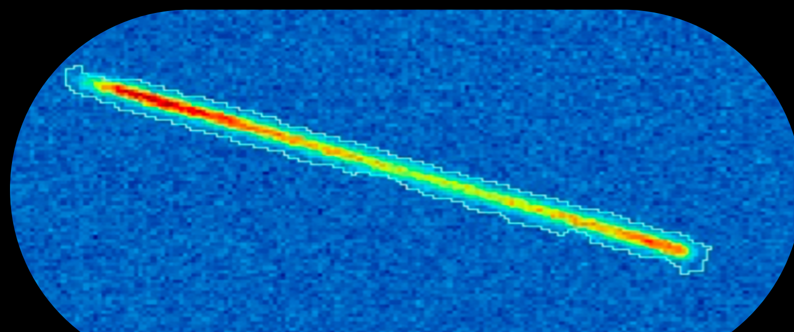
The OLIVIA Experiment - ‘Trapless’ ^{8}Li β-Decay Study

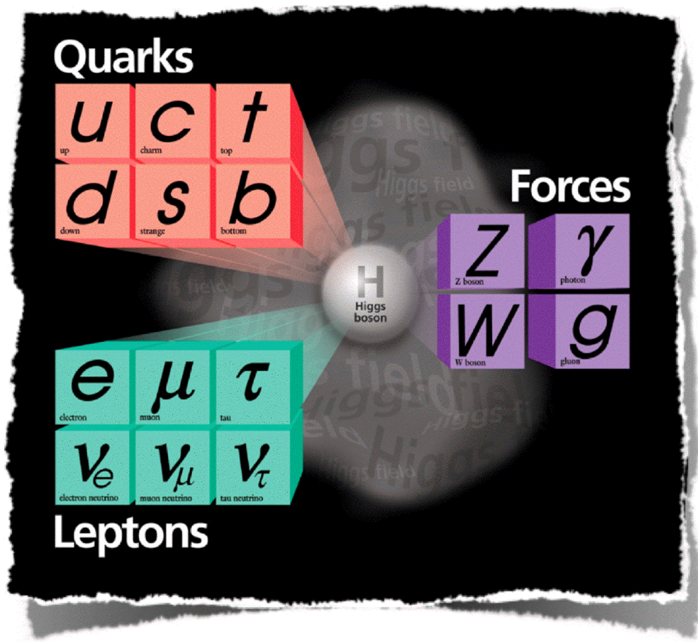
Or Hen
MIT



In Collaboration With:
J.M. Conrad (MIT), J. Spitz (U. Michigan), G. Ron (HUJI), D. Gazit (HUJI)

PSAS’2016, Hebrew University, May 26th, 2016.

The Standard Model



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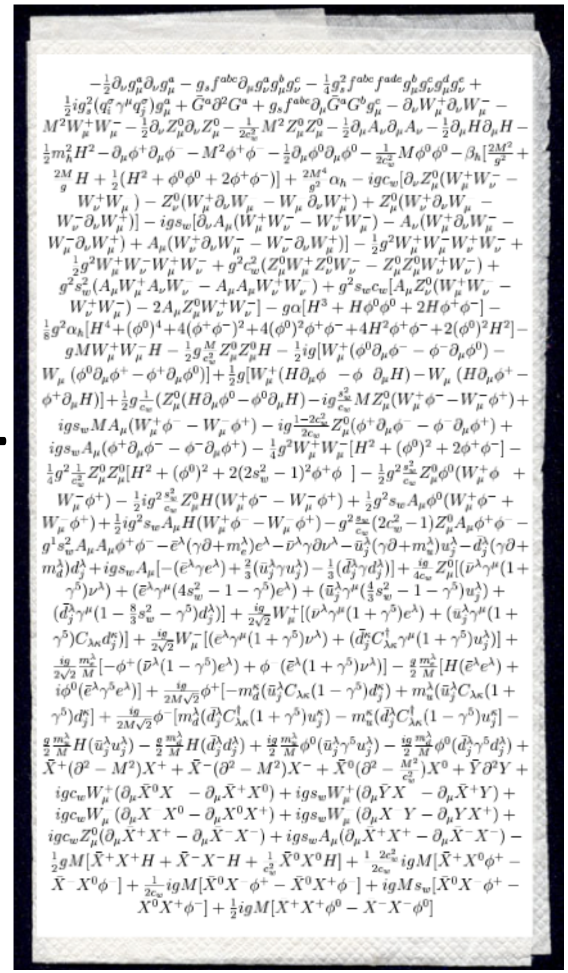

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