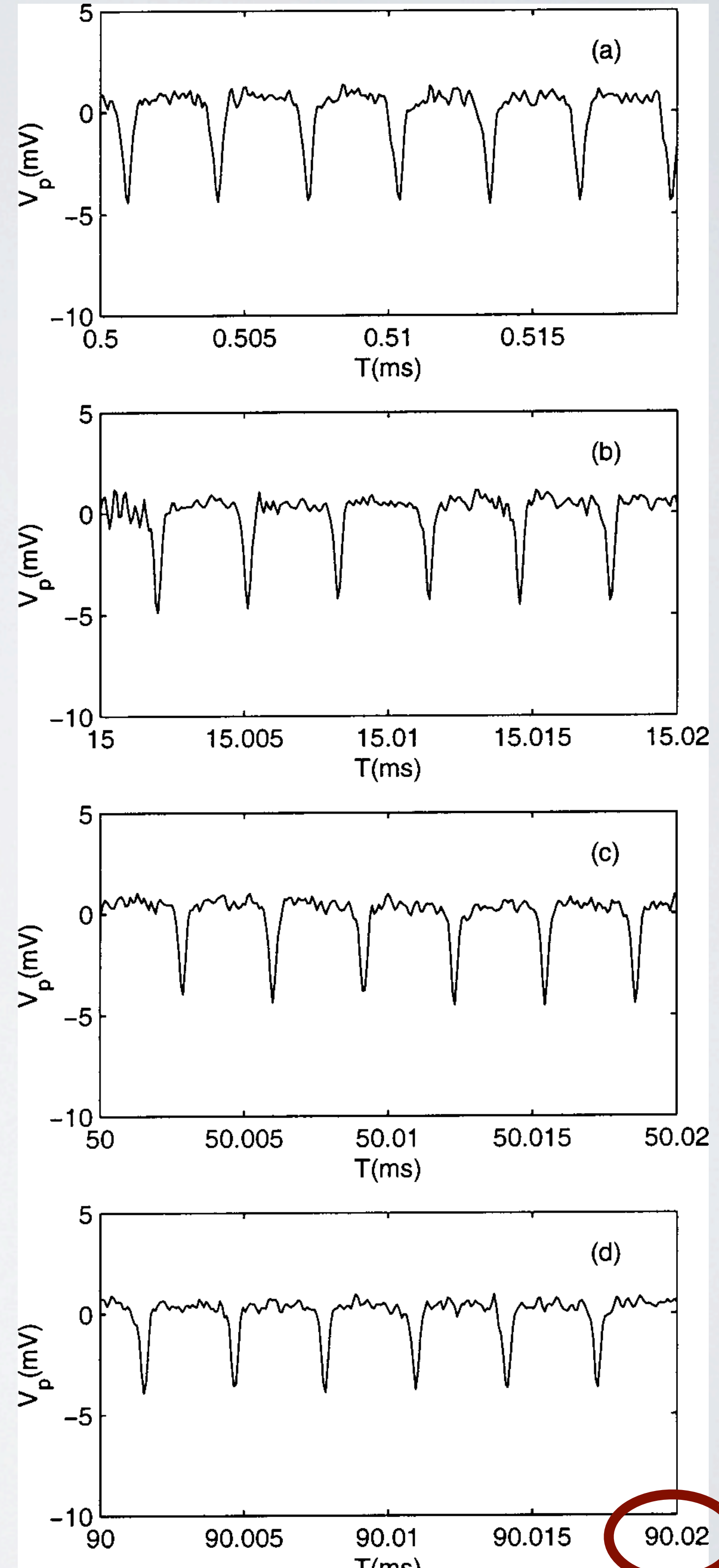

For some values of the potential there is no dispersion!

Why?

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

1D model for the potential in the trap

$$T = 4\left(\frac{L}{2\nu} + \frac{m\nu}{qF}\right)$$

Oscillation period for ion with initial velocity ν

$$\frac{dT}{d\nu} = \frac{4m}{qF} - \frac{2L}{\nu^2} = 0$$

Extremum (minimum) condition

For $V_1 < 4.75$ KV (empirically, for 4.2keV Ar^+ ions) $dT/d\nu > 0$

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Handwaving explanation (but can be "proved" analytically)

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... ion with

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... condition

For ... eV

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If you were an accelerator physicist you would call this:

"Negative Mass Instability"

(And try to avoid it!)

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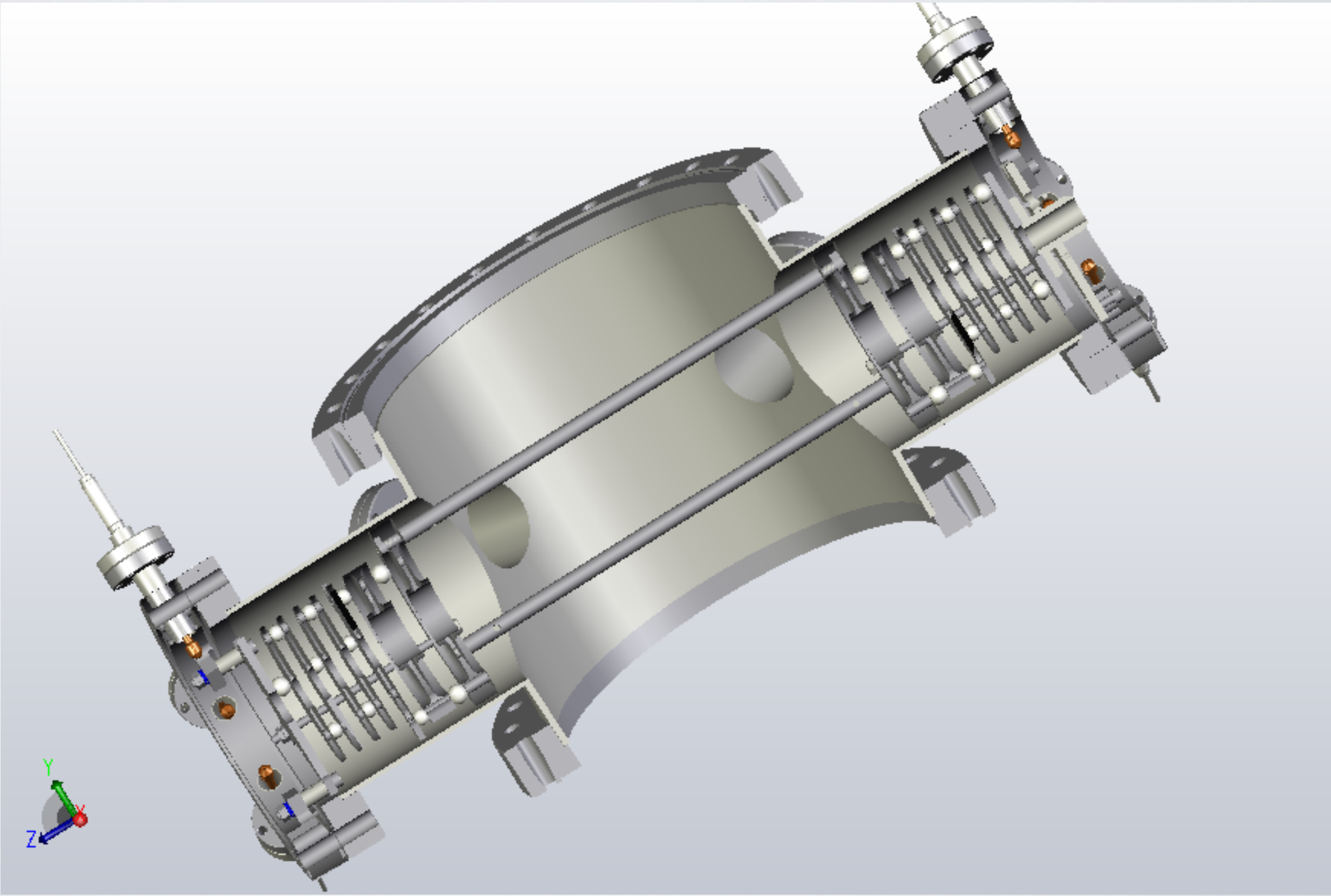
(SOME) POSSIBLE APPLICATIONS

So what is it good for? (1)

Mass

Spectroscopy



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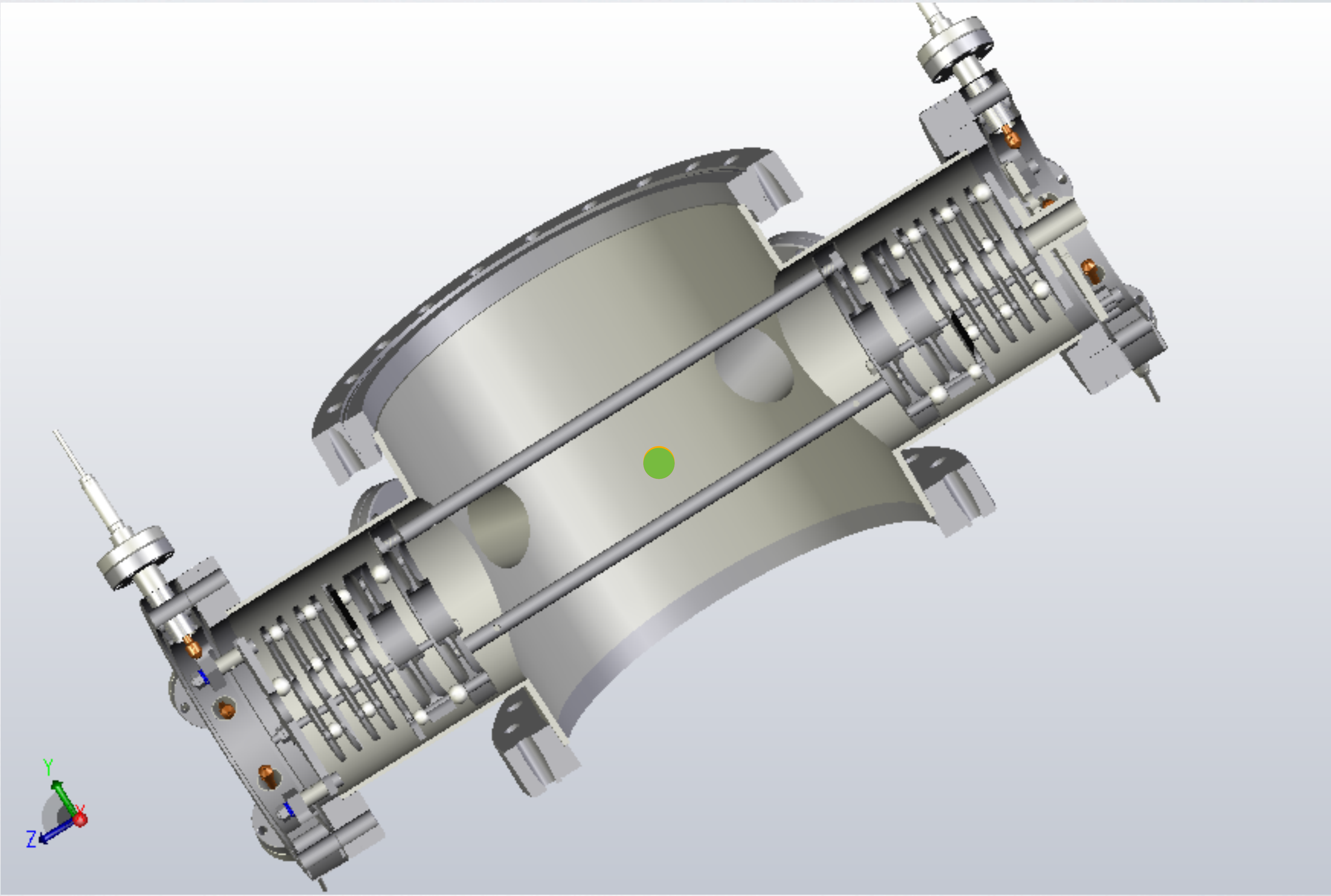

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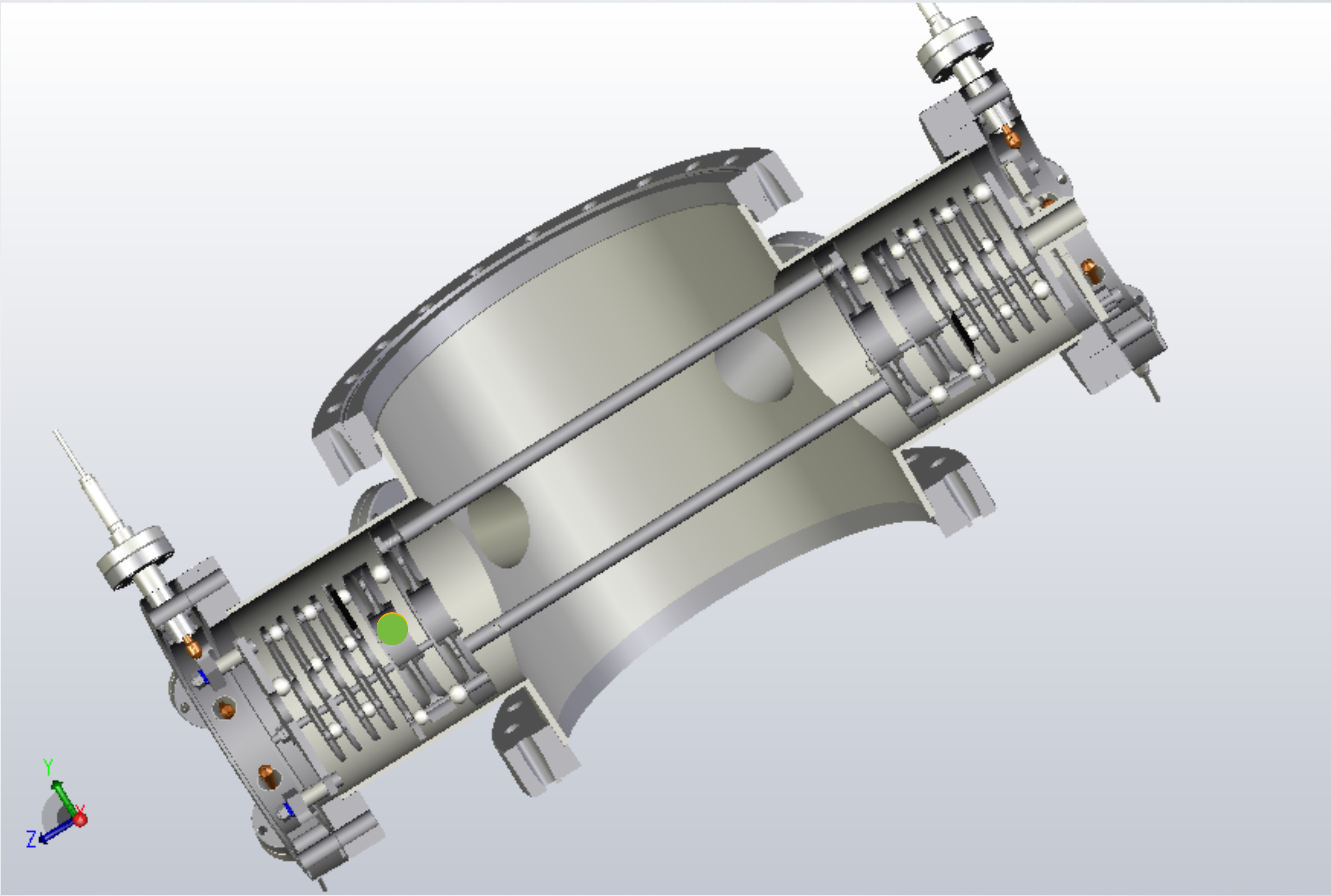

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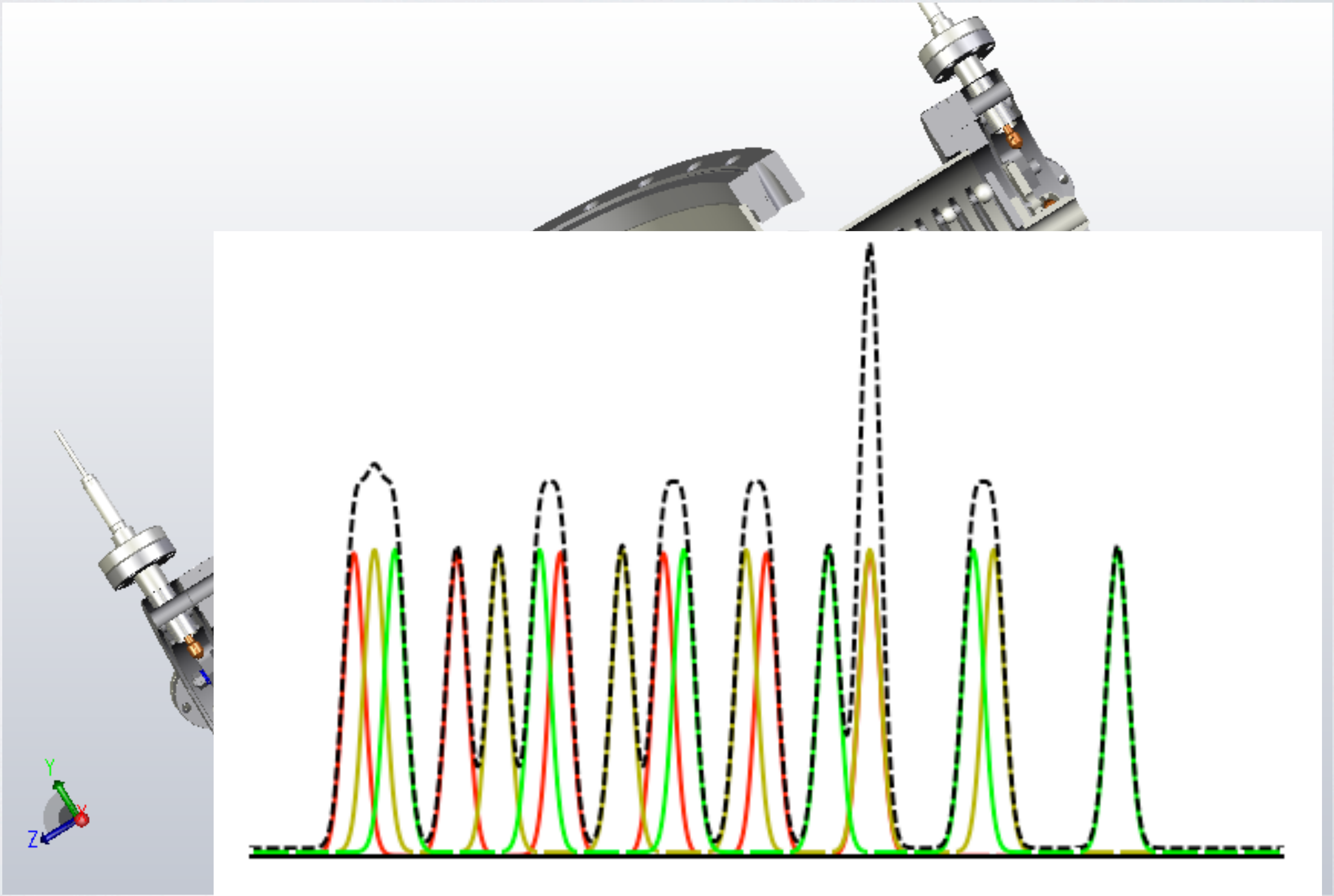

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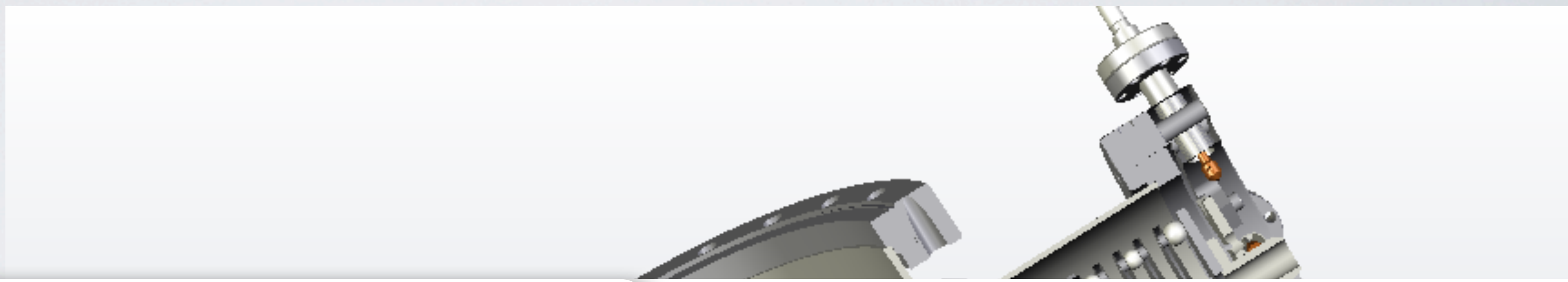
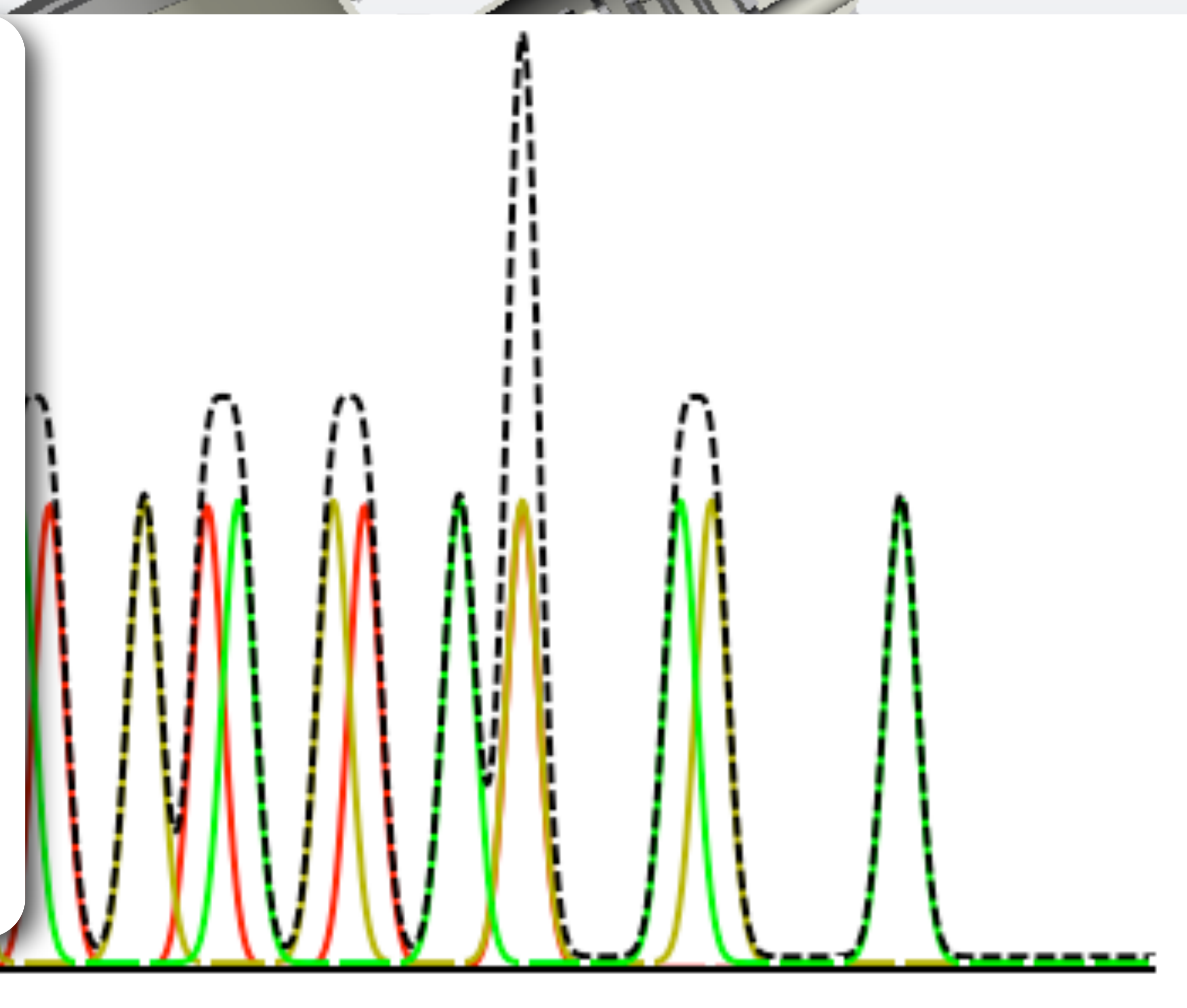
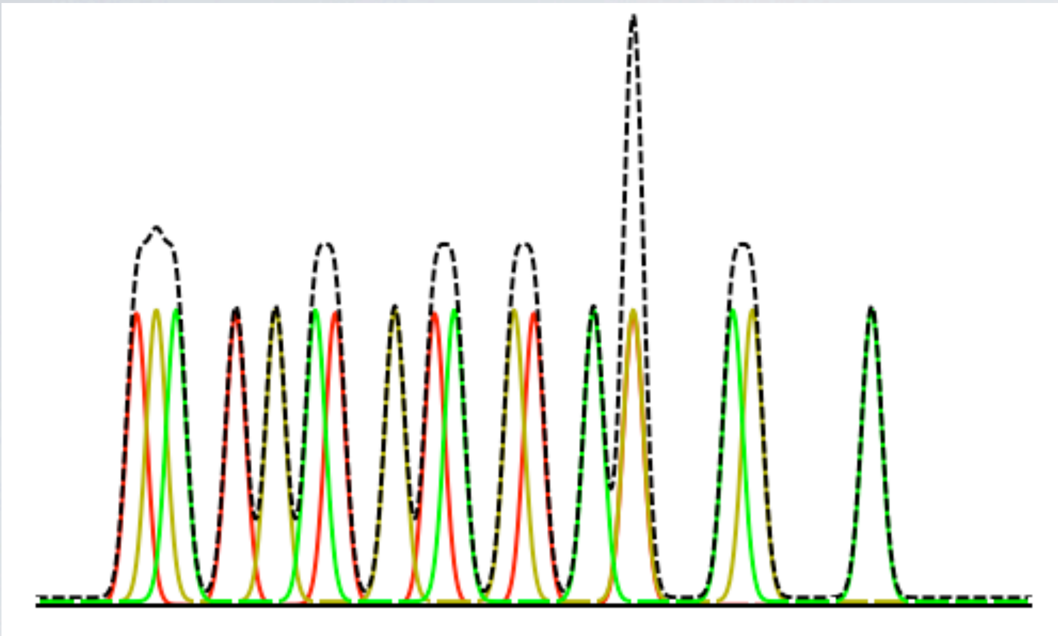




Trap selective in q/E. Different isotopes have a different oscillation frequency in the trap ($f \propto 1/\sqrt{m}$)

Fourier Transform the pickup charge



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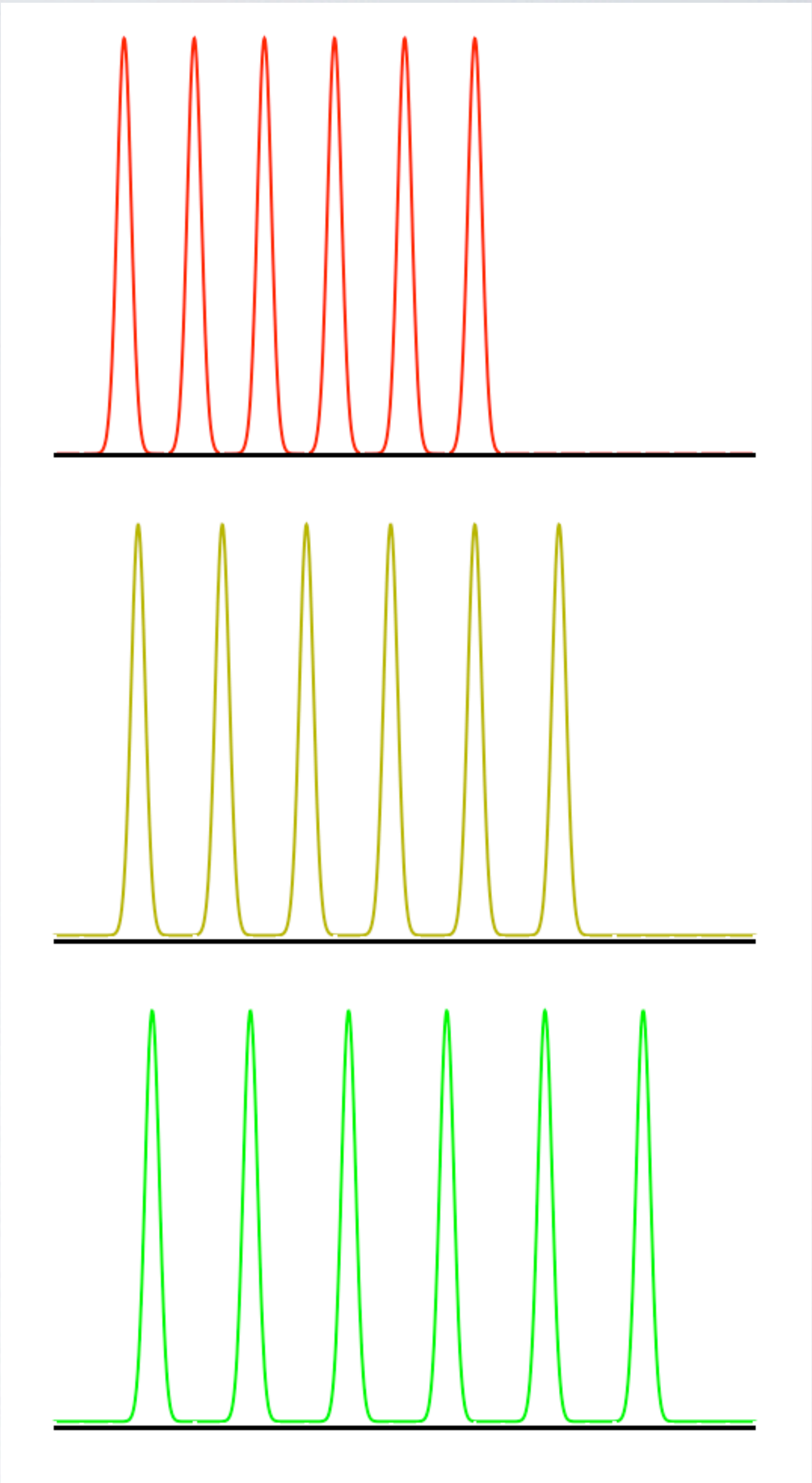

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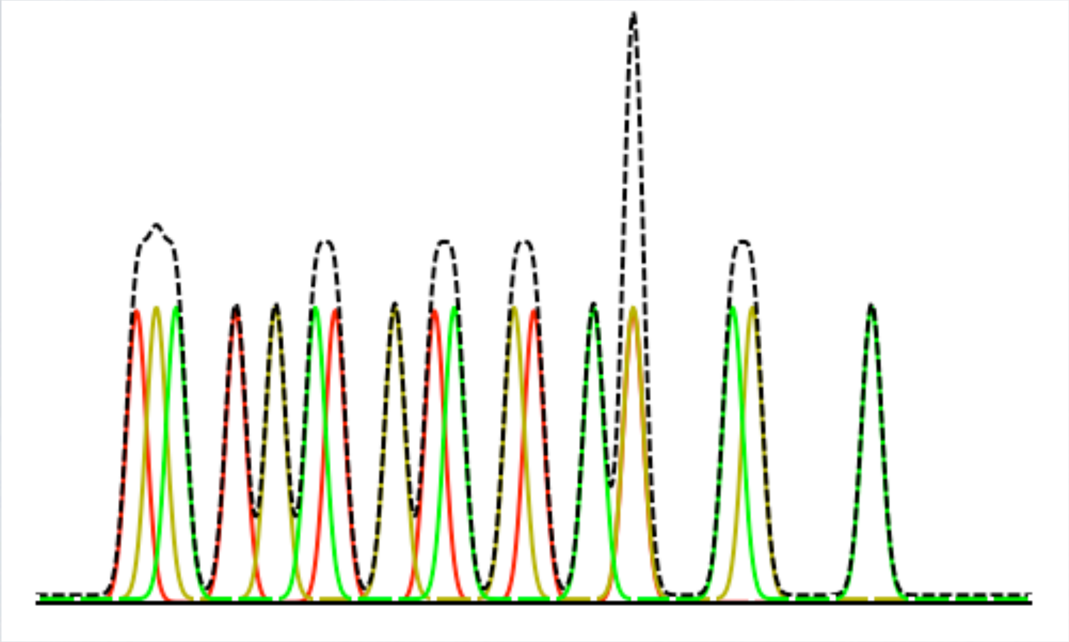

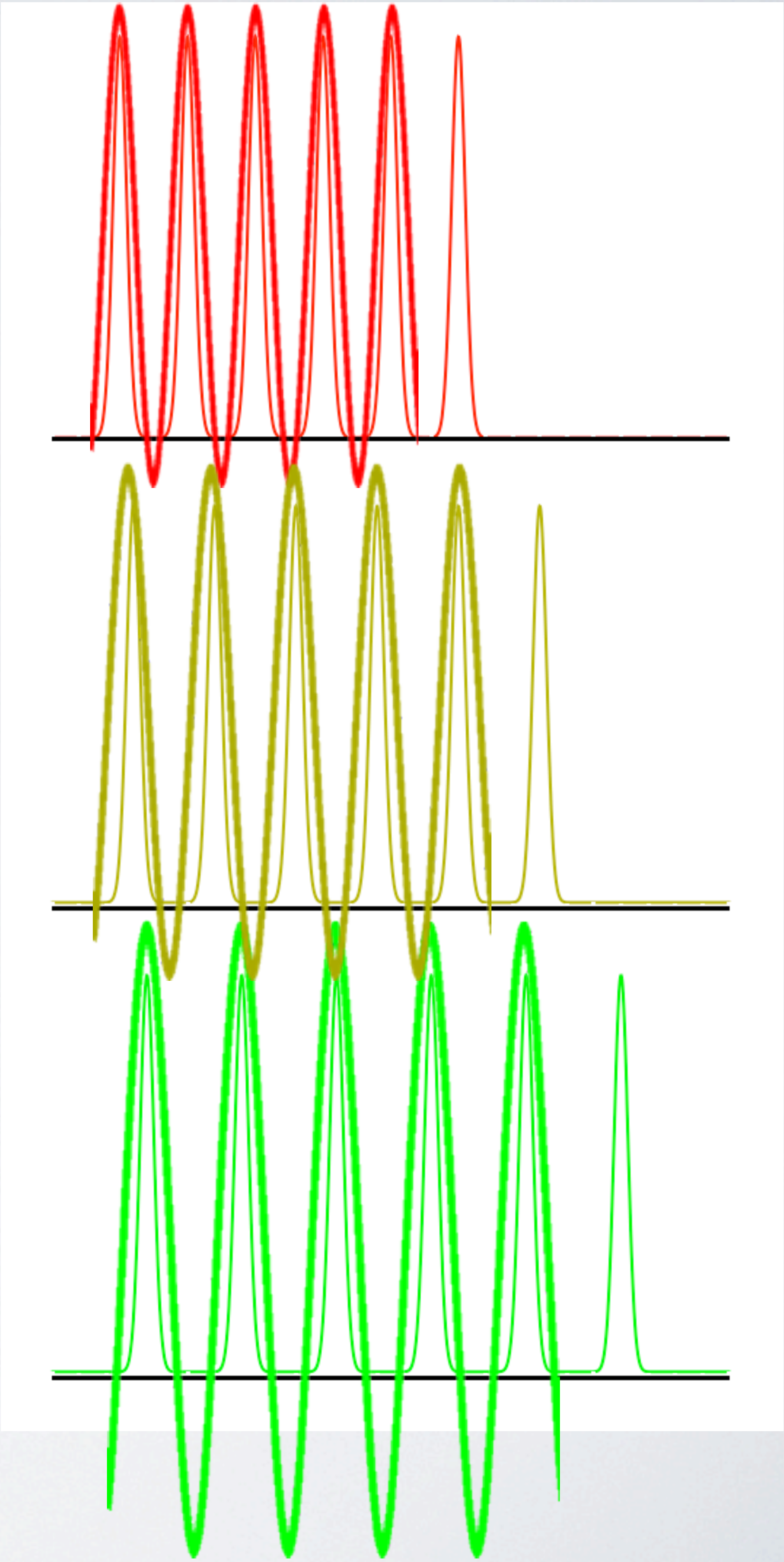

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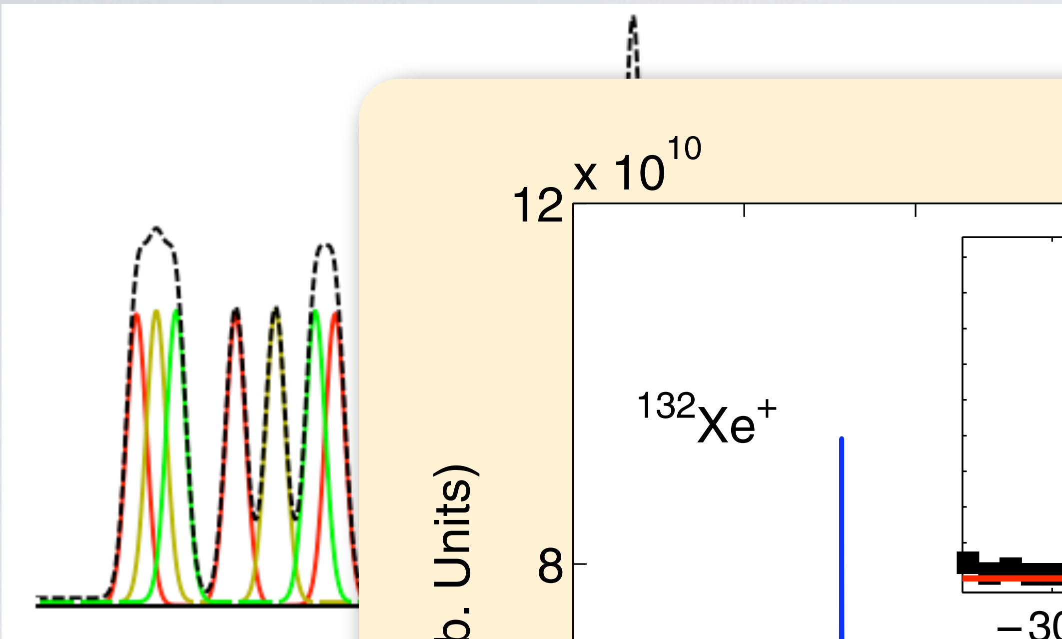

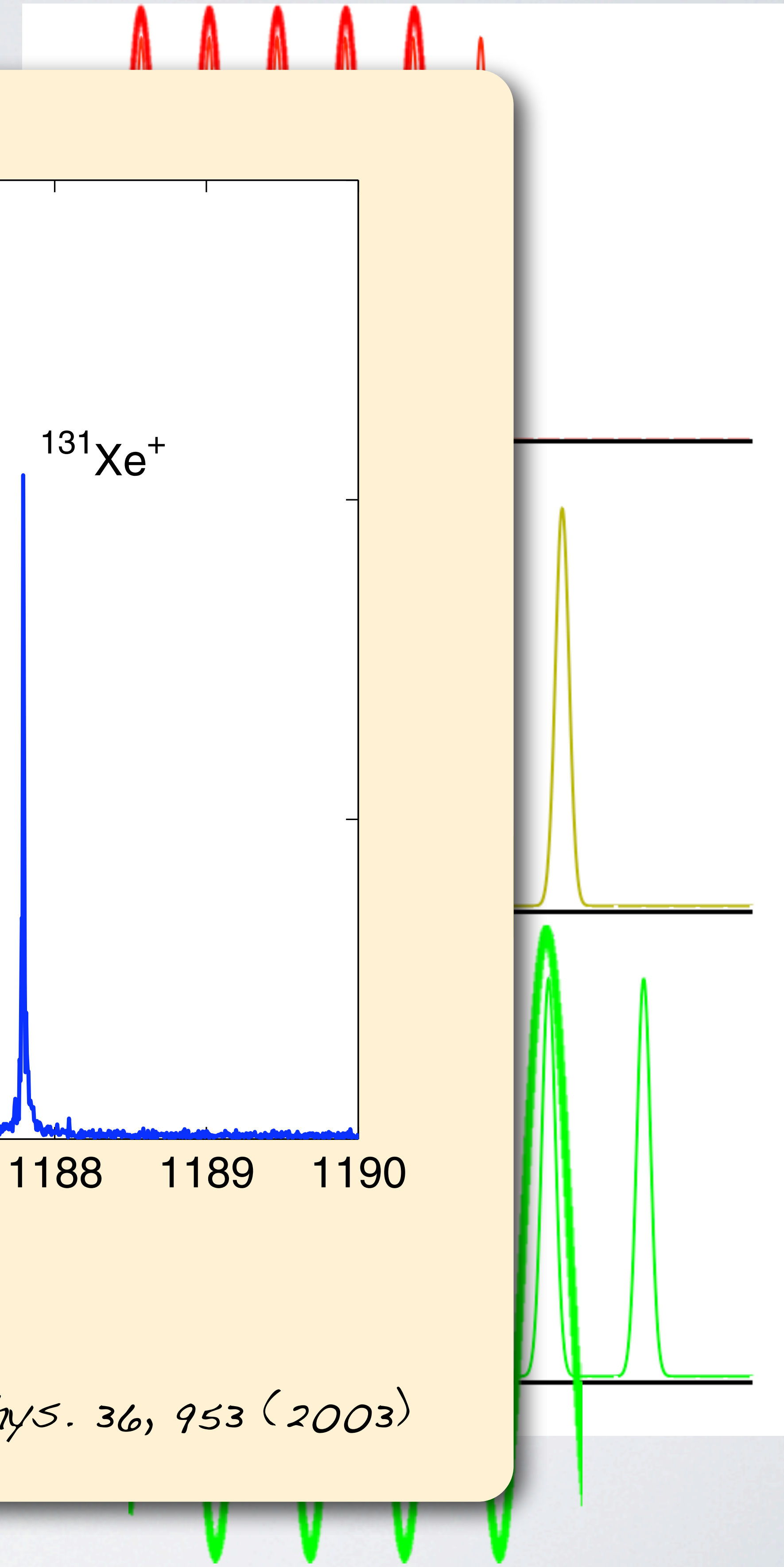

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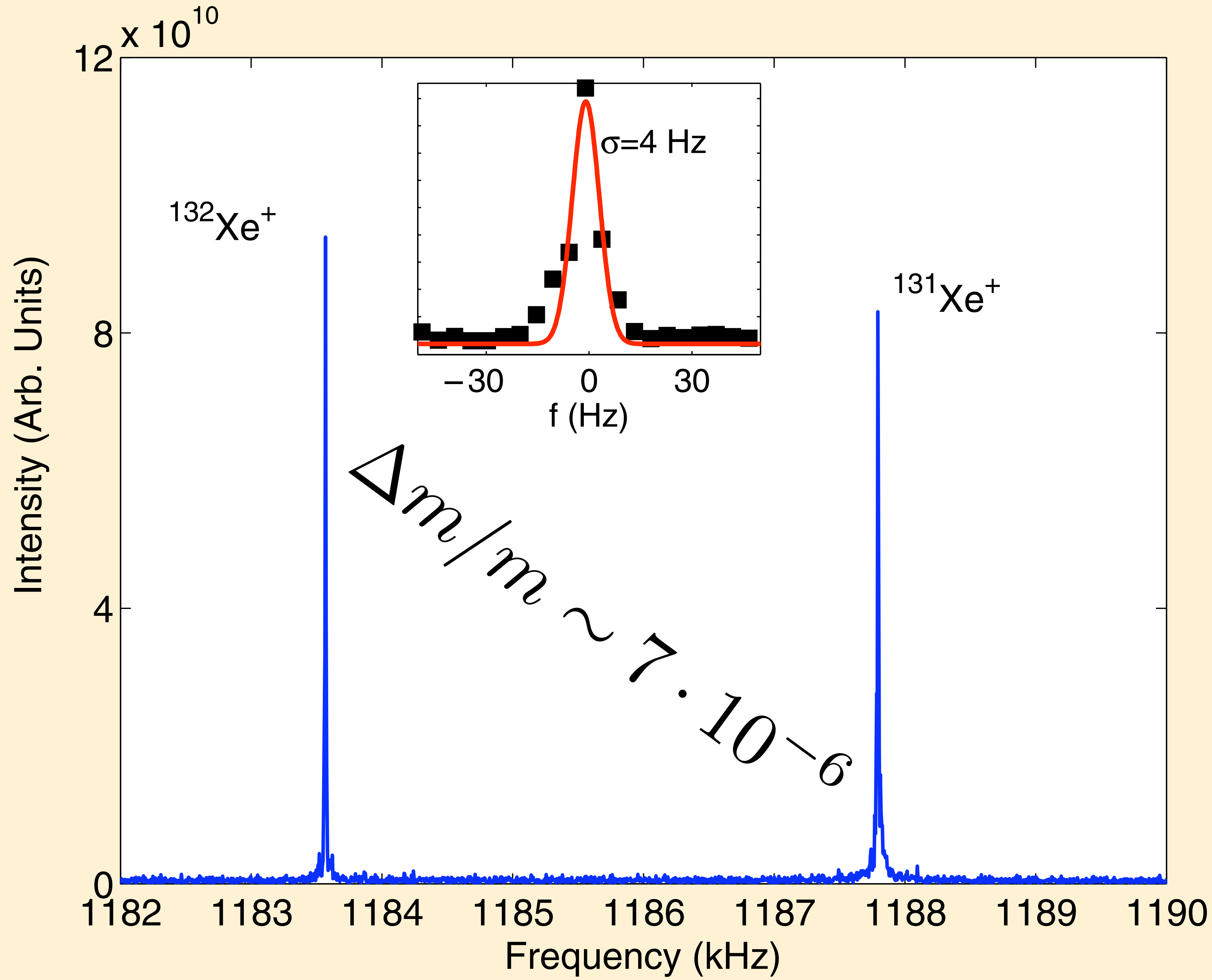

D. Strasser J. Phys. B: At. Mol. Opt. Phys. 36, 953 (2003)

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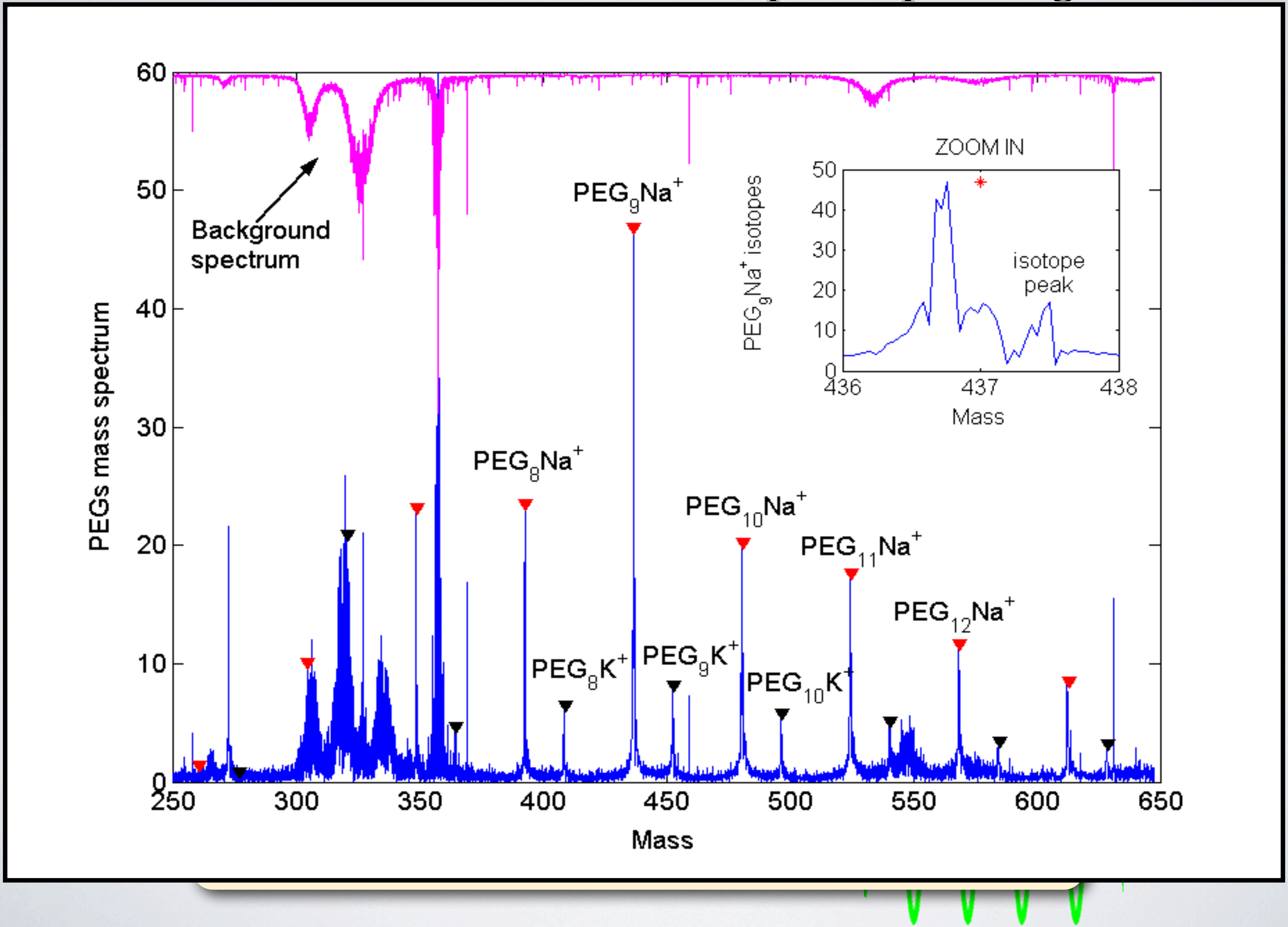

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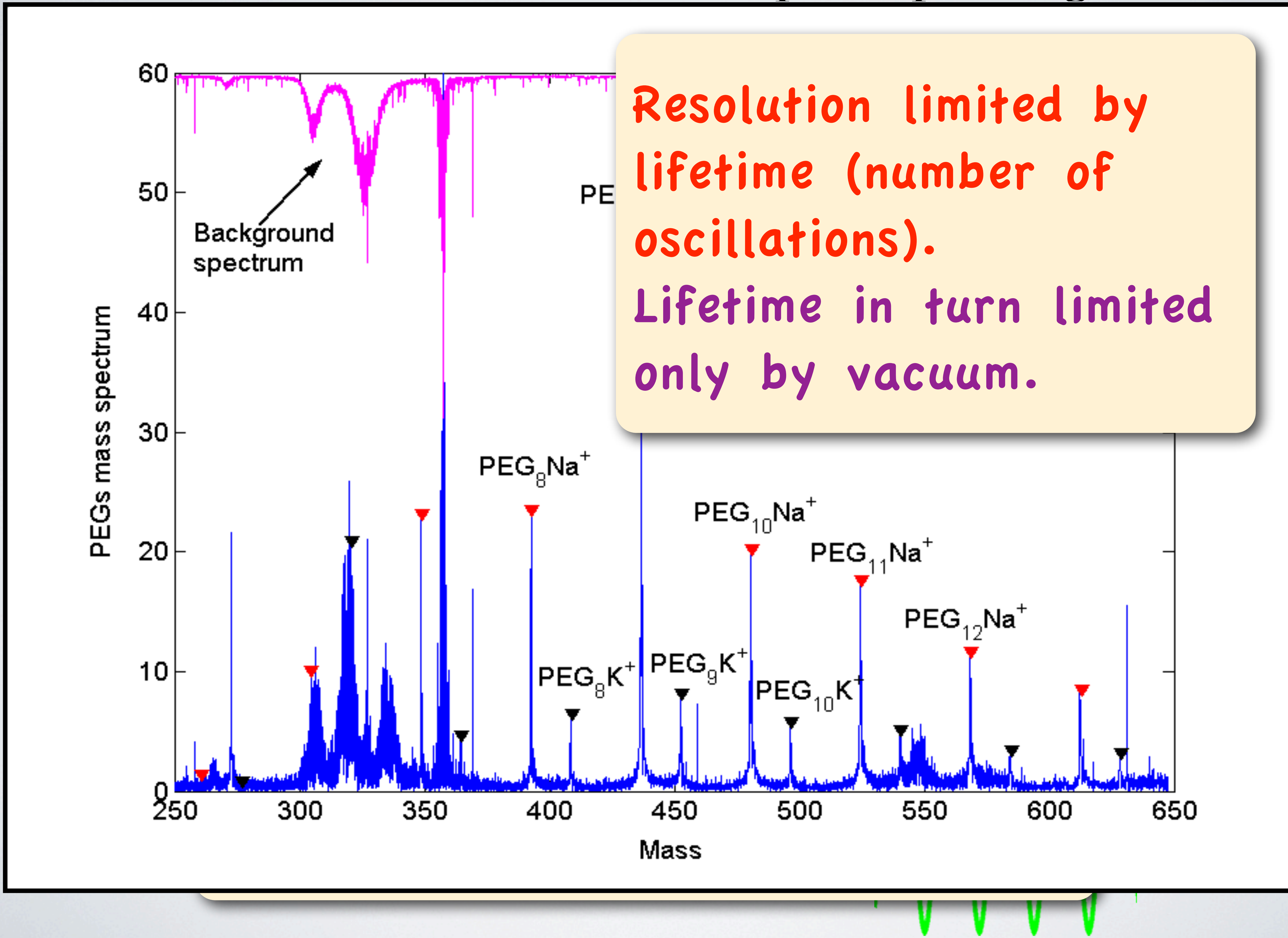

Resolution limited by lifetime (number of oscillations).

Lifetime in turn limited only by vacuum.

Why does this work so well?

In time-of-flight spectroscopy mass is determined by the time it takes an ion of known energy to traverse a known distance.

$$E = \frac{1}{2}mv^2 \rightarrow m = \frac{2E}{v^2} = \frac{2ET^2}{L^2}$$

$$\Delta m = \frac{2ET2\Delta T}{L^2}$$

$$\frac{\Delta m}{m} = 2\frac{\Delta T}{T}$$

Since T∝L increasing the flight distance increases the resolution.
For E~4KeV the oscillation period for and ion of mass 40 in the ES trap is ~3μsec. For a trap lifetime of ~300msec that gives 10^5 oscillations.

Why does this work so well?

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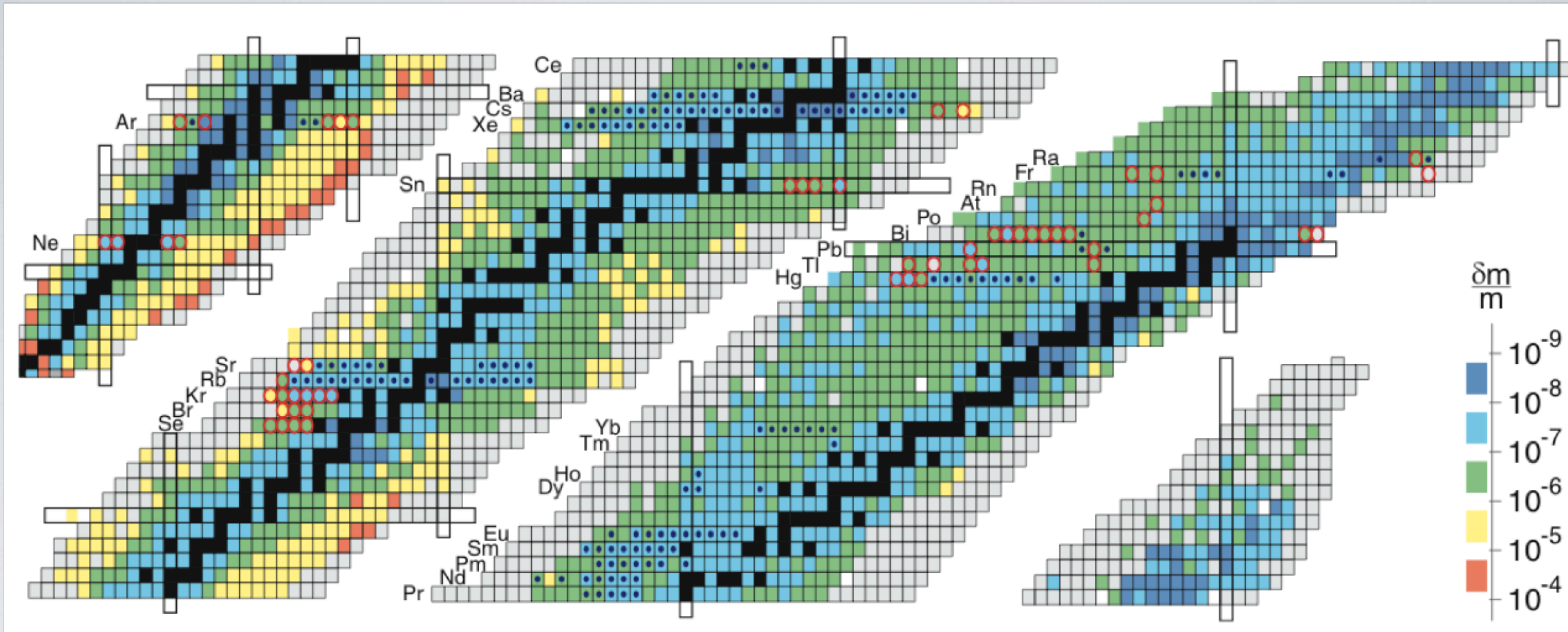
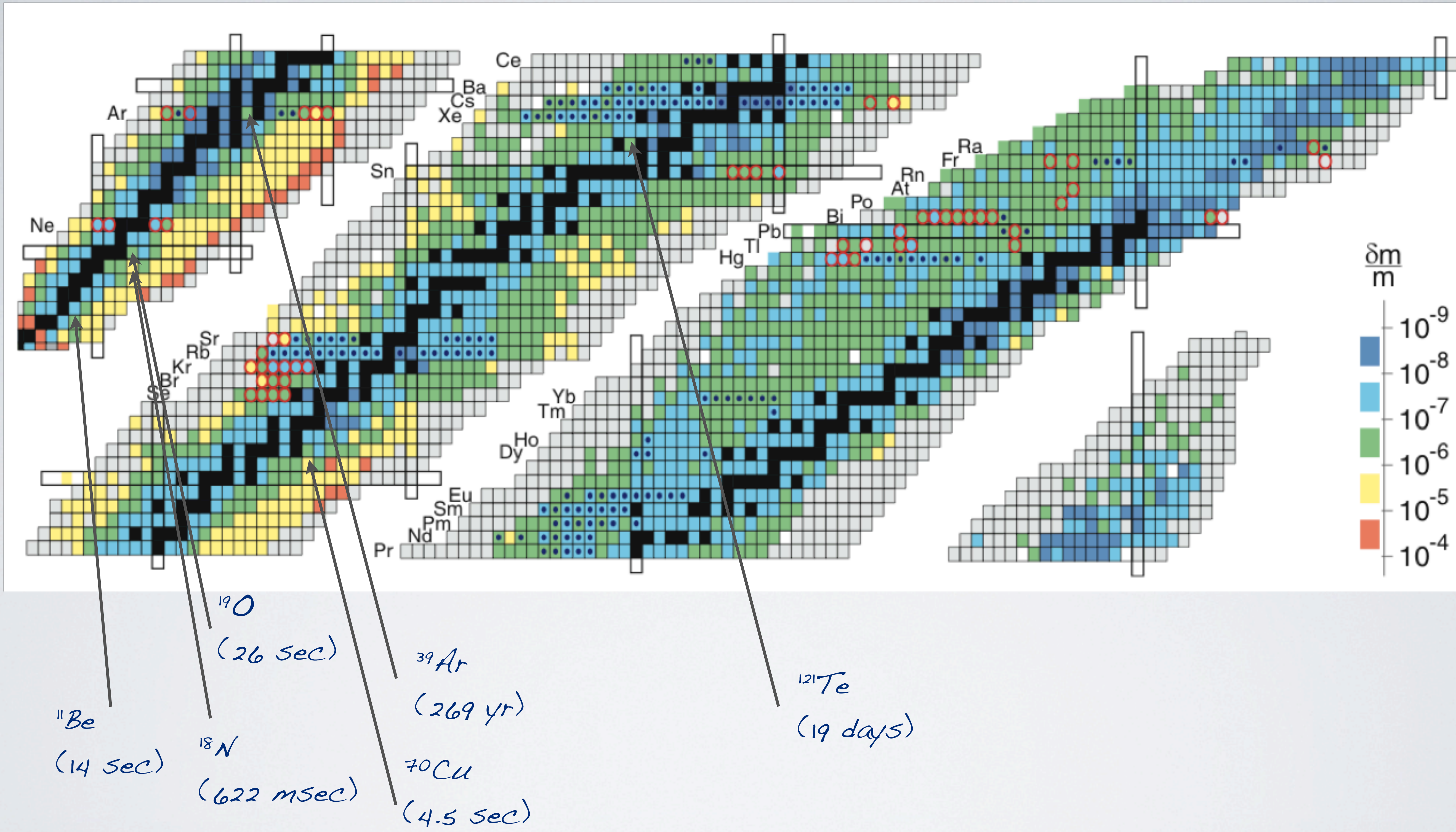
The electrostatic trap is equivalent to a folded flight path of ~20km!

World Mass Resolutions



F. Herfurth et al., J. Phys. B: At. Mol. Opt. Phys. 36, 931 (2003)

World Mass Resolutions



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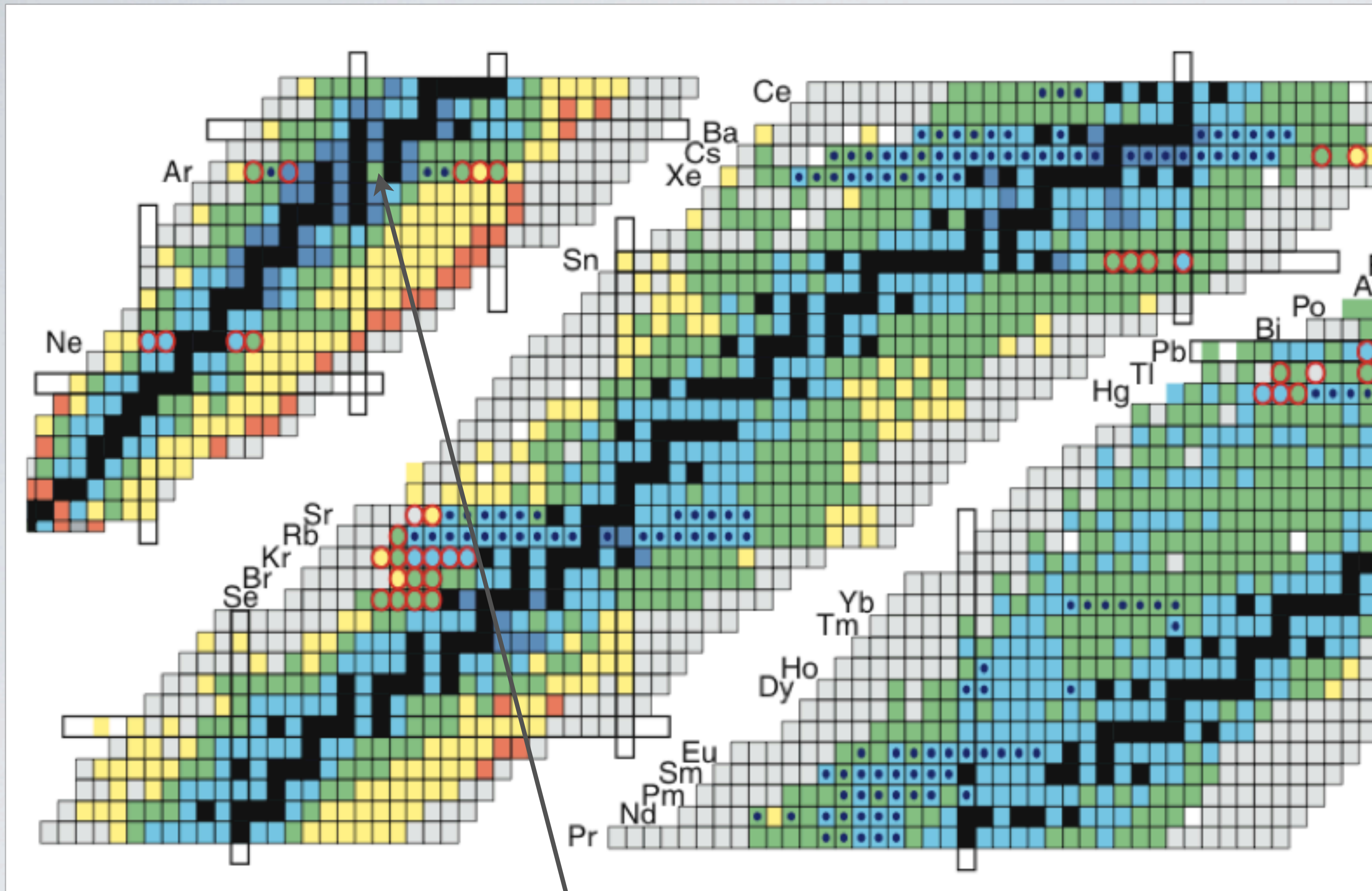
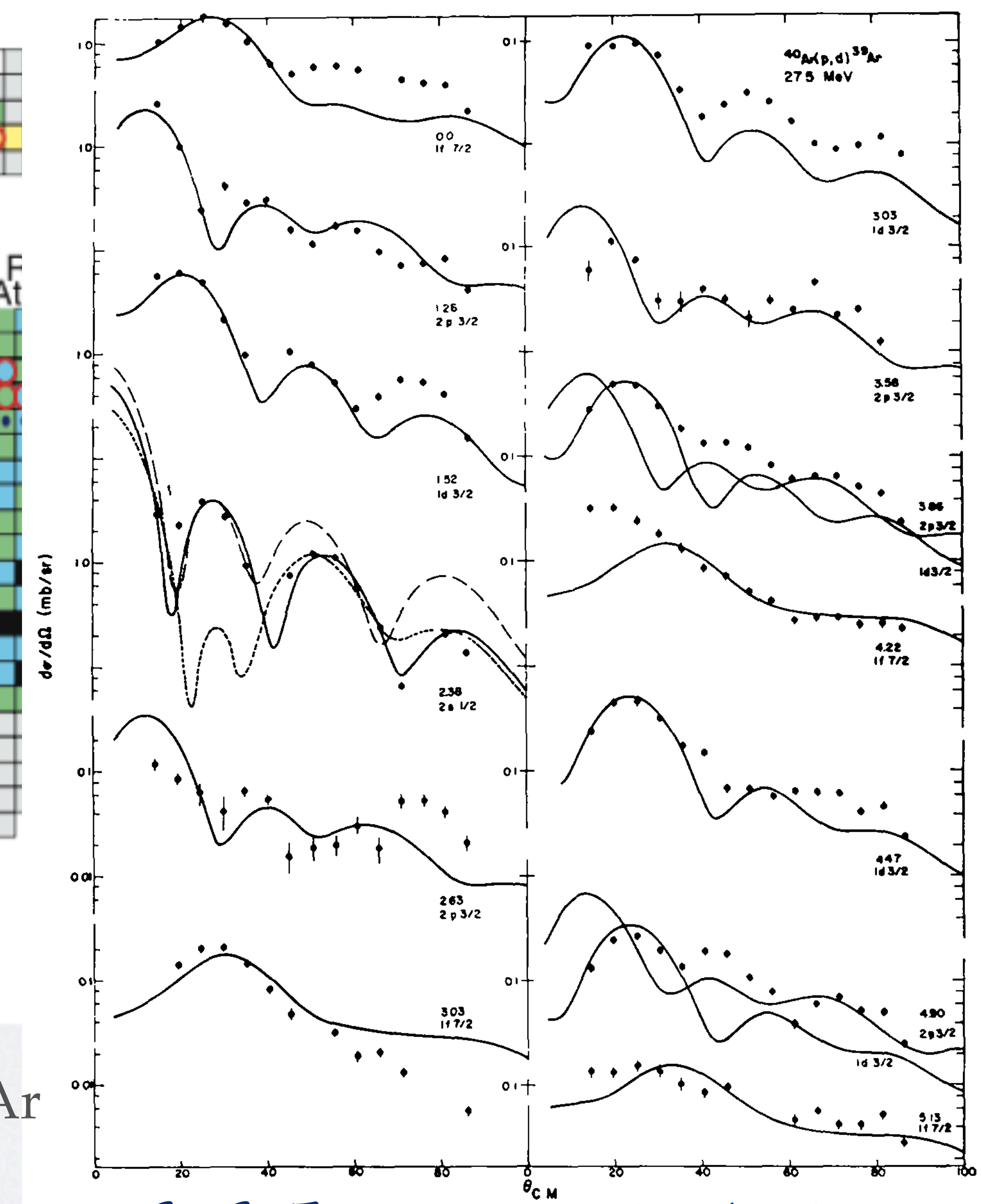


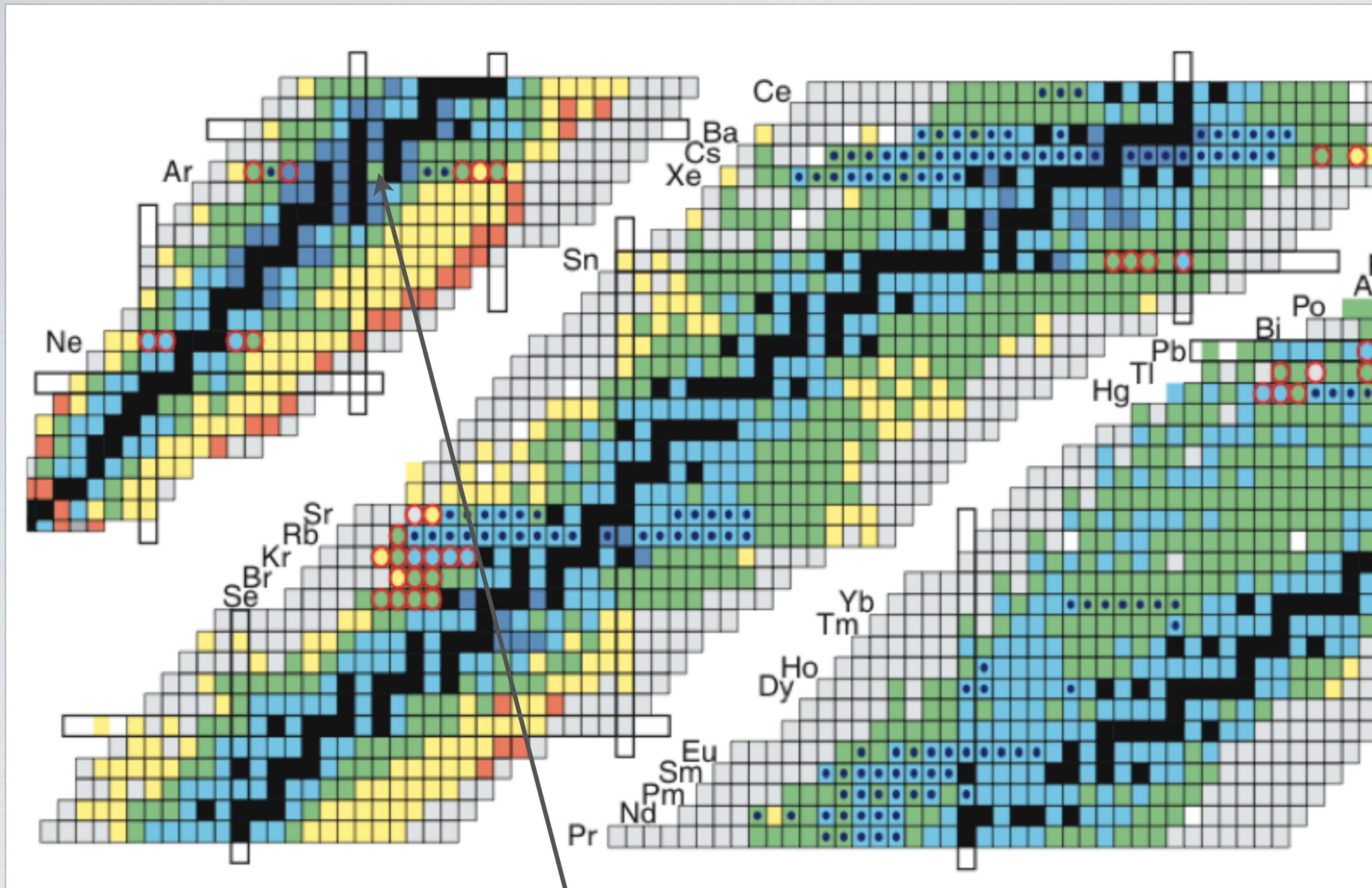


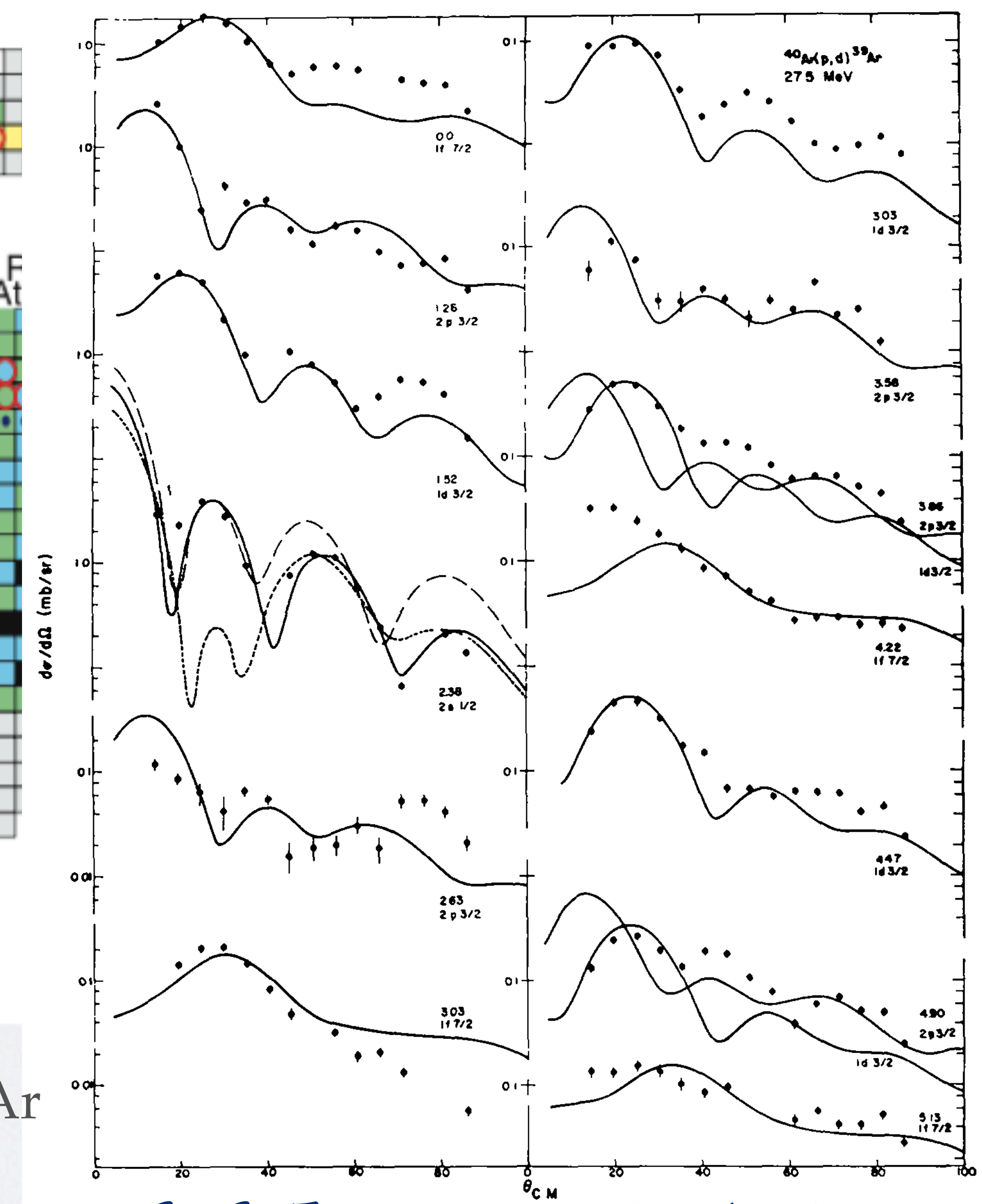
^{39}Ar
(269 yr)

- Produced via $^{40}Ar(p,d)^{39}Ar$ with ~27 MeV protons.
- ^{40}Ar pretty much the easiest stuff to get.
- Long lived - easy transport.
- $^{38,40}Ar$ stable - perfect for calibration.
- All-in-all a good test case.

R. R. Johnson et al., Nucl Phys A108, 113 (1968)

F. Herfurth et al., J. Phys. B: At. Mol. Opt. Phys. 36, 931 (2003)





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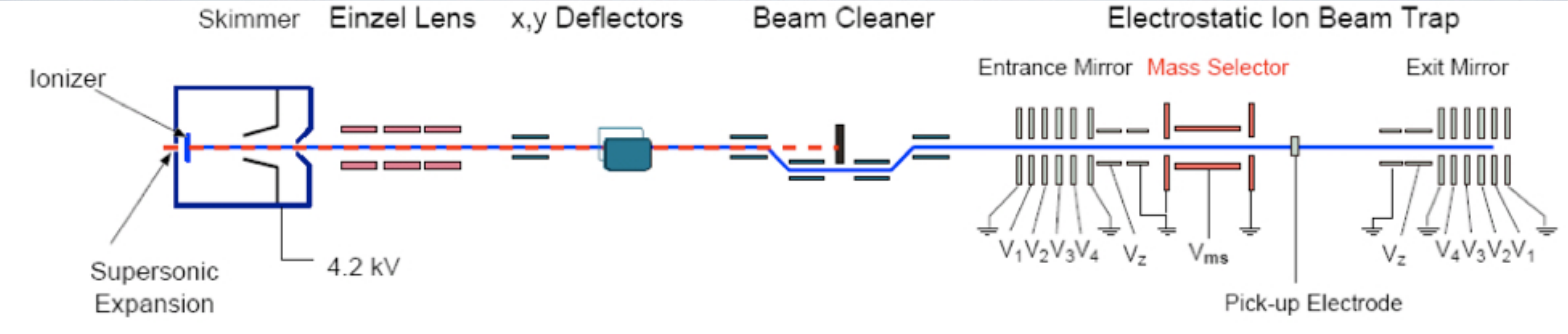
R. R. Johnson et al., Nucl Phys A108, 113 (1968)

What about superheavy elements?

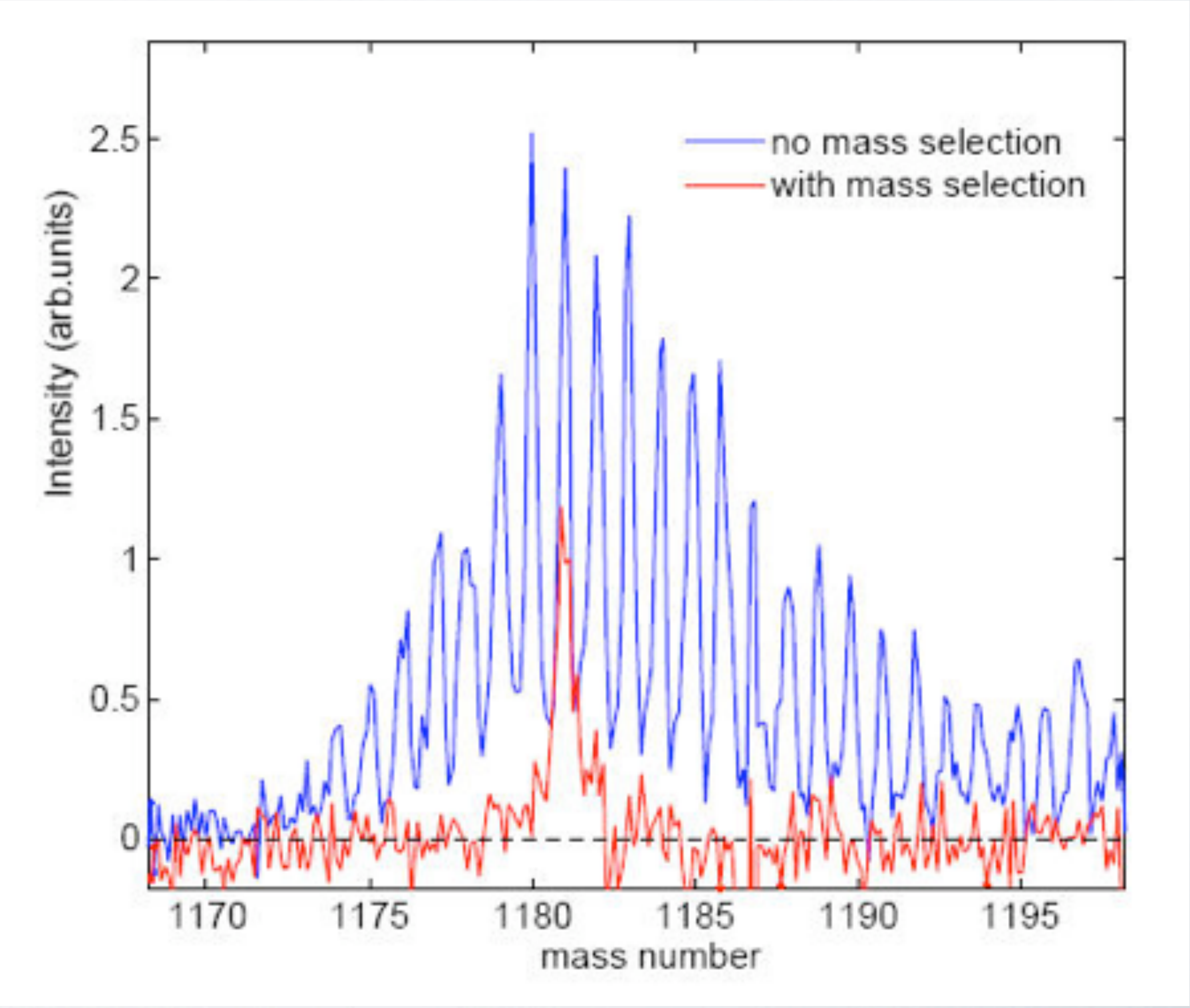
F. Herfurth et al., J. Phys. B: At. Mol. Opt. Phys. 36, 931 (2003)

So what is it good for? (2)

Mass Selection



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



So what is it good for? (3)

SM Tests - β decay

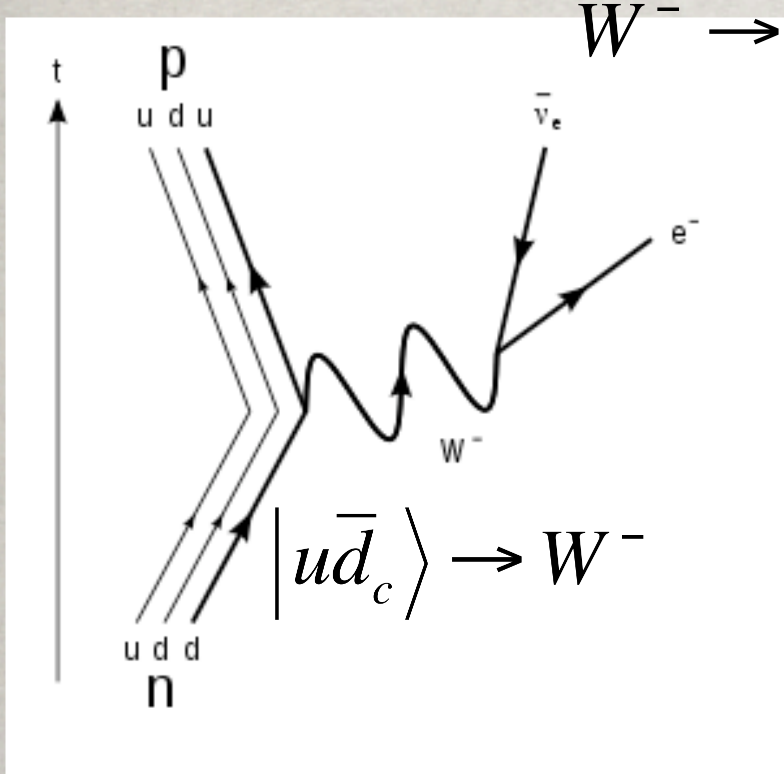
So what is it good for? (3)

SM Tests - β decay

A Short Detour through the Standard Model & Beta Decay

The weak interaction
(Weak Isospin)

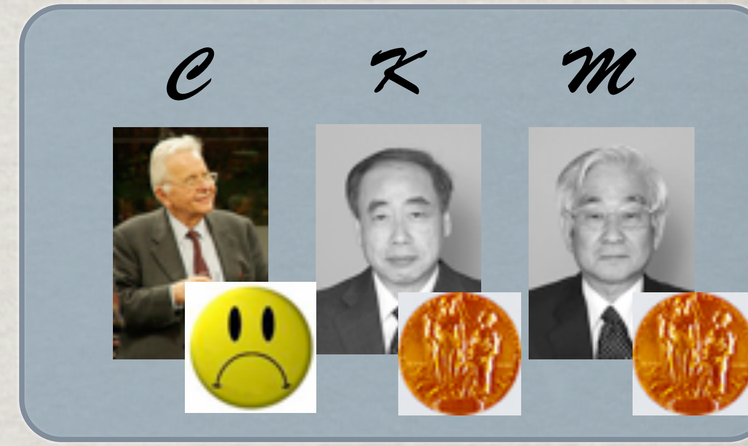
$$W^- \rightarrow \left| e^- \overline{\nu}_e \right\rangle$$



$$\left| u\overline{d}_c \right\rangle \rightarrow W^-$$

<u>Quarks</u>

$$\begin{pmatrix} u_L \\ d'_L \end{pmatrix} \quad \begin{pmatrix} c_L \\ s'_L \end{pmatrix} \quad \begin{pmatrix} t_L \\ b'_L \end{pmatrix}$$



$$| d'_L >= V_{ud} \, | d_L > + V_{us} \, | s_L > + V_{ub} \, | b_L >$$

<u>Leptons</u>

$$\begin{pmatrix} e_L \\ \nu_{eL} \end{pmatrix} \quad \begin{pmatrix} \mu_L \\ \nu_{\mu L} \end{pmatrix} \quad \begin{pmatrix} \tau_L \\ \nu_{\tau L} \end{pmatrix}$$

$$| \nu_{eL} >= U_{e1} \, | \nu_{1L} > + U_{e2} \, | \nu_{2L} > + U_{e3} \, | \nu_{3L} >$$

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).

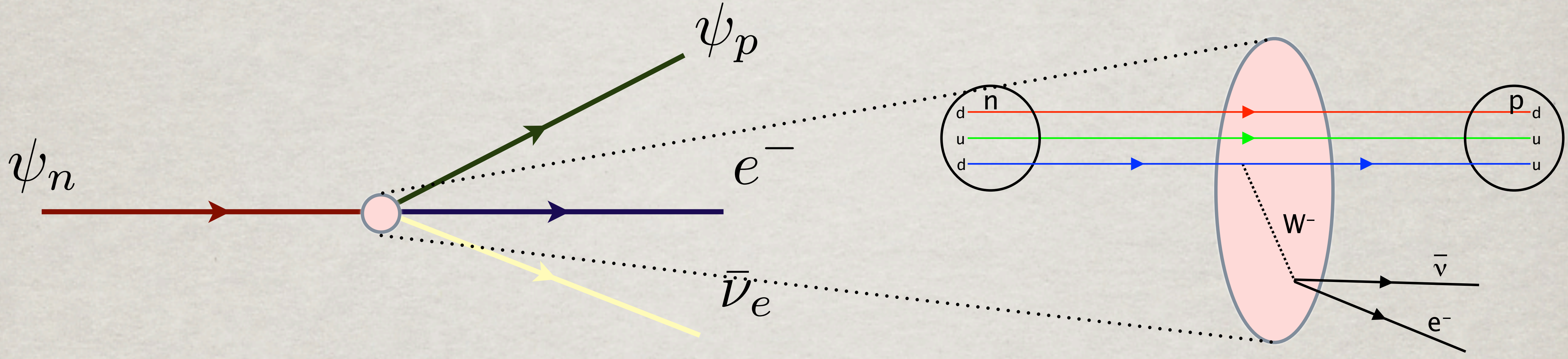
- But no apriori reason for this.

- Most general form for β-decay amplitude:

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

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

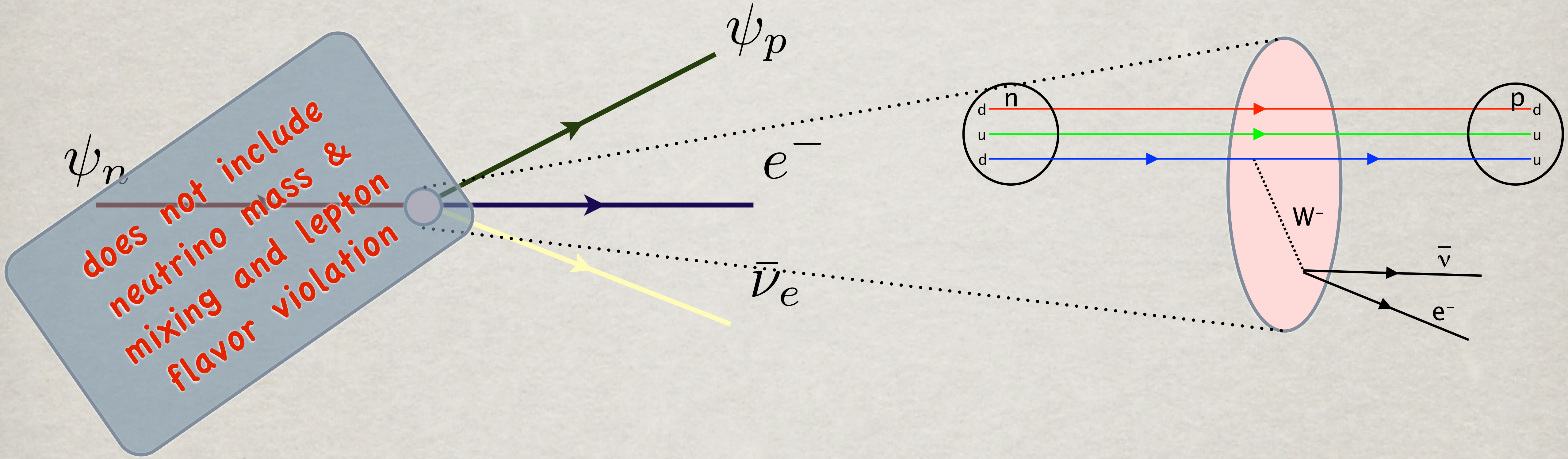
Nuclear β decay



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

19 free parameters
(10 complex couplings
- arbitrary phase)

Nuclear β decay



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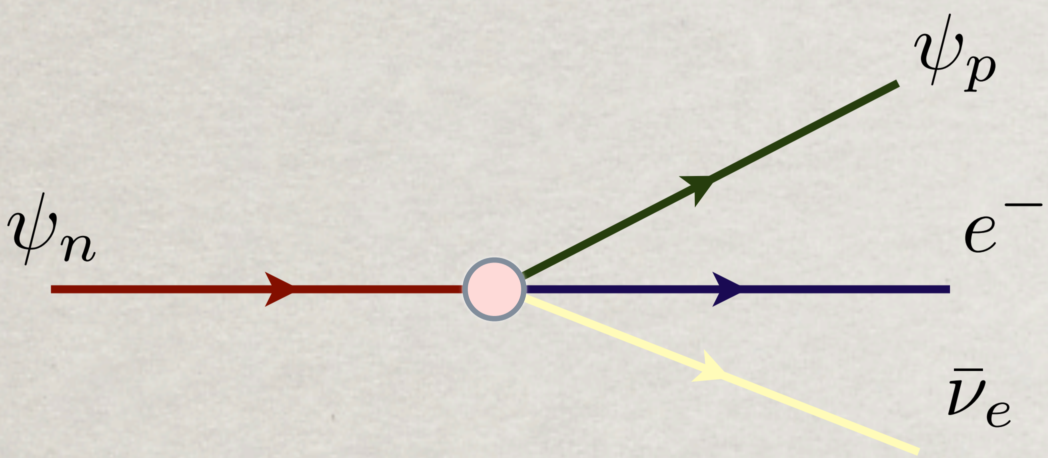
\end{aligned}
$$

19 free parameters
(10 complex couplings
- arbitrary phase)

This is Standard Model



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

$$C_V = C'_V = 1$$

$$C_A = C'_A = 1.26$$

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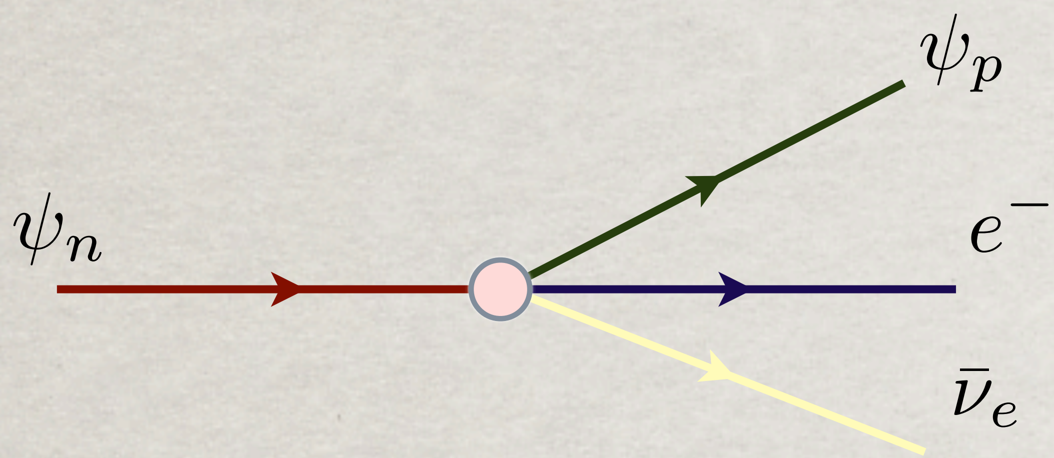
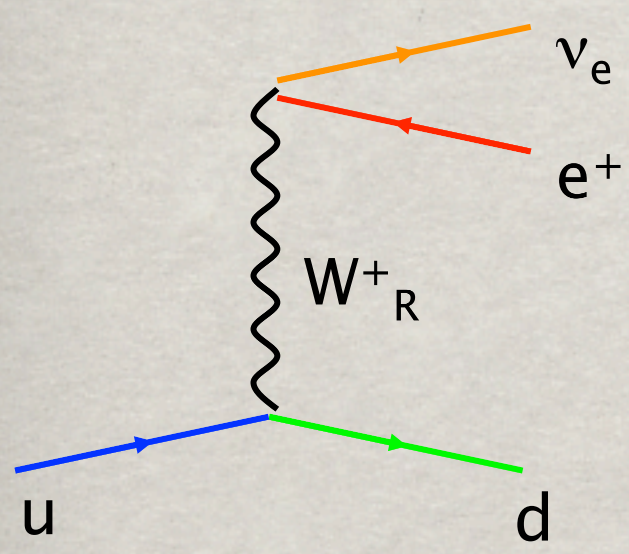


$$H_\beta = (\bar{\psi}_n \gamma_\mu \psi_p)(C_V \bar{\psi}_e \gamma^\mu \psi_\nu + C'_V \bar{\psi}_e \gamma^\mu \gamma_5 \psi_\nu)$$
$$-(\bar{\psi}_n \gamma_\mu \gamma_5 \psi_p)(C_A \bar{\psi}_e \gamma^\mu \gamma_5 \psi_\nu + C'_A \bar{\psi}_e \gamma^\mu \psi_\nu)$$

$C_V = C'_V = 1$

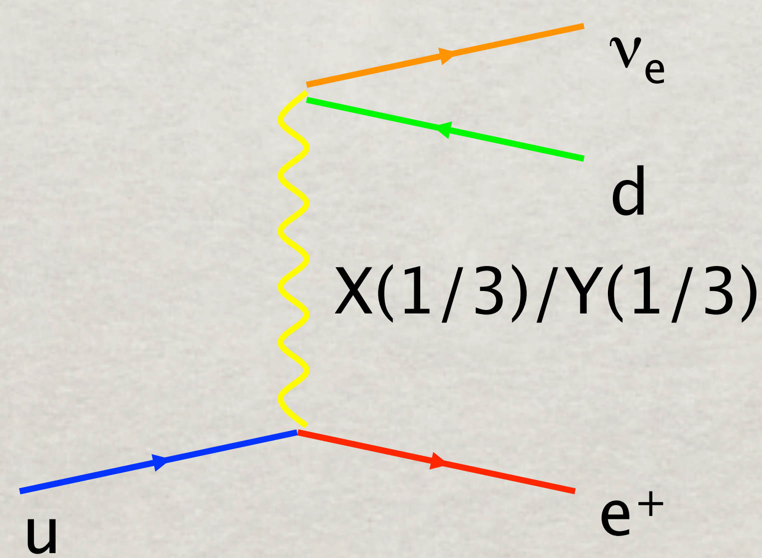
$C_A = C'_A = 1.26$

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)...

β decay 101

Total decay rate (electron polarization not detected)

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

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

β DECAY 101

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Electron-neutrino correlation

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

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β decay 101

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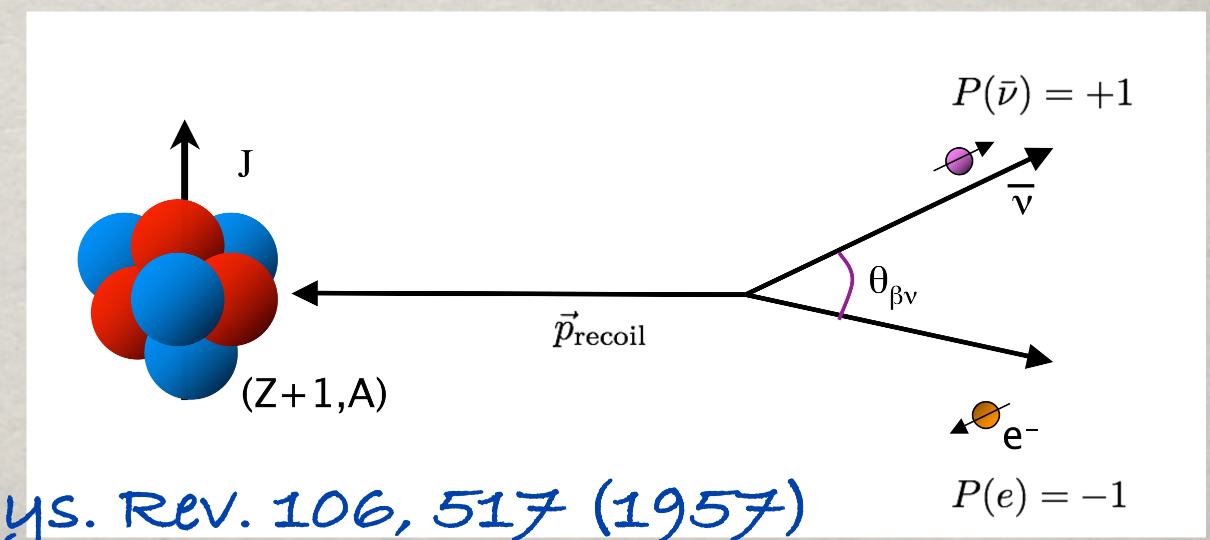
β + ν carry no AM → emitted in same direction (opposite helicities)

Pure Fermi: a = 1



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β decay 101

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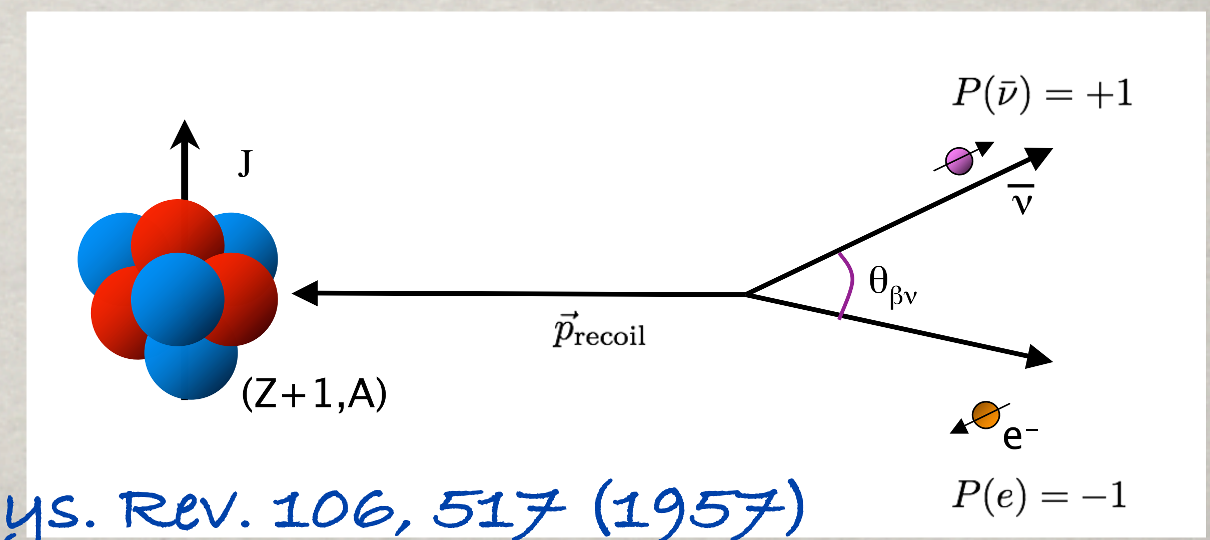
$$\xi = |M_F|^2 \left(|C_S|^2 + |C_V|^2 + |C'_S|^2 + |C'_V|^2\right) + |M_{GT}|^2\left(|C_T|^2 + |C_A|^2 + |C'_T|^2 + |C'_A|^2\right)$$

β + ν carry 1 unit AM → emitted in opposite directions (factor of 3 from spin directions)

Pure GT: $a = -1/3$



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

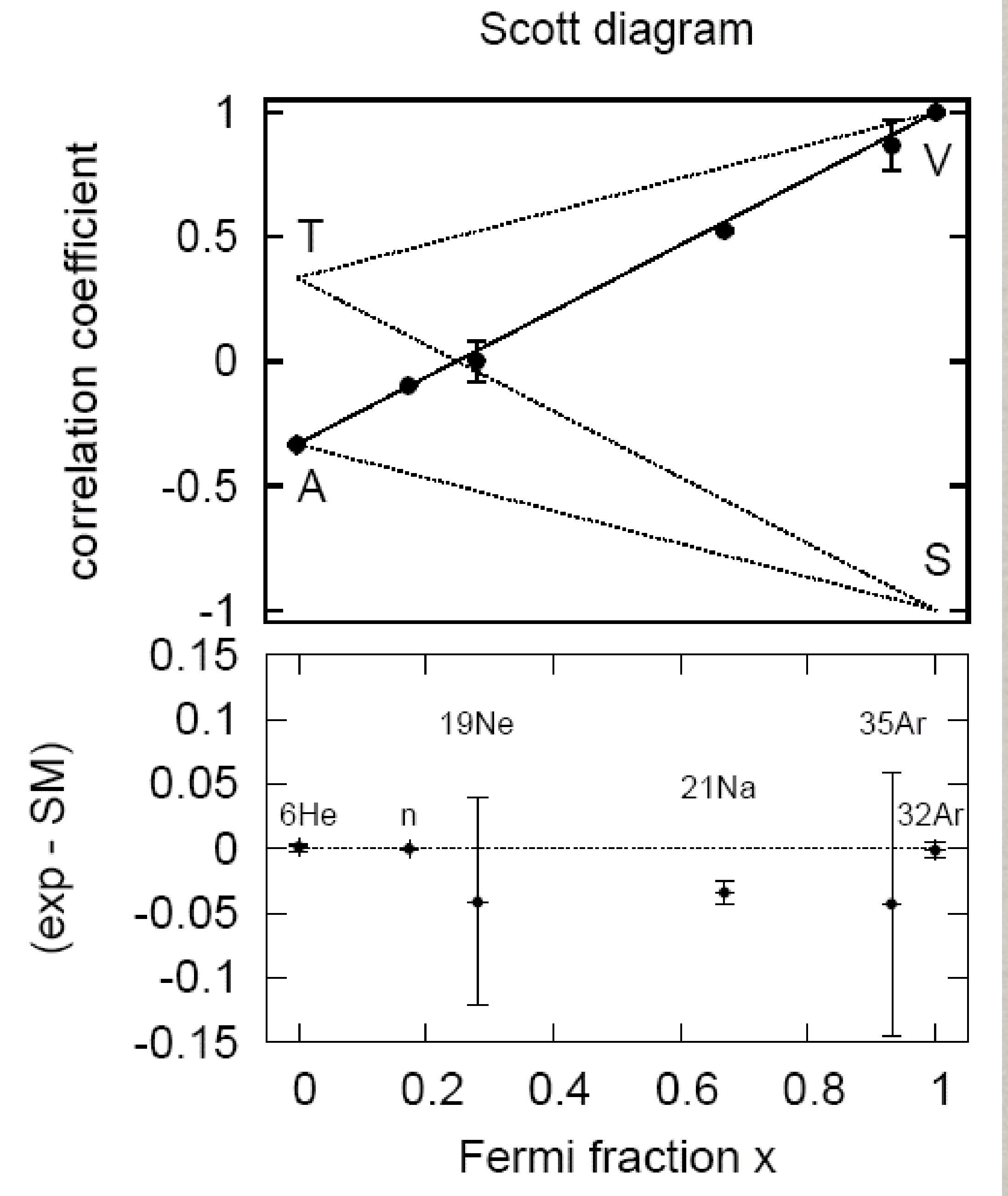
So... is β decay V-A?

In SM

$$a_0 = \frac{1}{3}\left(\frac{3-\rho^2}{1+\rho^2}\right) = \frac{1}{3}(4x-1)$$

$$x = \frac{1}{1+\rho^2}$$

$$\rho = \frac{C_A M_{GT}}{C_V M_F}$$



Beyond SM

$$a \approx a_0(1-\alpha)$$

F:	$a_0 = 1$	$\alpha = (\lvert C_s\rvert^2 + \lvert C'_s\rvert^2)/C_V^2$
GT	$a_0 = -1/3$	$\alpha = (\lvert C_T\rvert^2 + \lvert C'_T\rvert^2)/C_A^2$

β DECAY 101

Possible observables in nuclei

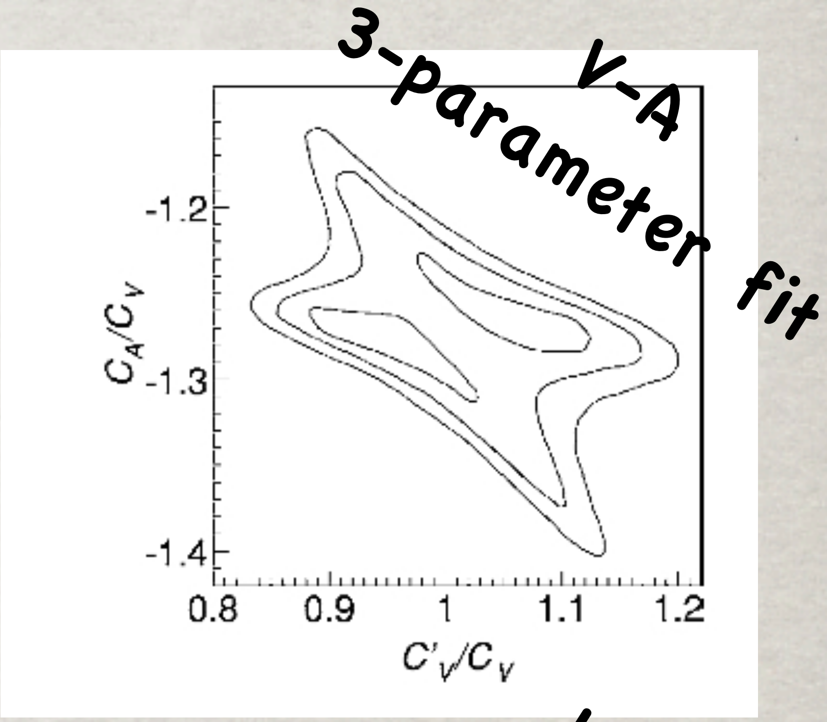
$$\frac{d\Gamma}{dE_\beta d\Omega_\beta d\Omega_\nu} \propto \xi \left\{ 1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e} + c\left[\frac{1}{3}\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} - \frac{(\vec{p}_e \cdot \vec{j})(\vec{p}_\nu \cdot \vec{j})}{E_e E_\nu}\right] \right.$$

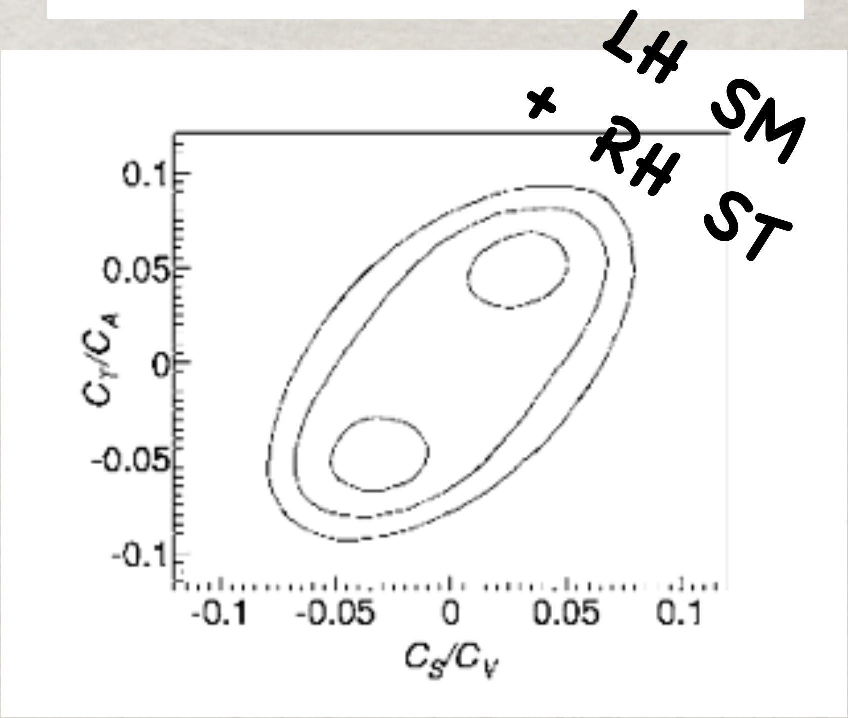
$$\left. \left[\frac{J(J+1) - 3 < (\vec{J} \cdot \vec{j})^2 >}{J(2J-1)}\right] + \frac{< \vec{J} >}{J} \cdot \left[A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right] \right\}$$

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

Limits on non-SM coupling

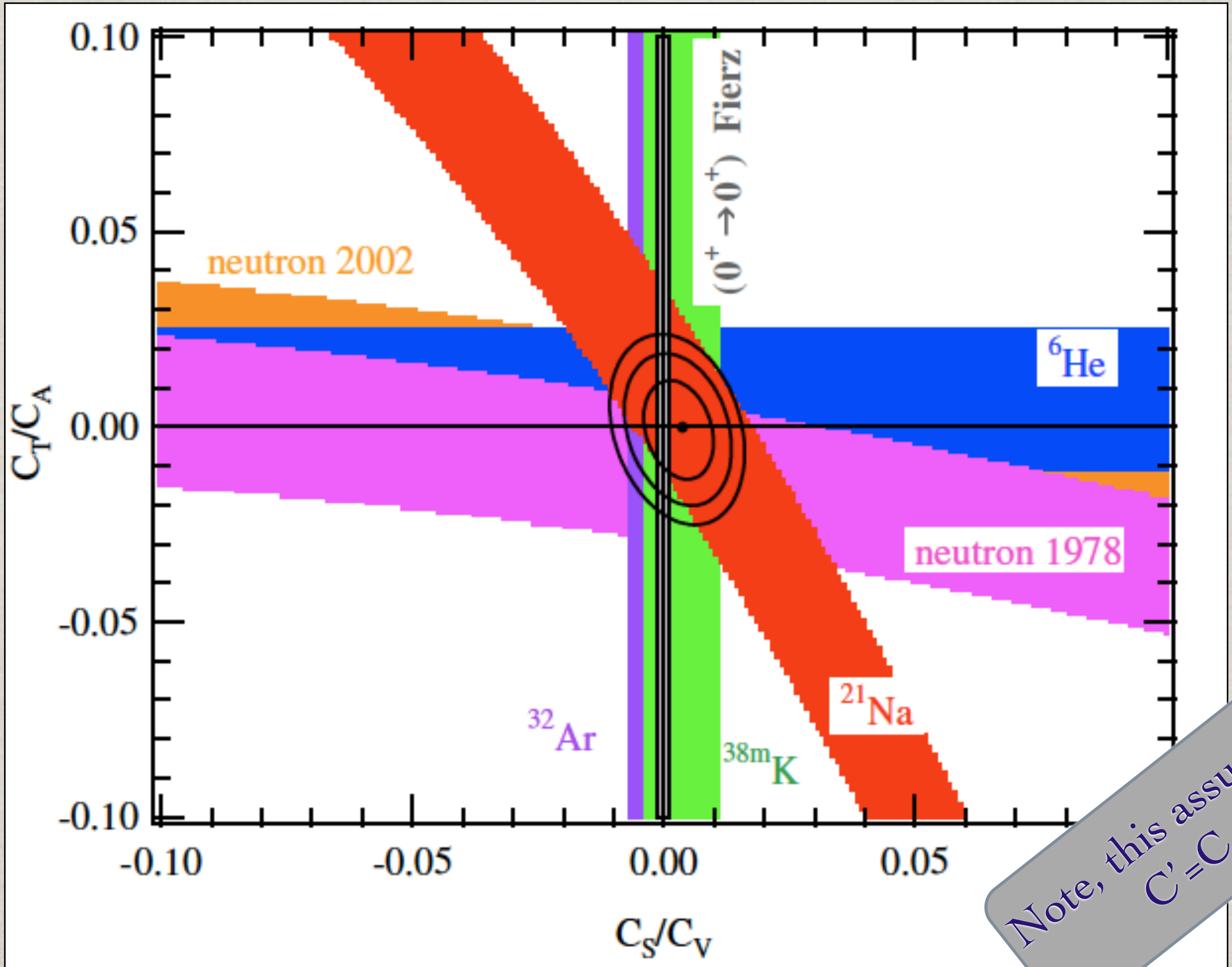
- Very large model space.
- Not spanned by collider experiments.
- Current best limits not very stringent.
- Naively $\frac{C_T}{C_A}, \frac{C_S}{C_V} \propto \left(\frac{M_W}{M_{NewPhys}}\right)^2$
  so uncertainty to 0.01 probes new physics at ~ 1TeV!





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

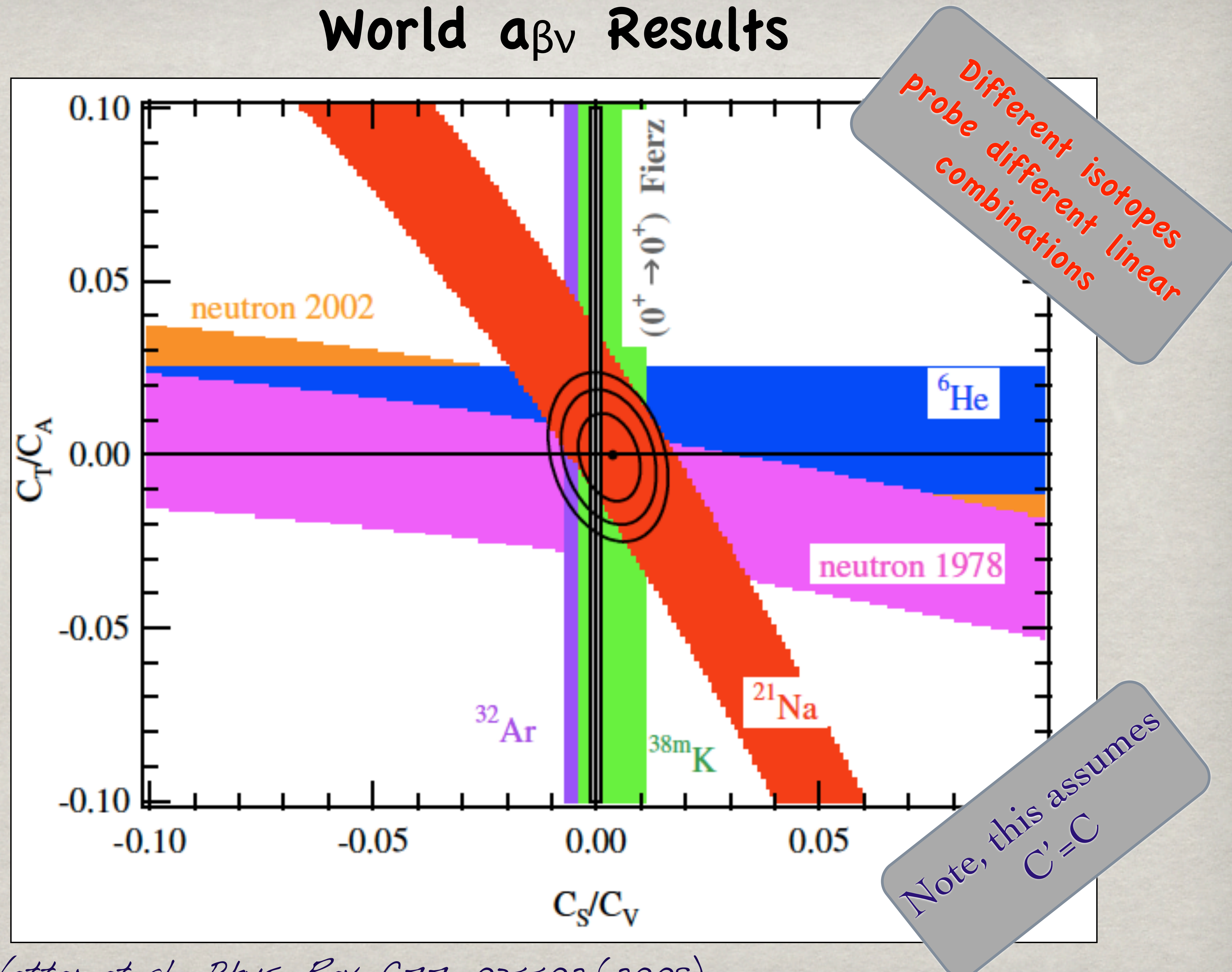
World $a_{\beta\nu}$ Results



Note, this assumes C'=C

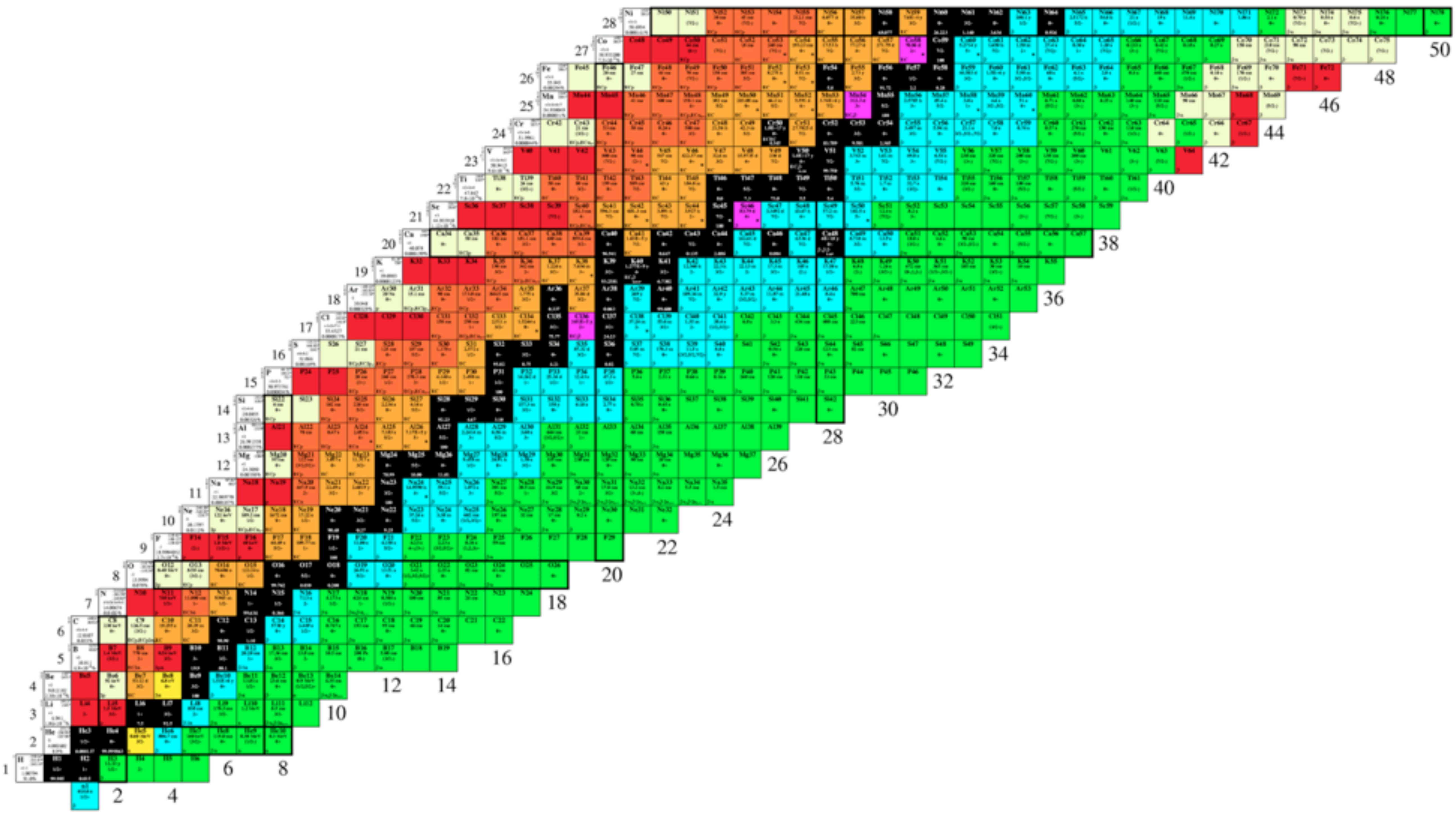
P. A. Vetter et al., Phys. Rev. C77, 035502 (2008)

World $a_{\beta\nu}$ Results

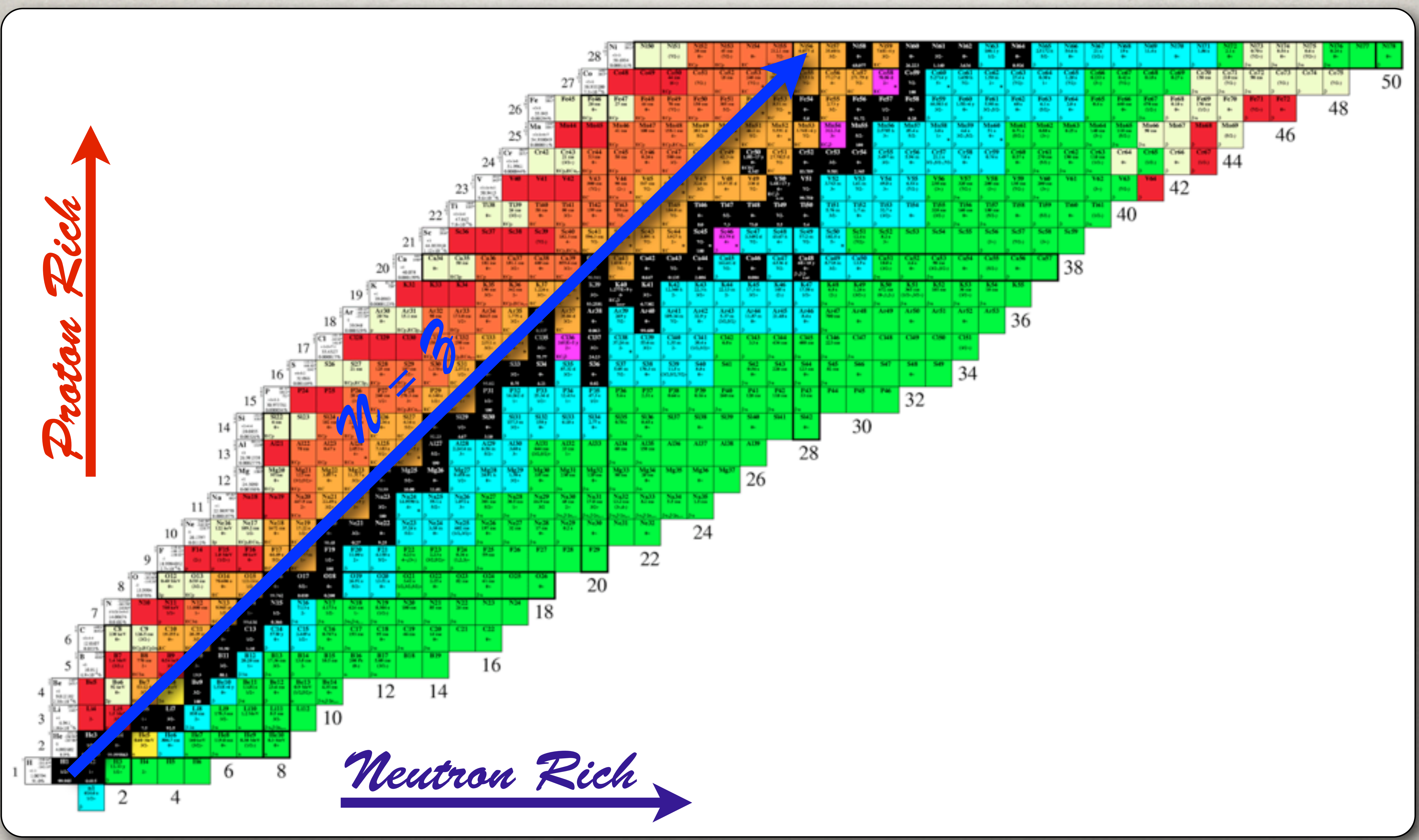


P. A. Vetter et al., Phys. Rev. C77, 035502 (2008)

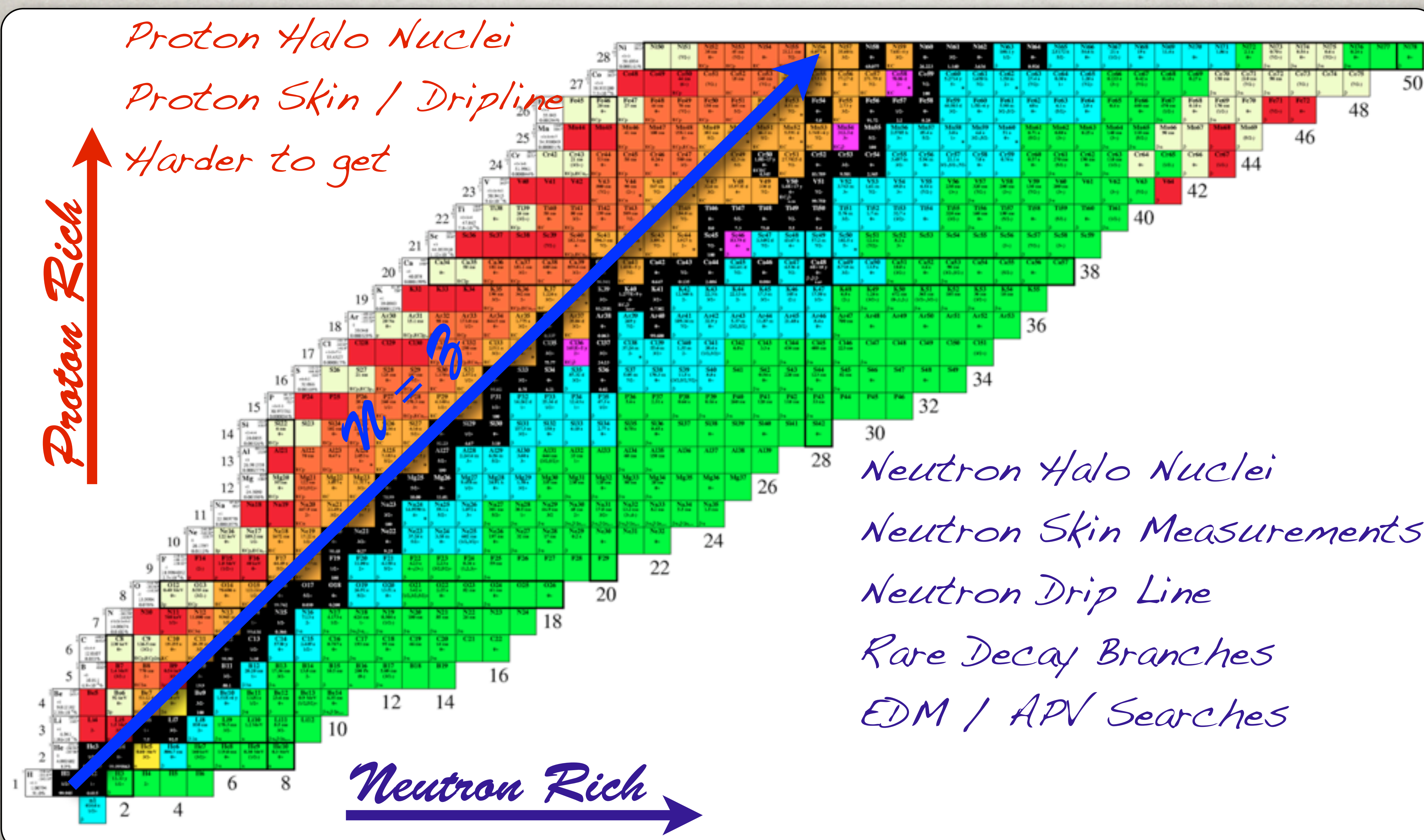
The Nuclear Landscape



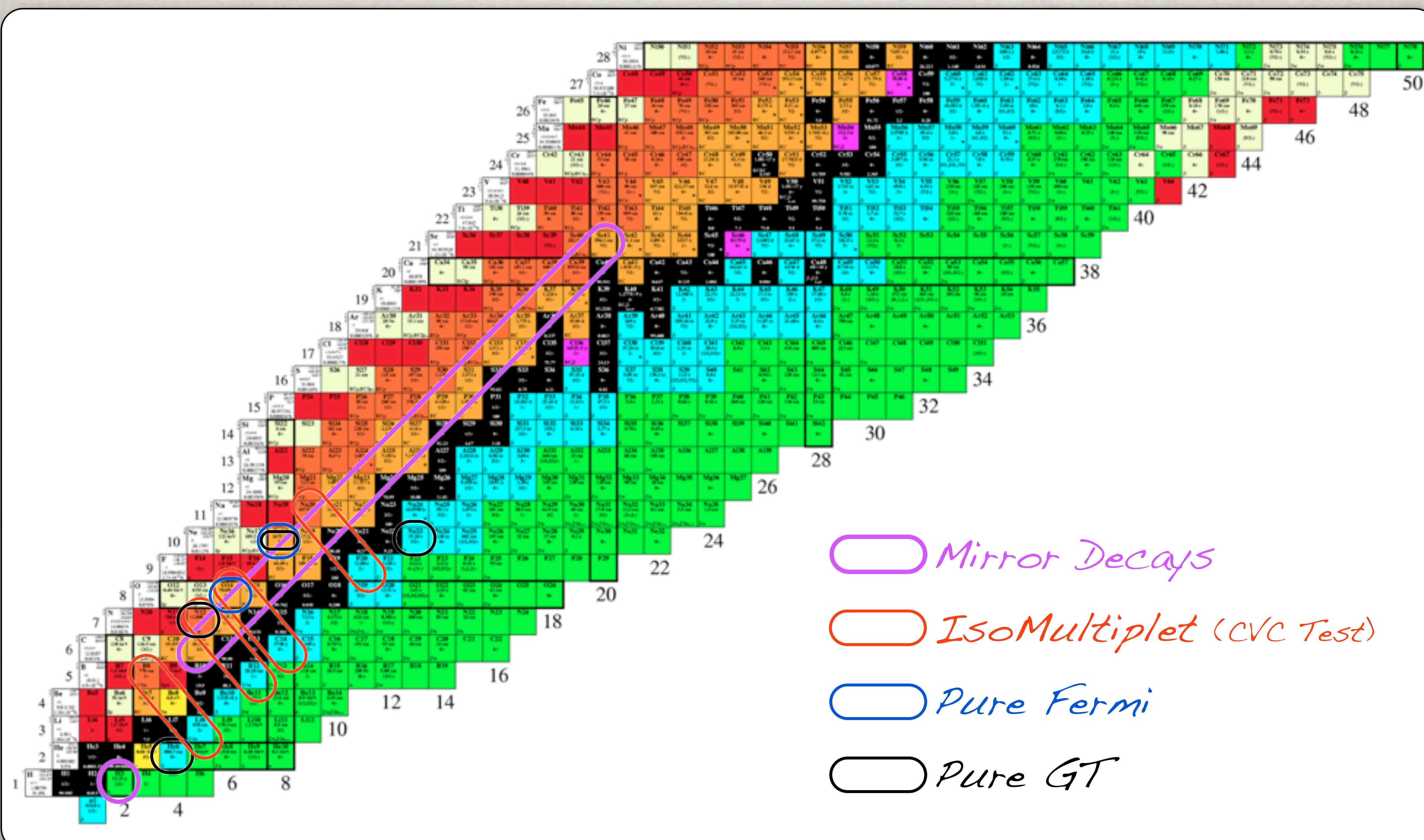
The Nuclear Landscape



The Nuclear Landscape



Some Interesting Candidates
(Low Mass)



Anatomy of an Experiment

Produce Radioactive Atoms

(Produce, Transport, Neutralize)

↓

Trap

(MOT, Dipole, Ion, Electrostatic)

↓

Wait...

↓

Detect decay products (β, Ion)

(Scintillators, MCPs,...)

↓

Analyze and compare to SM

Typical Experimental Schemes (Traps)

Magneto-Optical Traps (MOTs)

Trap neutral atoms by interaction of laser light with atomic electrons.

Trapped atoms form a localized, dilute system.
Can be (not easily) polarized.

Only atoms with appropriate energy levels may be trapped (laser accessible).
Recoiling decay products must be accelerated for detection.
Expensive, complicated setup (lasers).

"Standard" Ion Traps (Paul/Penning)

Trap ions by interaction of ion charge with electric (Paul) or magnetic (Penning) fields.

Localized, dilute system.
Any ion species is potentially trappable.

Recoiling decay products must be accelerated for detection or guided by magnetic field to spectrometer.
Expensive, complicated setup (RF, superconducting magnets).

The β-Decay EIBT Scheme

Trap moving ions in Electrostatic Ion Beam Trap.

Simple, cheap setup.

Easy to polarize (appropriate ions).

No need for acceleration of products - simple detection scheme.

Kinematic focusing.

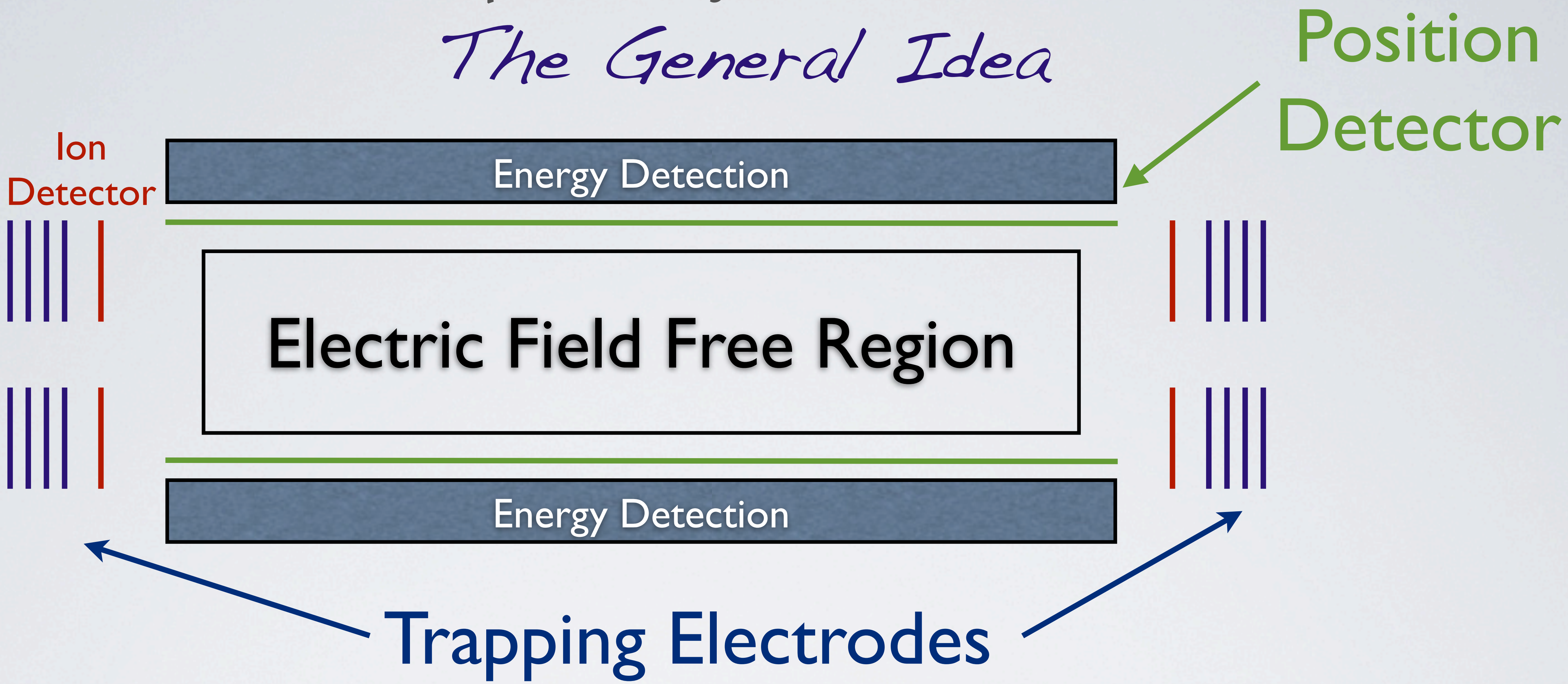
Decay in field free region.

Moving system - position of decay harder to infer.

Large initial spatial extent (bunch).

β-Decay Studies

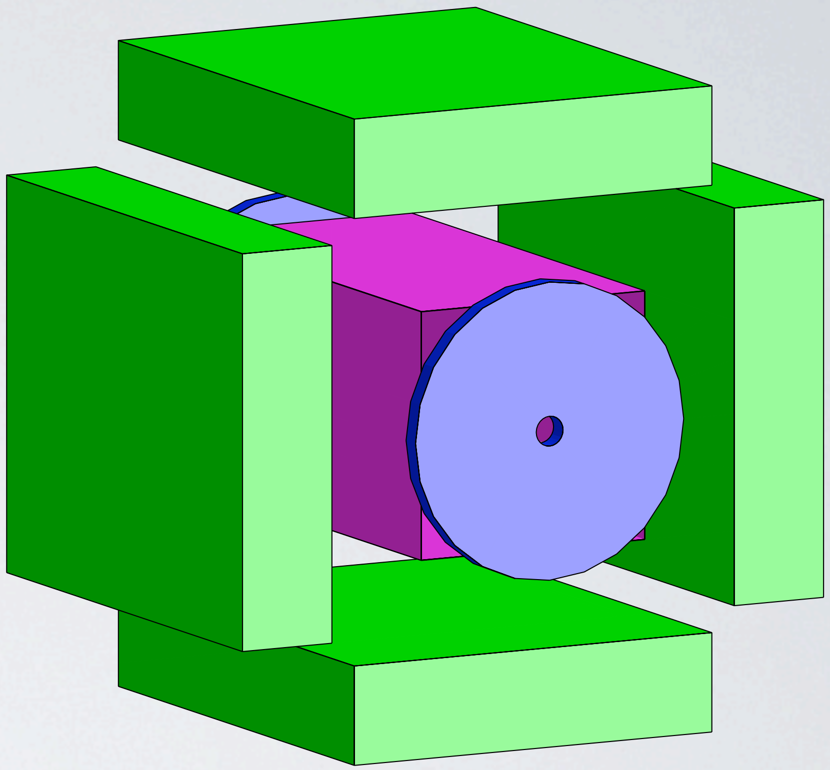
The General Idea

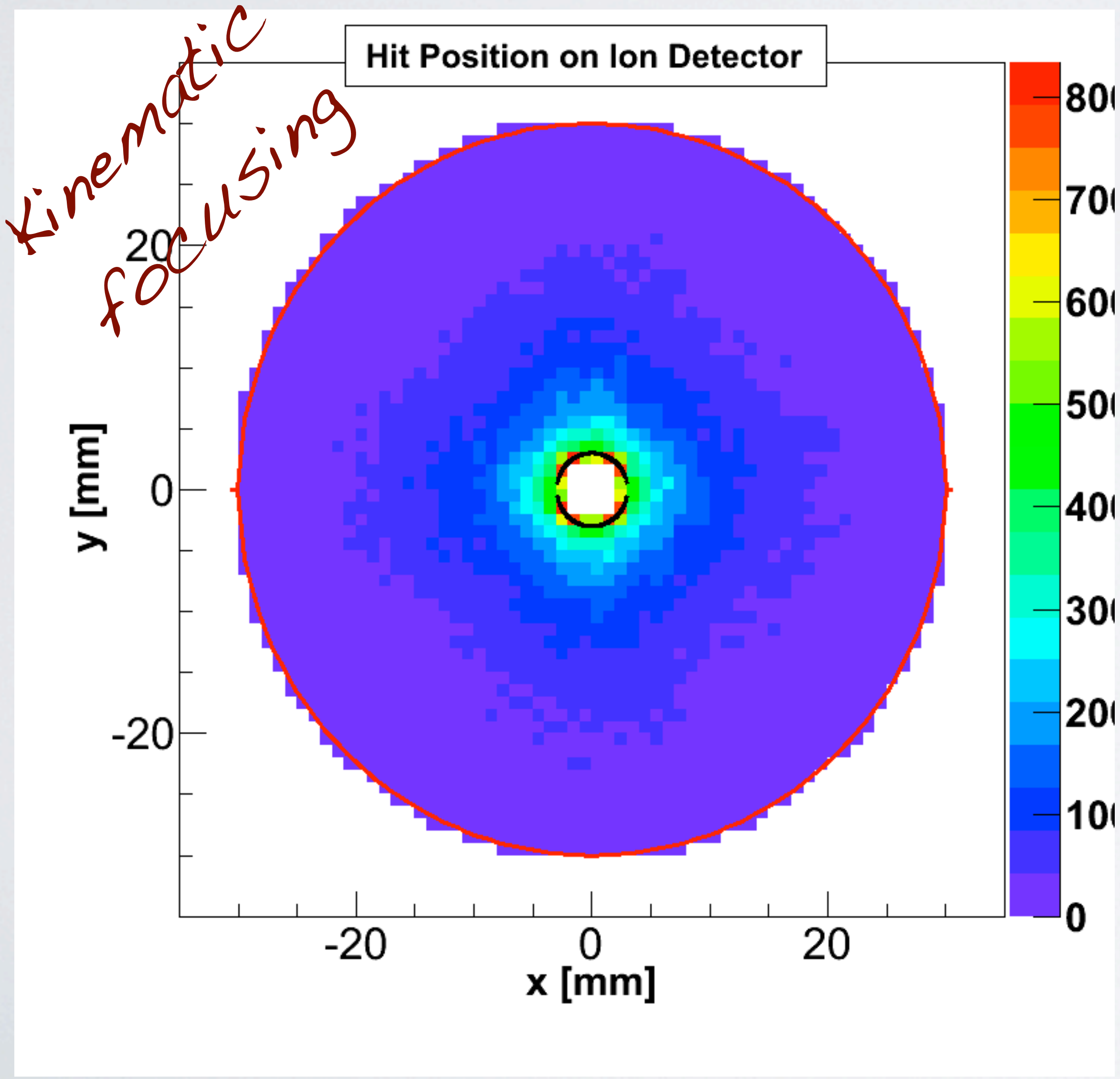


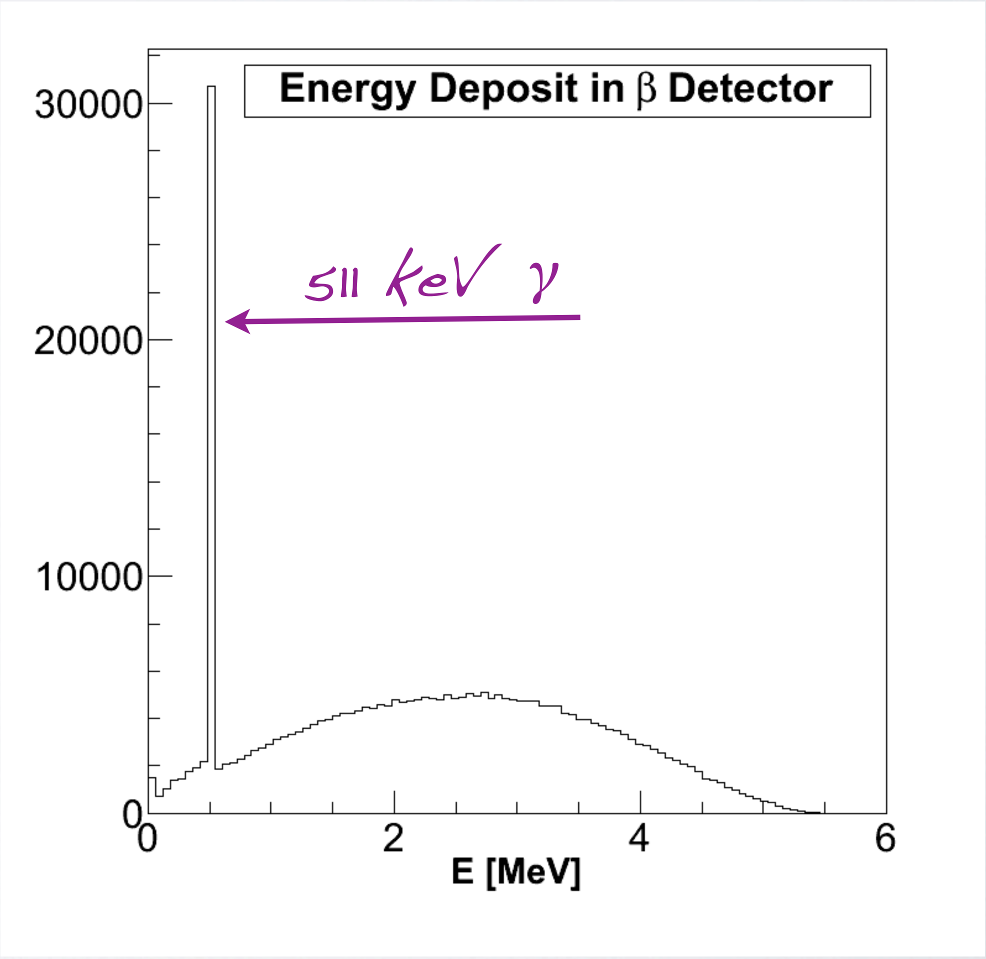
- Recoil ion detected in MCP.
- β detected in position detectors.
- Need bunch position for full reconstruction (multiple scattering of β in detectors).
- Large solid angle + kinematic focussing → detection efficiency > 50%.
- No need for electrostatic acceleration (ions at ~keV). Decay in field free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

Some Simulation Results

β decay of $^{39}Ca^{+} \rightarrow {}^{39}K^{+} + \beta^{+} + \nu$
Kinetic energy of original ion 4.2KeV
Cuts require hits in only one MCP and only one SSD (no ambiguity)







Measuring aβυ

Time-of-flight Technique

(or, why is TOF related to $a_{\beta\nu}$)

$$\vec{P}_{recoil} = \vec{p}_\beta + \vec{p}_\nu$$

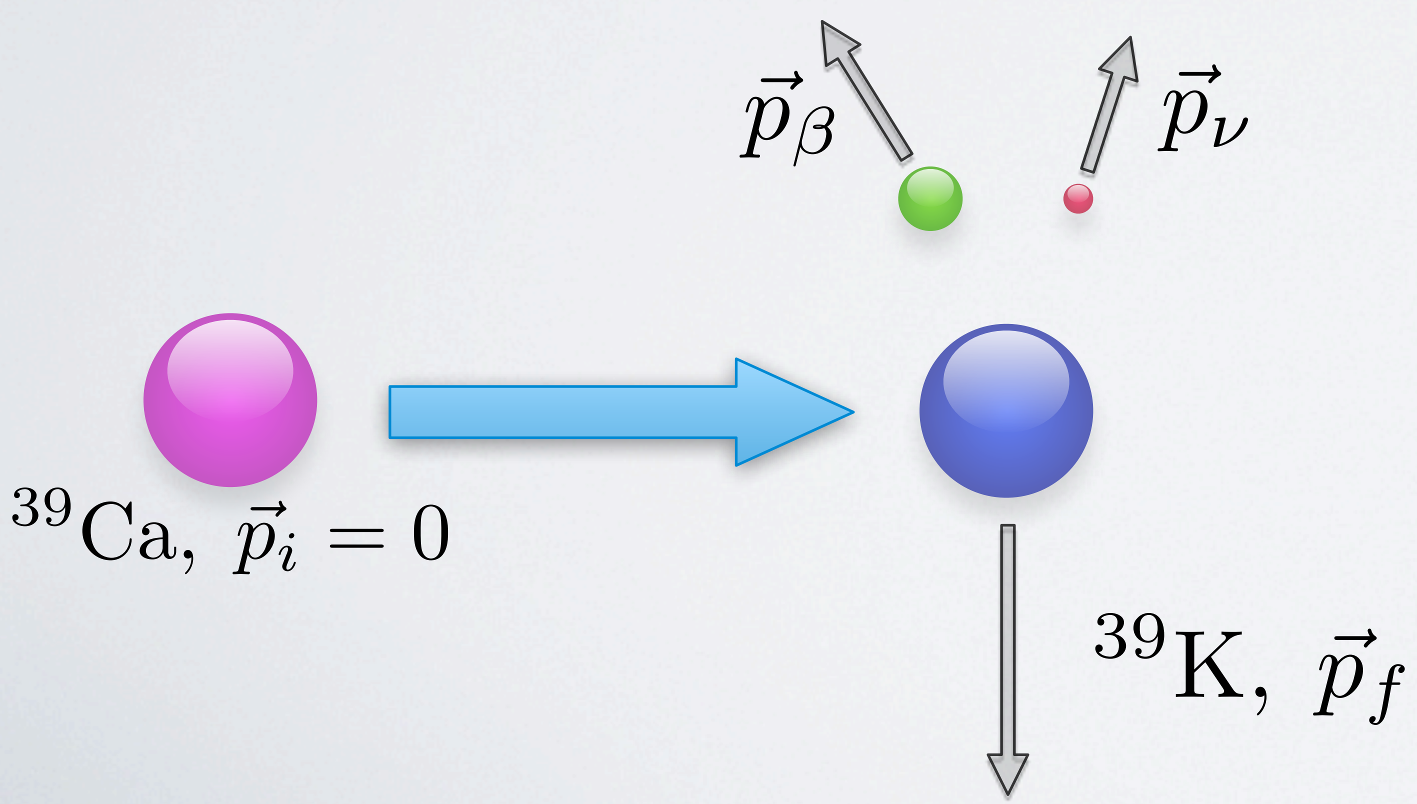
$$\left|\vec{P}_{recoil,0}\right| = |\vec{p}_{\beta,0}|$$

$$= \sqrt{(E_0 + m_e)^2 - m_e^2}$$

$$E_{recoil,0} = \sqrt{P^2_{recoil,0} + M_A^2} - M_A$$

Positive correlation ➛ large recoil momentum ➛ low TOF

Negative correlation ➛ low recoil momentum ➛ high TOF

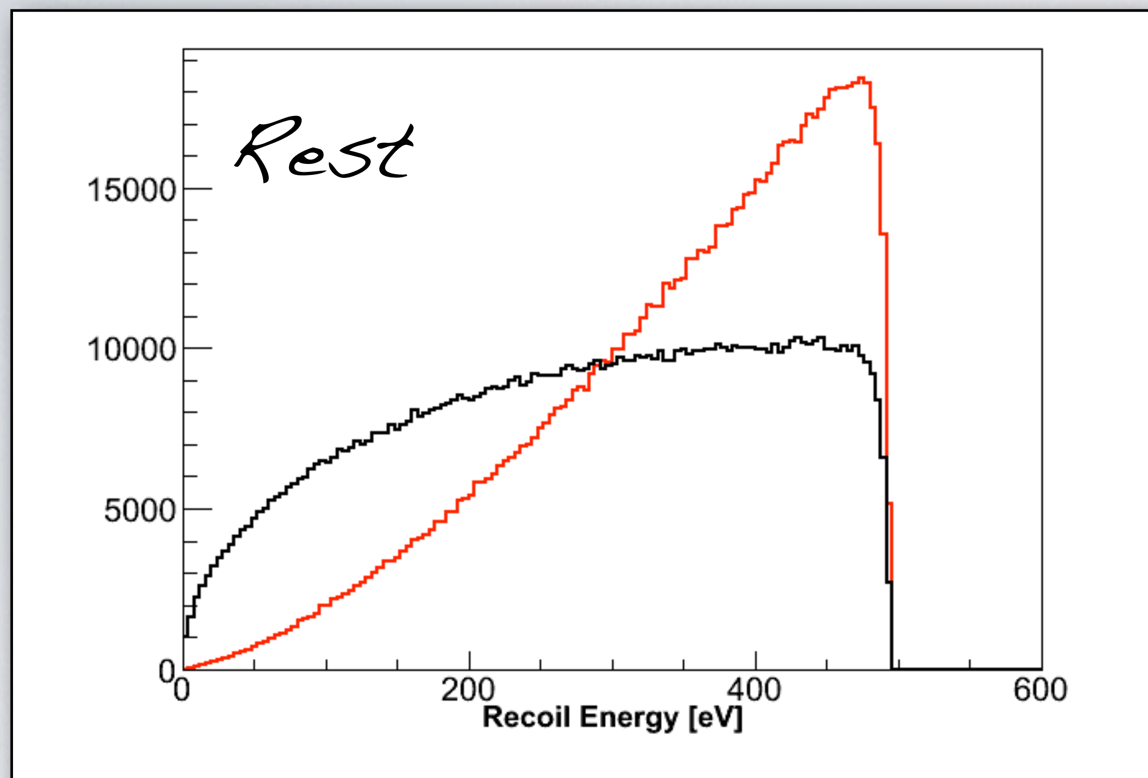


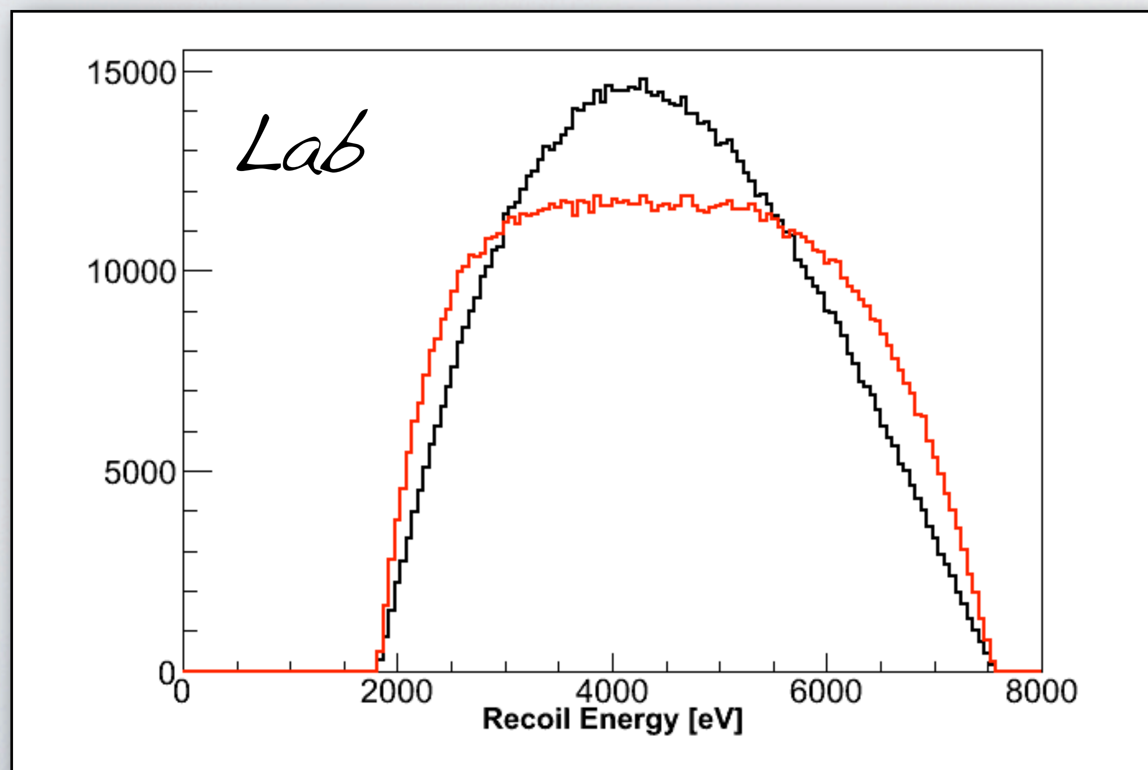
For ^{39}Ca $E_0 \sim 6$ MeV

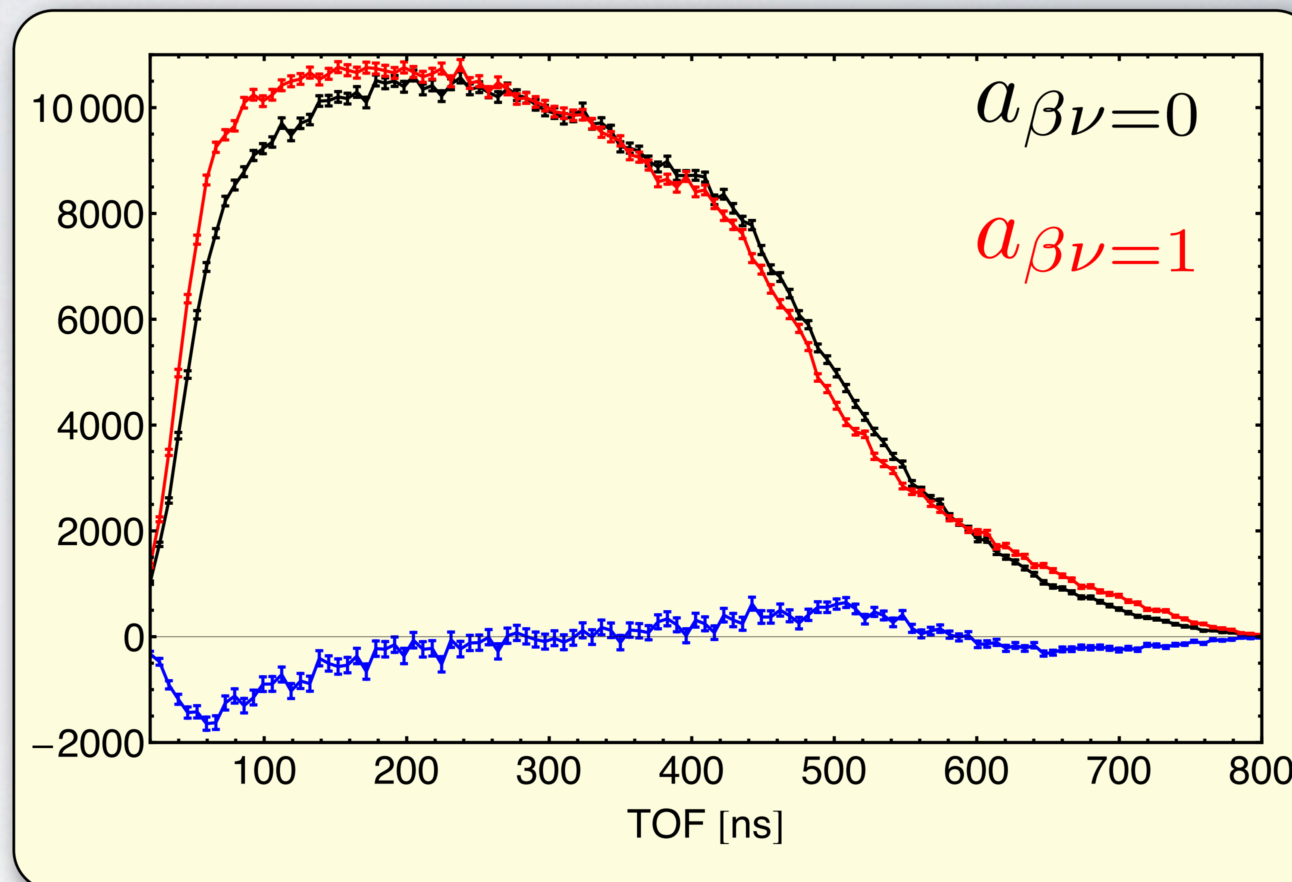
$E_{recoil} \sim 550$ eV

Measuring $a_{\beta\upsilon}$

Time-of-flight Technique







Only recoil ion detection needed.

Generate templates from simulation and fit for real data (1-parameter fit).

Measuring $a_{\beta\upsilon}$

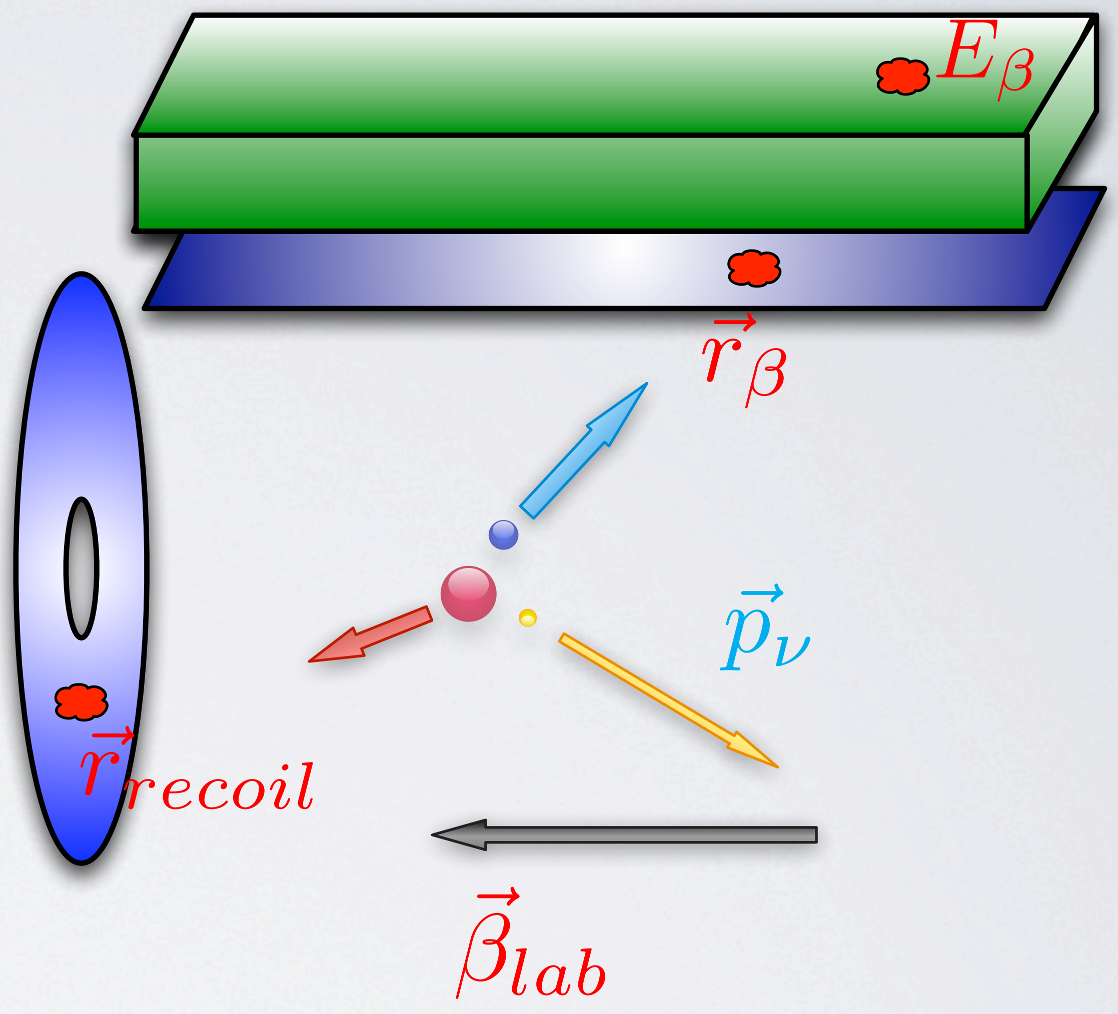
Direct Measurement - Do we have enough observables?

Detector setup:

- Recoil ion - MCP (Position + Time).
- β - Silicon Strip/GEM + Scintillator (Position, Time, Energy).

Measured Quantities:

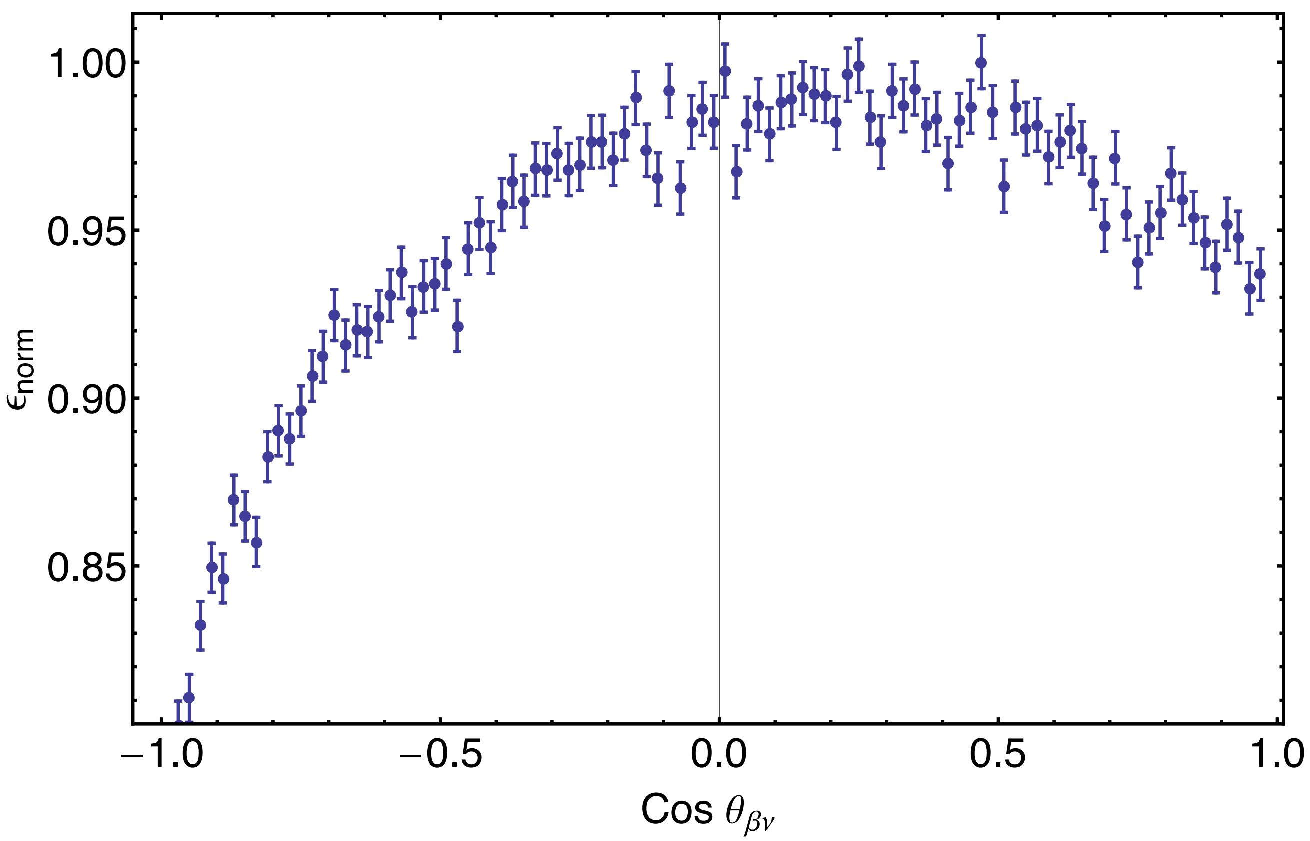
- β 4-vector: $(E_\beta, P_\beta)_{lab}$.
- Recoil 3 vector - using timing from β: $(P_{recoil})_{lab}$.
- Initial ion kinetic energy: β_{lab} - Known from kinematic focusing.
- Recoil ion mass - from decay scheme.
- Decay position - from pickup.

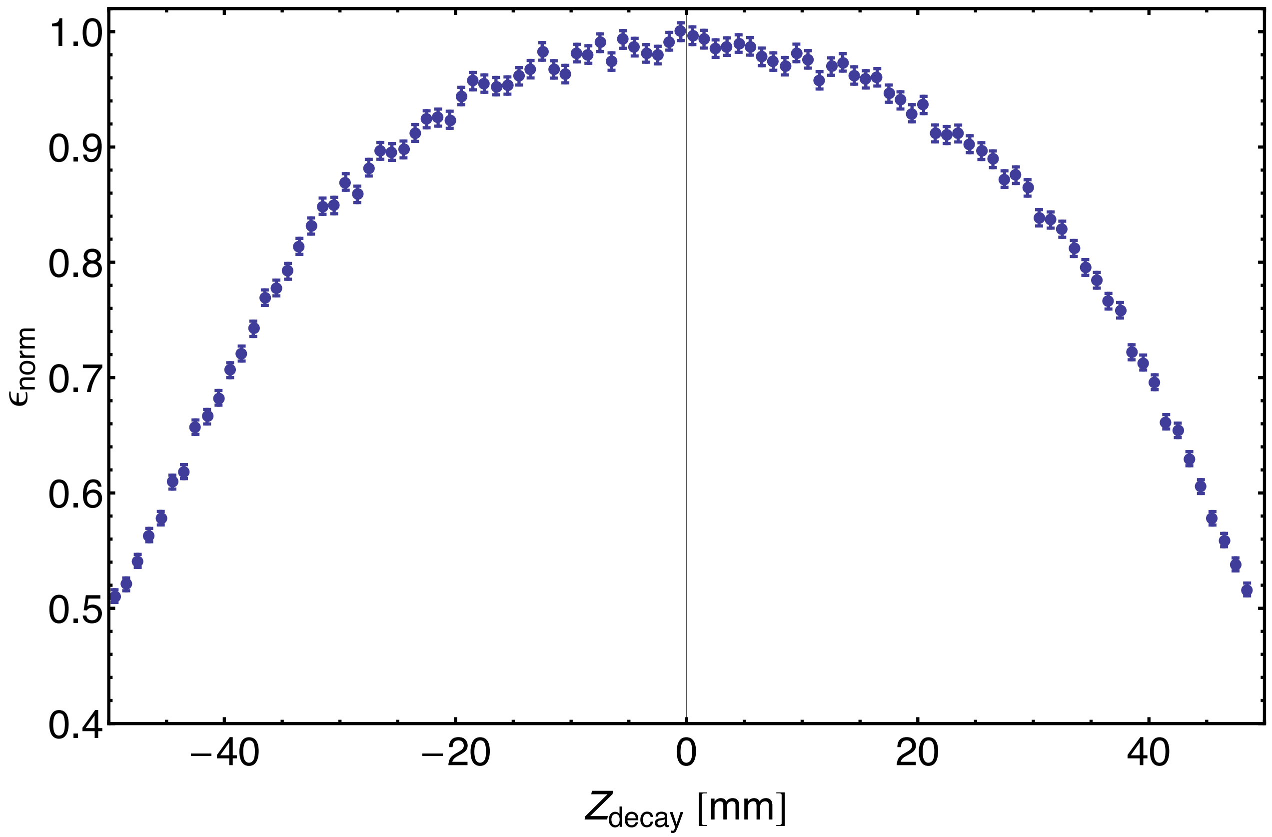


$$E_{recoil} = \sqrt{M^2_{recoil} + \vec{P}^2_{recoil}}$$
$$\underline{P}^{rest}_{recoil} = \Lambda(-\beta_{lab})\underline{P}^{lab}_{recoil}$$
$$\underline{P}_\beta = \Lambda(-\beta_{lab})\underline{P}^{lab}_\beta (\sim \underline{P}^{lab}_\beta)$$
$$\underline{P}_\nu = -\underline{P}_\beta - \underline{P}_{recoil}$$

$$\cos\theta_{\beta\nu} = \frac{\vec{p}_\beta \cdot \vec{p}_\nu}{|\vec{p}_\beta||\vec{p}_\nu|}$$

Measuring $a_{\beta\upsilon}$





But still need to correct for non-uniform detection efficiency (position/angle).

Accurate simulation of trap + detectors still needed.

Statistical Aside

How does this stack up?

Compare with ^{21}Na:

LBL ^{21}Na experiment needed 3.6×10^6 decays (in 66h) to get 0.7% statistical uncertainty.

$T_{1/2}(^{21}Na)$ = 22.49 sec.

For the ES Trap:

Trap lifetime (measurement time) ~ 300 msec

Trap population = 10^4 ions

Duty factor: 1 injection / 3 sec (f = 0.1).

Detection Efficiency: ε = 0.3

} *Conservative Estimates*

$$R = 10^4 \left(1 - e^{-\tau_{trap}/\tau_{1/2}}\right) \cdot f \cdot \varepsilon \sim 66\,\mathrm{sec}^{-1}$$

$$T_{3.6\cdot 10^6} \sim 15\,\mathrm{h}$$

Polarization Dependent Observables

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

- Requires polarization of initial sample.
- Measurement typically of position asymmetry.
- Usually flip field for systematic control.

But....

- Polarization requires magnetic field (hard in MOT/Ion Trap).
- Accurate control of polarization shifts?
- Position Asymmetry hard to measure.

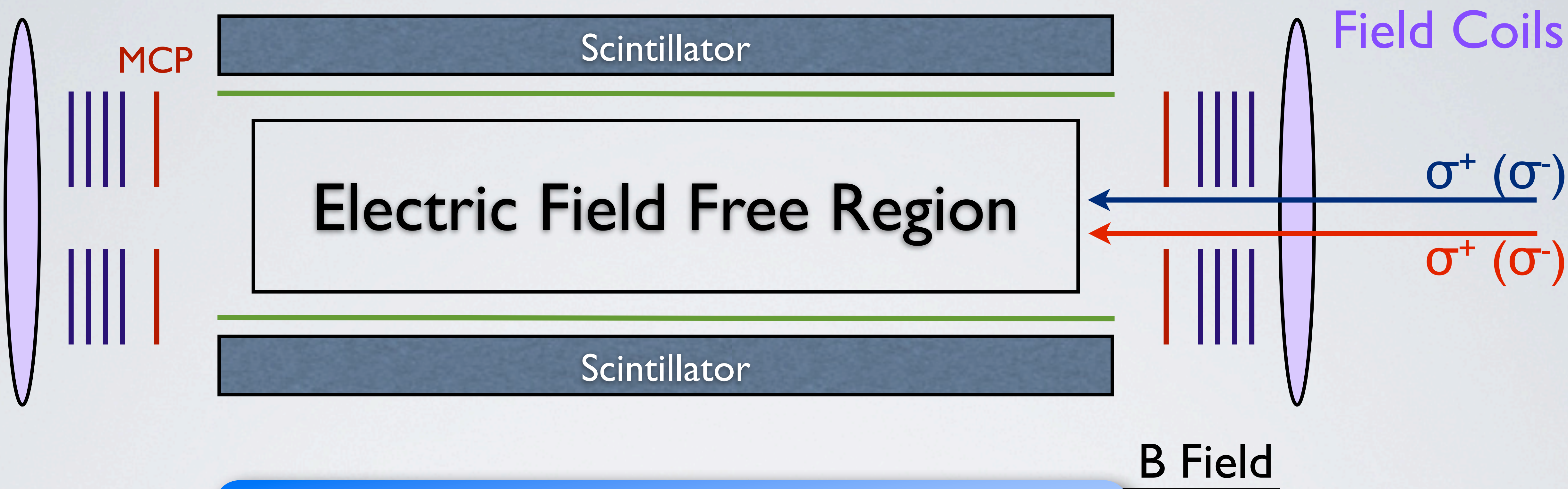
Polarization in β-Decay Studies

Neat trick

- Add on-axis magnetic field for Zeeman splitting.
- On-axis field does not effect the trajectories (V X B = 0).
- Polarize ions with circularly polarized lasers.
- Due to large doppler shift (high energy ions) → two independent ion populations (parallel/anti-parallel).
- MCP hit is determined by direction of ion → each MCP sees only one population.
- Need polarizable ions (usually singly ionized alkaline earth metals - which look like alkali metals when singly ionized).

Polarization in β-Decay Studies

Neat trick



Pretty much only possible in optical and ES traps

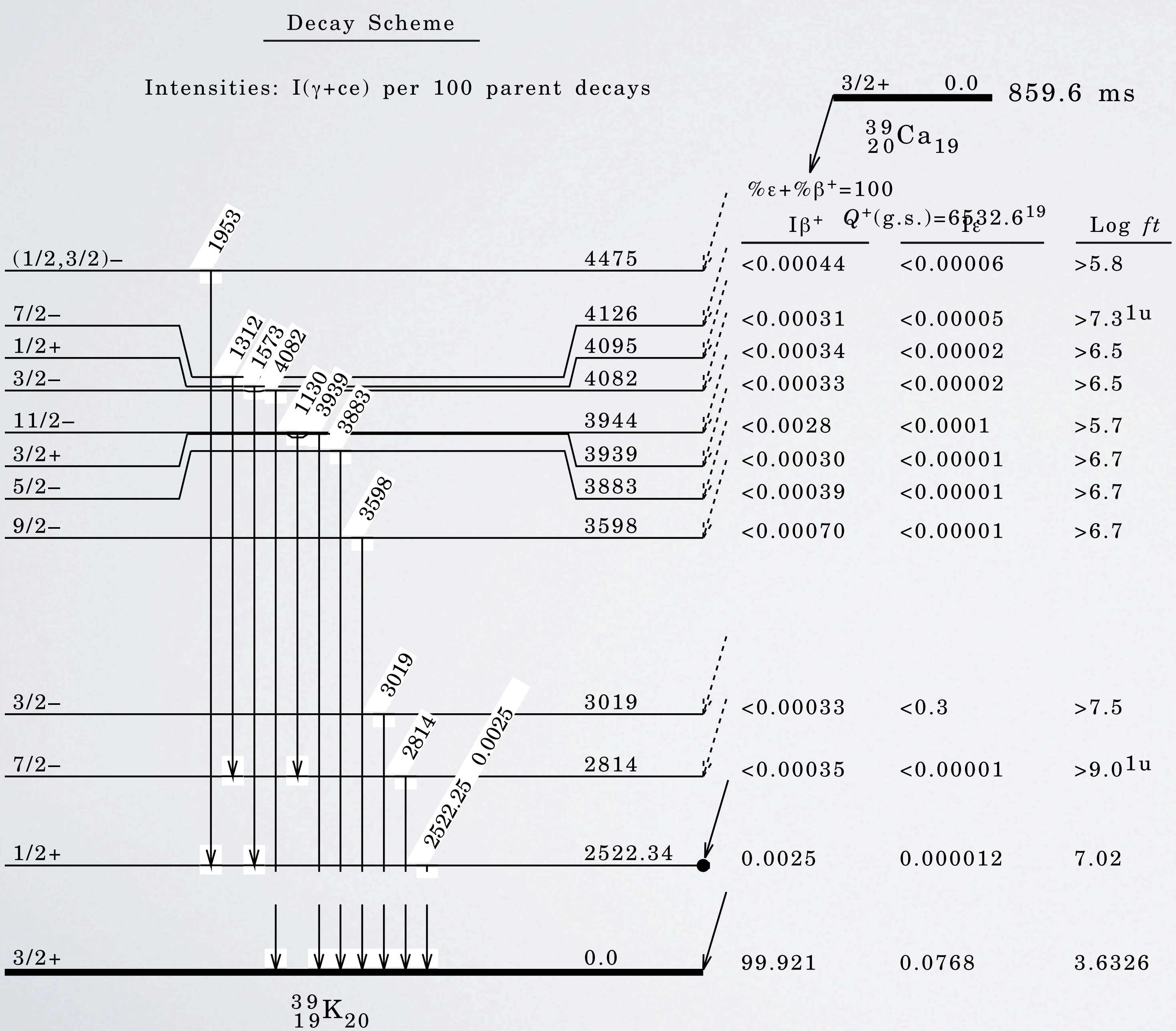
- Add on-axis
- On-axis fiel
- Polarize ion
- Due to large doppler shift (high energy ions) ➞ two independent ion populations (parallel/anti-parallel).
- MCP hit is determined by direction of ion ➞ each MCP sees only one population.
- Need polarizable ions (usually singly ionized alkaline earth metals - which look like alkali metals when singly ionized).

EXAMPLE ^{39}K

?

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

Translates to TOF on MCPs



$$^{39}Ca \rightarrow {}^{39}K + \beta^+ + \nu_e$$

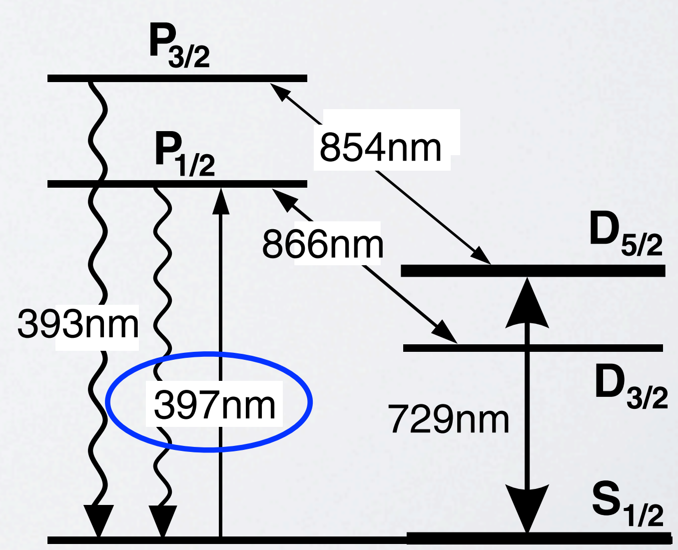
Mirror decay $3/2^+ \rightarrow 3/2^+$

Combination GF and F but calculable

Q = 6.532 MeV

$\tau_{1/2}$=860 ms

For 4.2keV ~360GHz doppler shift → 720GHz separation.



“High Energy” Chemistry (IV)

An experiment looking for a theorist

- Production of radioactive molecules/dimer/clusters is fairly trivial (usually a side effect of the production of radioactive atoms/ions).
- Ionization of such molecules - also trivial.
- ES trap can easily trap molecules of hundreds of amu (also used for bio-molecules).

- Radioactive decay dumps a lot of energy and momentum into the decay products.
- Time scale for decay/emission of shakeoff products is effectively instantaneous.

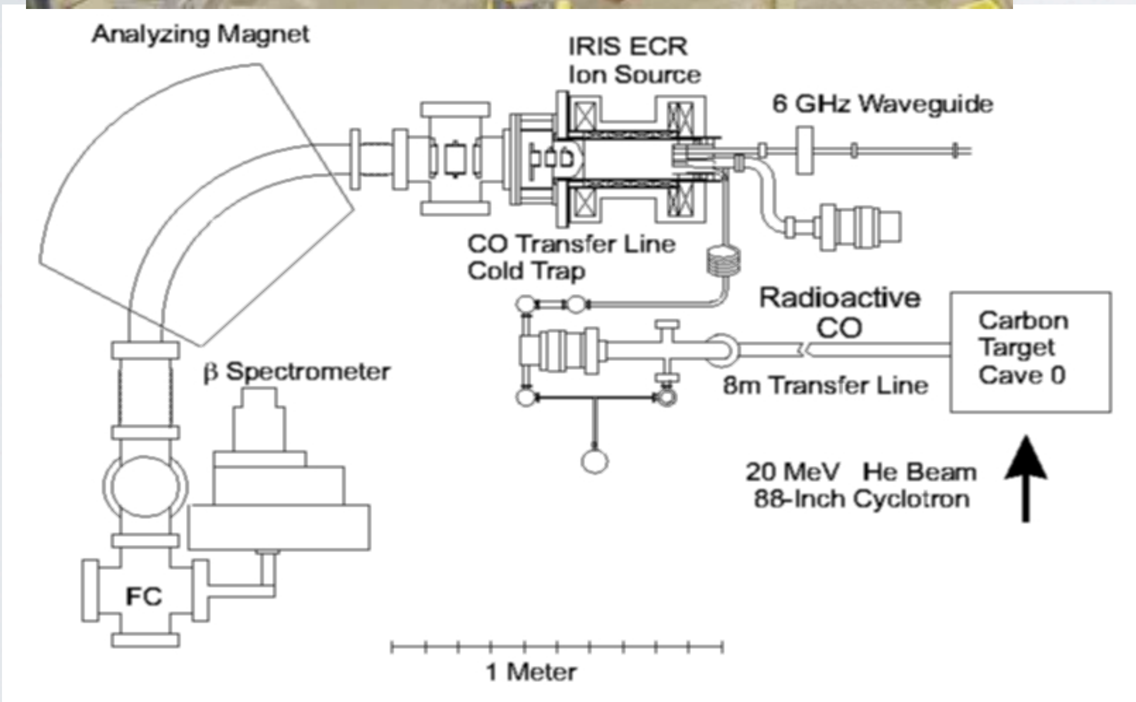
- Detect molecular decays in ES trap.
- Energy/Momentum sharing between decay products (electronic interaction timescales?).
- Angular correlation in decays (potential?).
- High detection efficiency.
- Mass resolution good enough for selection of different numbers of radioactive atoms in clusters

$$\frac{{}^{23}\mathrm{Na}_4 - {}^{21}\mathrm{Na}{}^{23}\mathrm{Na}_3}{{}^{4}\mathrm{Na}_{23}} \sim \frac{2}{92}$$

$$\frac{{}^{23}\mathrm{Na}_4 - {}^{21}\mathrm{Na}_2{}^{23}\mathrm{Na}_2}{{}^{4}\mathrm{Na}_{23}} \sim \frac{4}{92}$$

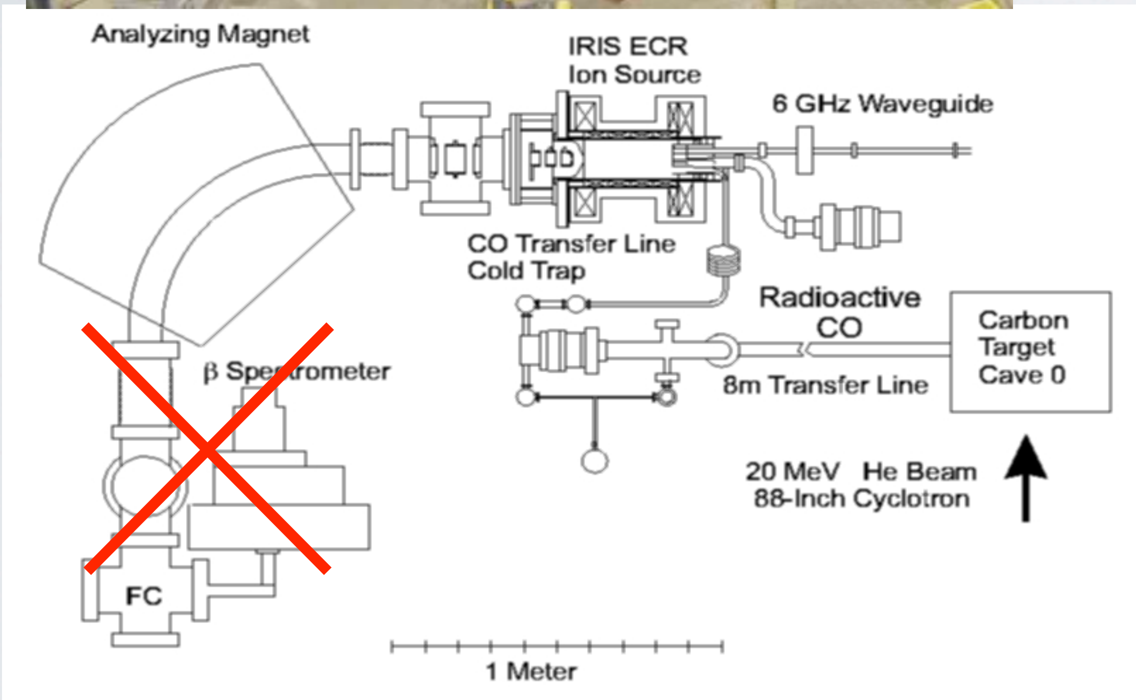
Trivial

Where are we now?



- Berkeley IRIS source used for production of ^{14}O.
- Now recommissioning for BEST.

Where are we now?



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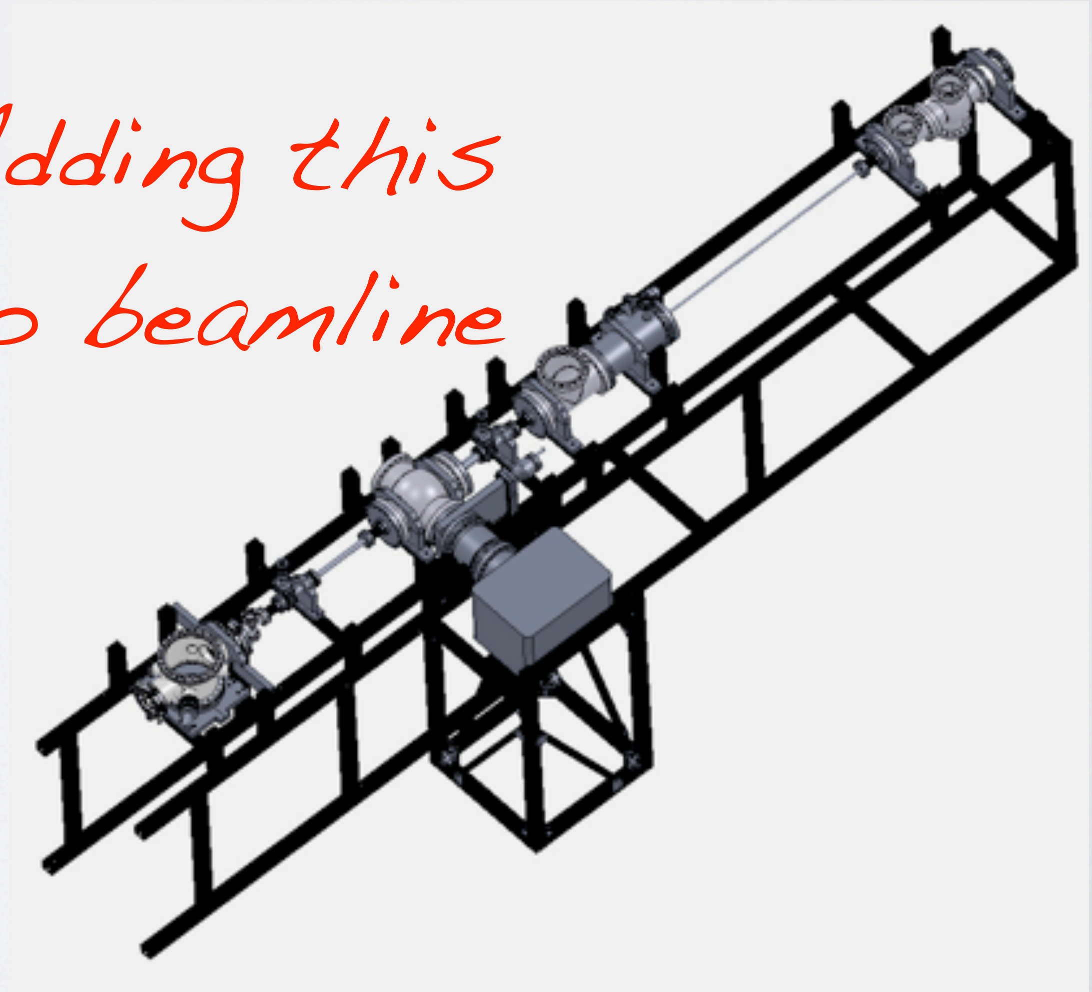
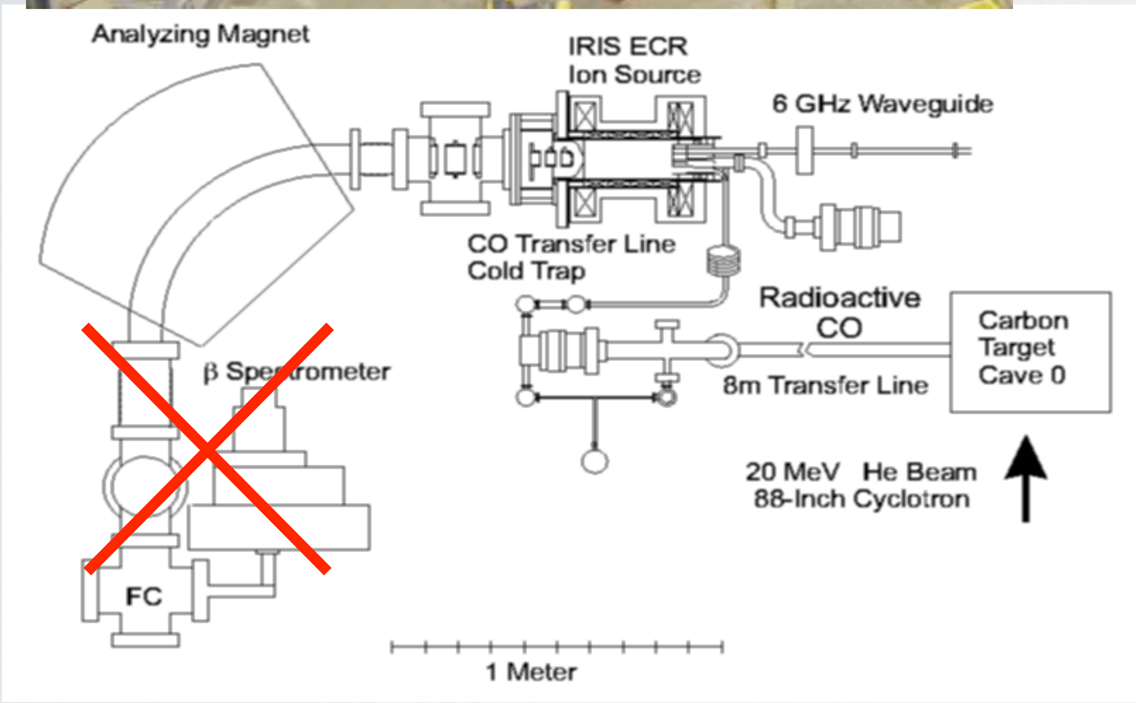
Adding this to beamline



Where are we now?



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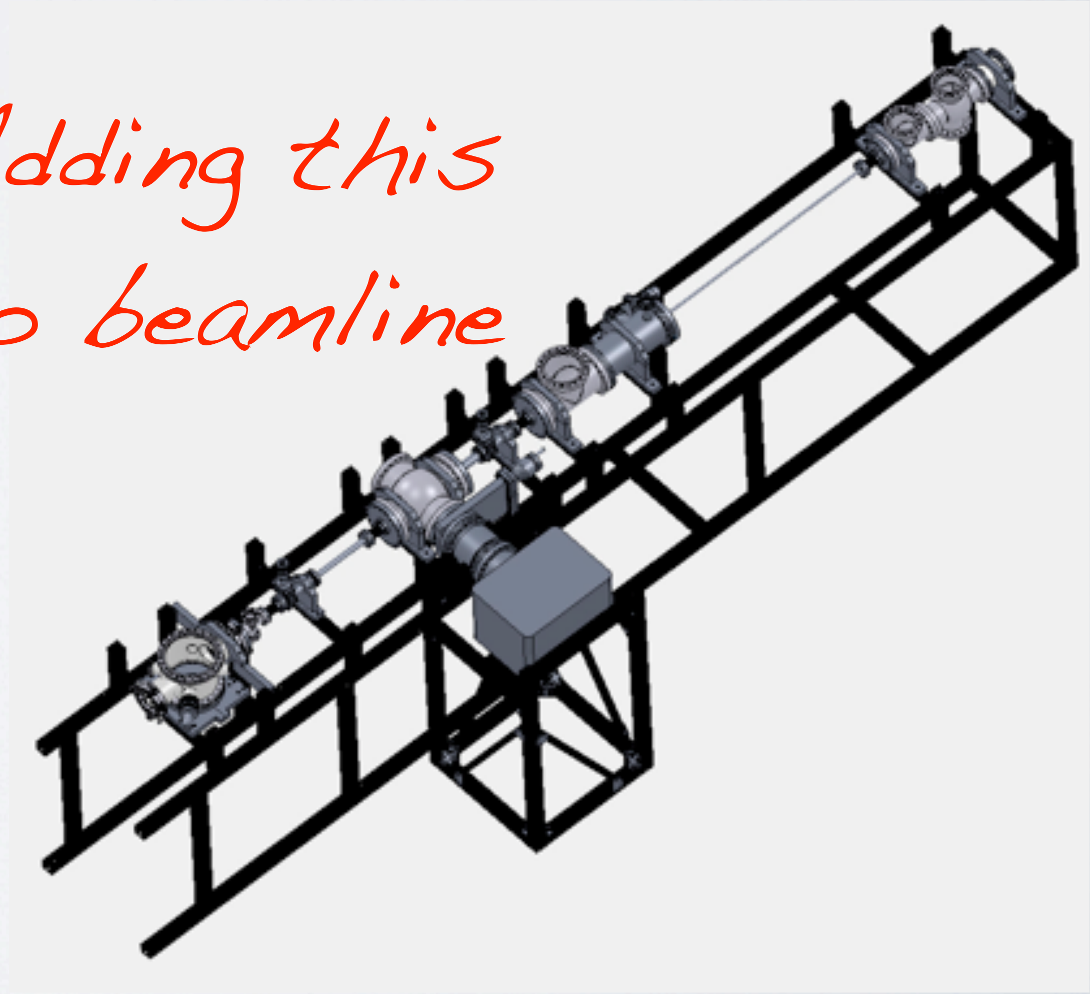
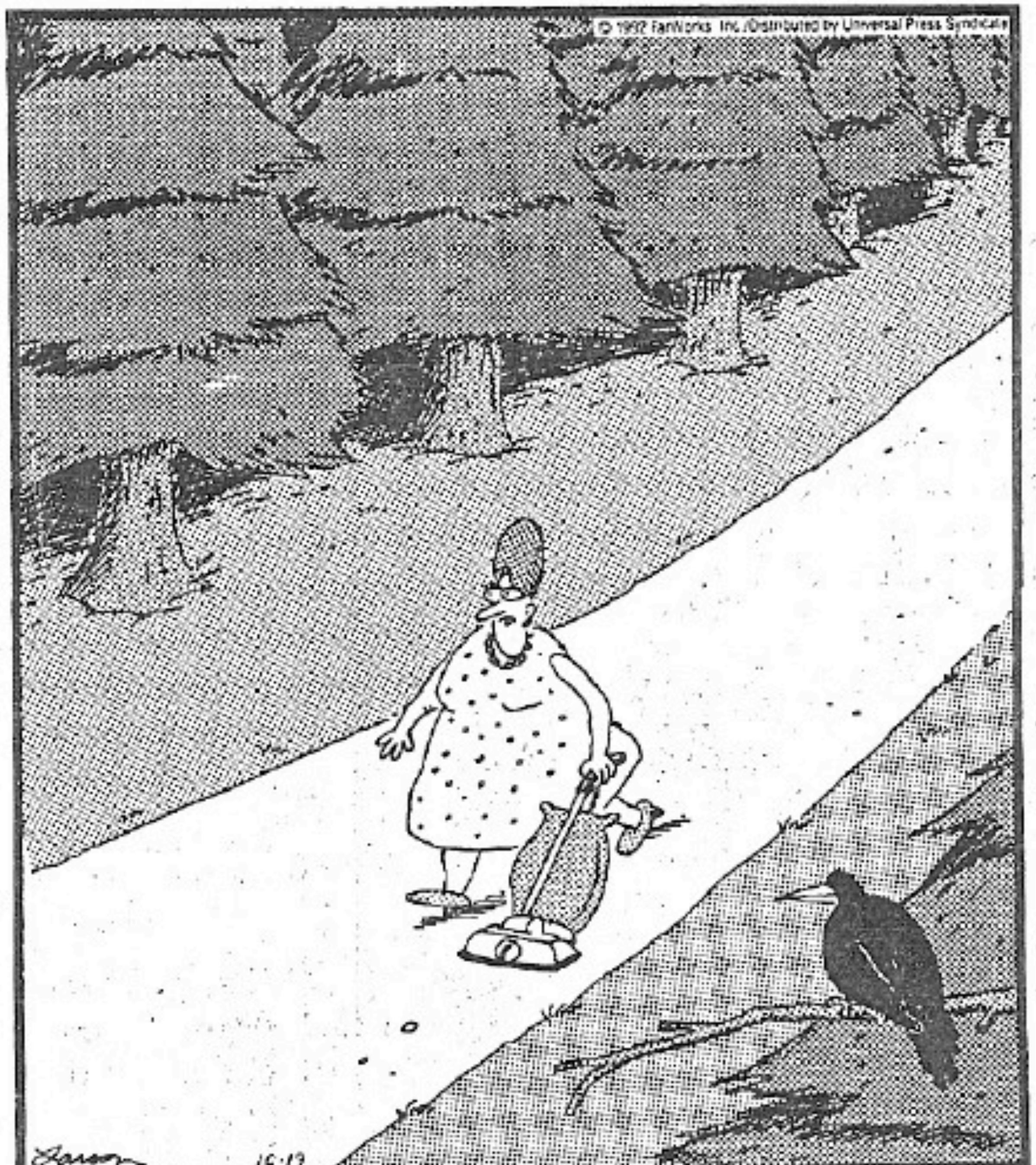
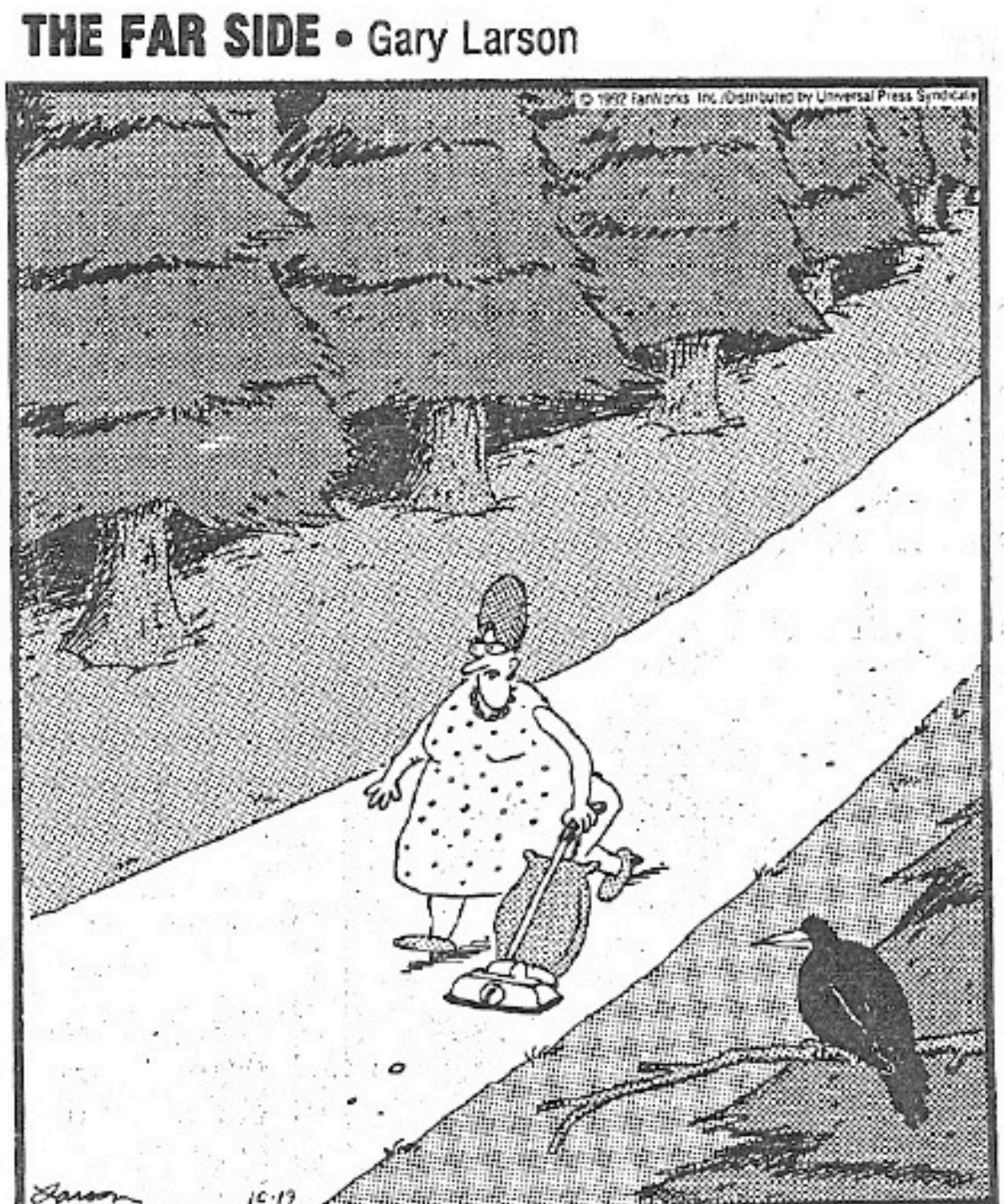


Developing targets for ^{35}Ar and ^{18}Ne

THE FAR SIDE • Gary Larson



The woods were dark and foreboding, and Alice sensed that sinister eyes were watching her every step. Worst of all, she knew that Nature abhorred a vacuum.



The woods were dark and foreboding, and Alice sensed that sinister eyes were watching her every step. Worst of all, she knew that Nature abhorred a vacuum.

Trap lifetime essentially determined by vacuum

Problem:

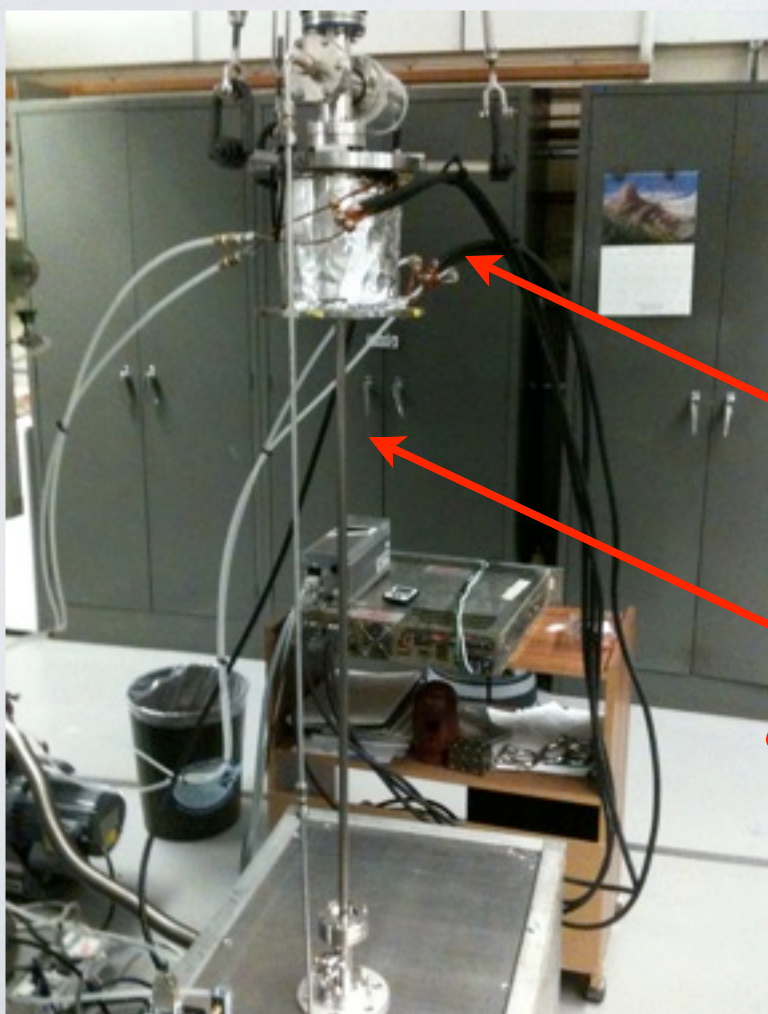
How do we get from 10^{-7} Torr to 10^{-12} in a few meters

Differential Pumping with a twist

Non Evaporable Getter (NEG)

- Ti alloy which when absorbs residual gasses in the vacuum (pretty much anything except noble gases).
- Originally developed as a "NEG pump" by SAES getters.

A page from the LHC playbook
Thin-film deposition of NEG in beamline



Developed magnetron sputtering system for NEG. Designed to coat long, thin, tubes (in other words - differential pumping stages).

400G DI water cooled magnet (axial field)

Tube being coated
Cathode wire inside tubes (radial field)

Ooh... Shiny....

Non Evaporable Getter (NEG)

- Ti alloy which when absorbs residual gasses in the vacuum (pretty much anything except noble gases).
- Originally developed as a “NEG pump” by SAES getters.

A page from the LHC playbook

Thin-fi… …mline

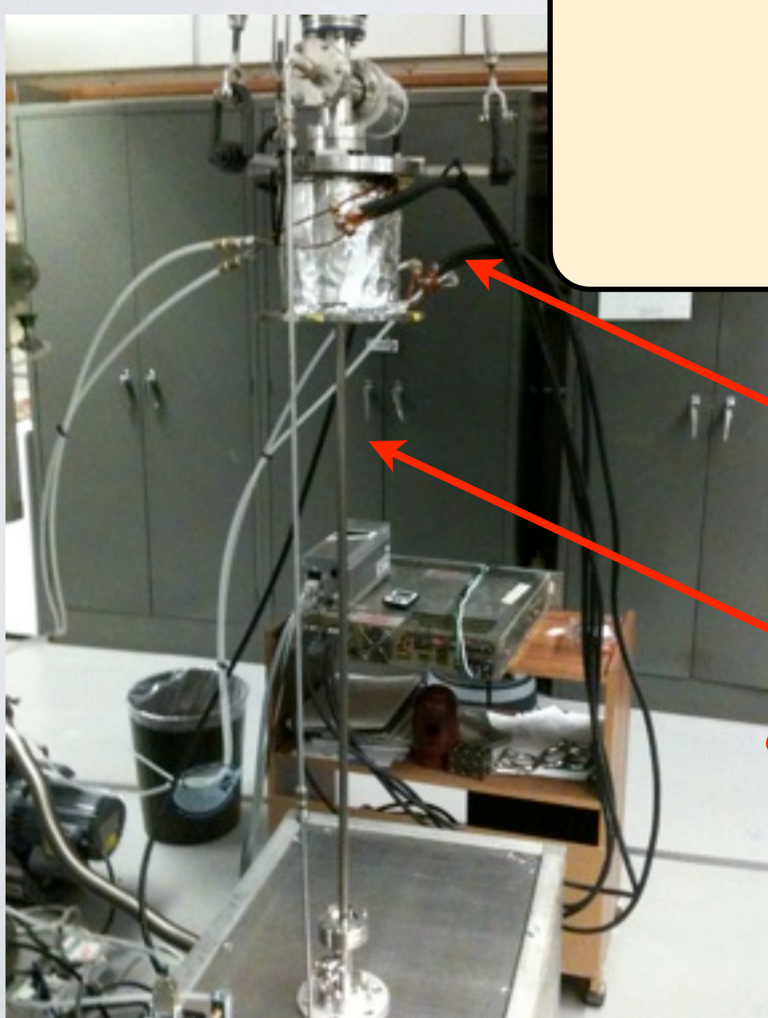
Easily achieving speeds of

1-2 l sec^{-1} cm^{-2}

…em for NEG.

…n other

…differential pumping stages).



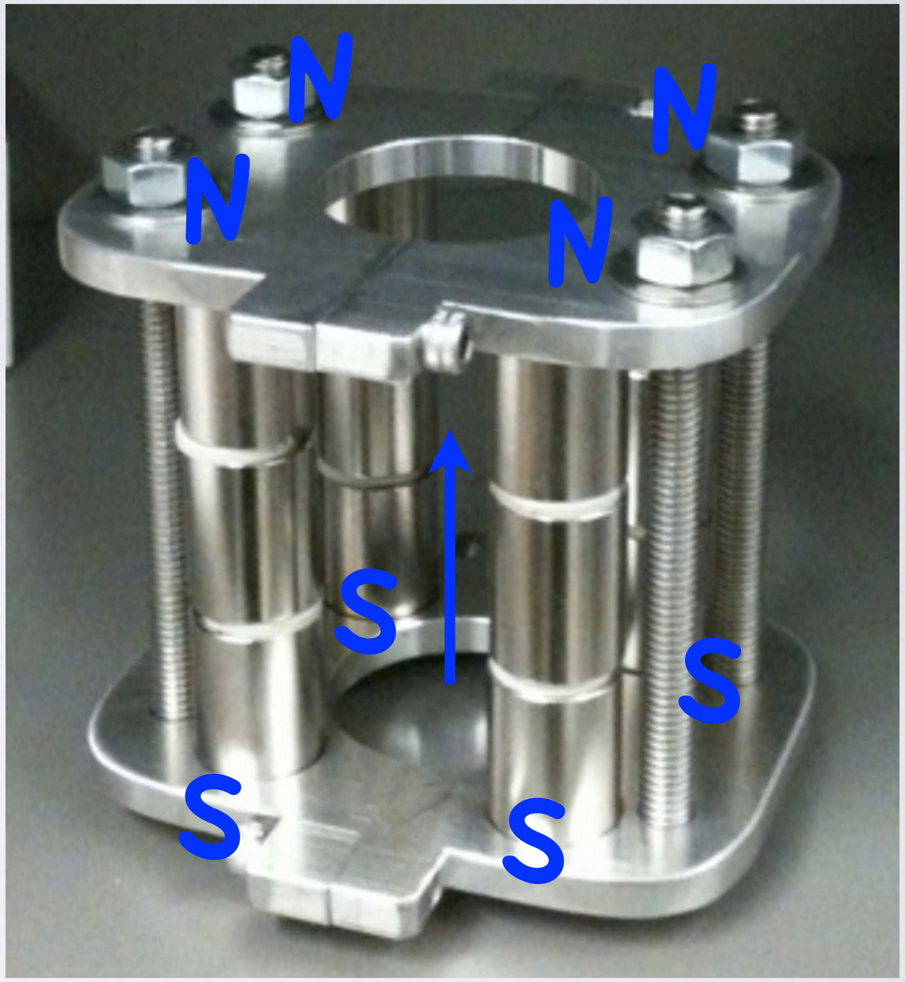
400G DI water cooled magnet (axial field)

Tube being coated Cathode wire inside tubes (radial field)

Ooh… Shiny….

Electrostatic Trap
NEG - Phase II

- Currently requires air core solenoid.
  - Water cooling (>1kW).
  - Heavy magnet.
  - High current power supply (~200A required).
- Working on replacement system using permanent magnets.
  - High field Nd magnets.
  - No cooling required.
  - Light.
  - Non-Uniform field, but probably uniform enough on and near axis.
  - Clamshell design for easy installation.
  - **Measured 560G on axis!**
- Achieving ~ the same deposition rate in a much simpler system.



Future Studies

(Undergraduate/Graduate Projects/Theses)

- Production methods.
- Transverse/Longitudinal cooling of ion bunch:
  - Laser cooling.
  - Stochastic cooling.
  - Light ion cooling.
- Detection Schemes:
  - Initially image charge detection (pickup).
  - Optical (laser).
  - Single ion detection (Relevant for SHE)? SQUID?
- Ion beam polarization.
- Detector design for β - position + energy:
  - SSD + Scintillator.
  - Thick GEM + Scintillator.
- Detector design for recoil ion (should not interfere with bunch).
- Production schemes for rare ions.

Summary

- It is possible to circumvent Ernshaw's theorem by electrostatic trapping of a moving bunch of ions.
- Trap design is extremely simple and cheap (much more so than conventional ion or optical traps).
- Trap design is almost a "black box" which can be easily transported to different experimental facilities.
- Many possible applications for such a trap exist:
  - Mass spectrometry.
  - Beyond SM searches.
  - "High energy chemistry".
  - Many more not talked about (Chemistry / Biology / ...).
- Ongoing development at LBL.

BACKUP

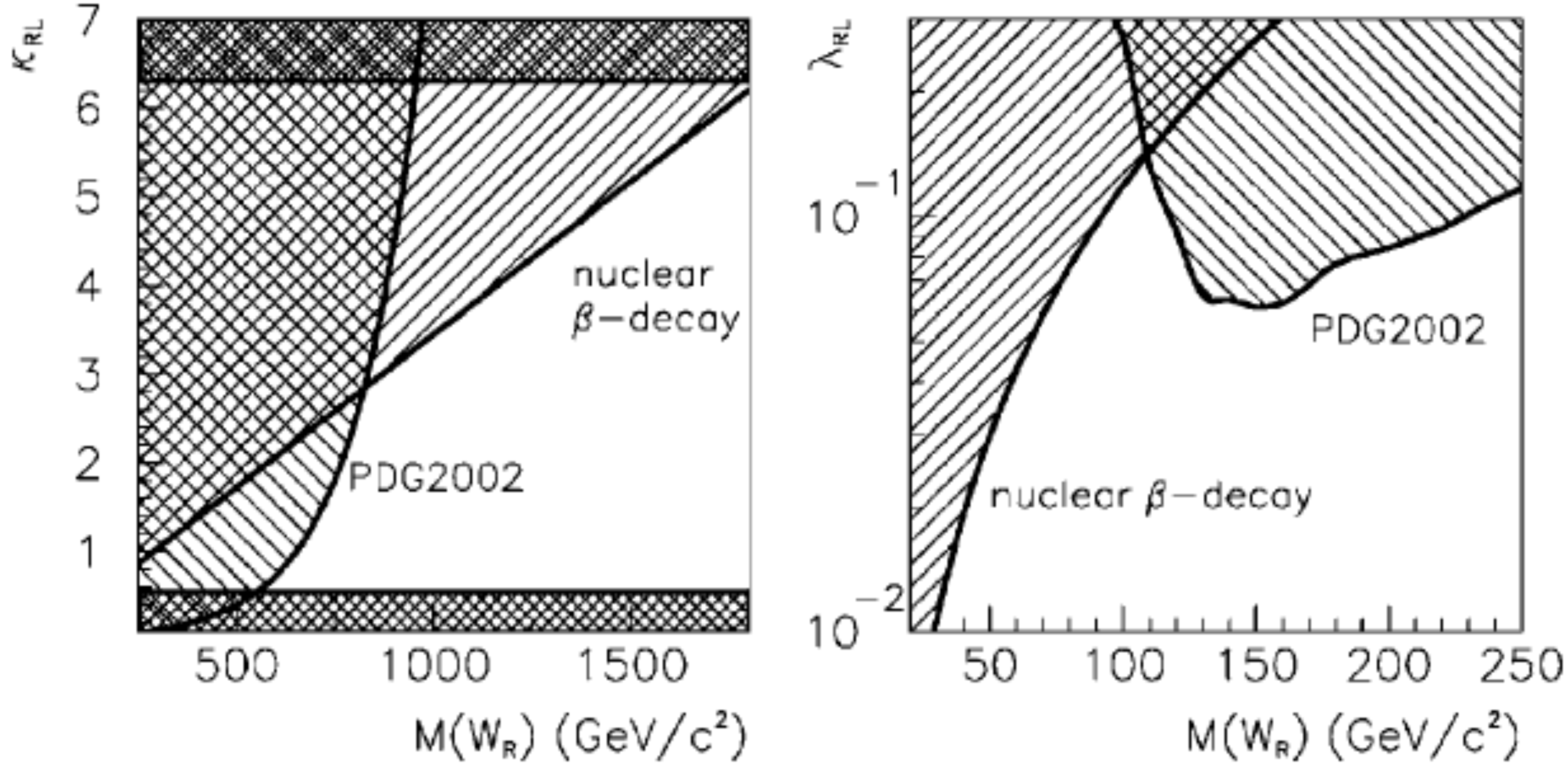


FIG. 28. Exclusion plots on parameters of generalized left-right symmetric extensions of the standard model. The parameter $\kappa_{RL}=g_R/g_L$ characterizes the intrinsic gauge coupling of the right-handed sector relative to the left-handed one, while $\lambda_{RL} =|V^R_{ud}|/|V^L_{ud}|$ denotes the relative coupling strength of first generation quarks to a hypothetical right-handed gauge boson with mass $M(W_R)$. The hatched areas are excluded either by direct searches at colliders (PDG2002) or by precision experiments in nuclear β decay. The horizontal bands in the left panel are bounds from theory. The contours in the left panel assume $|V^R_{ud}|=|V^L_{ud}|$; those in the right panel assume $g_R=g_L$. Adapted from Thomas *et al.*, 2001.

β decay sensitive to helicity of W or W' - colliders are not

Colliders insensitive to TRV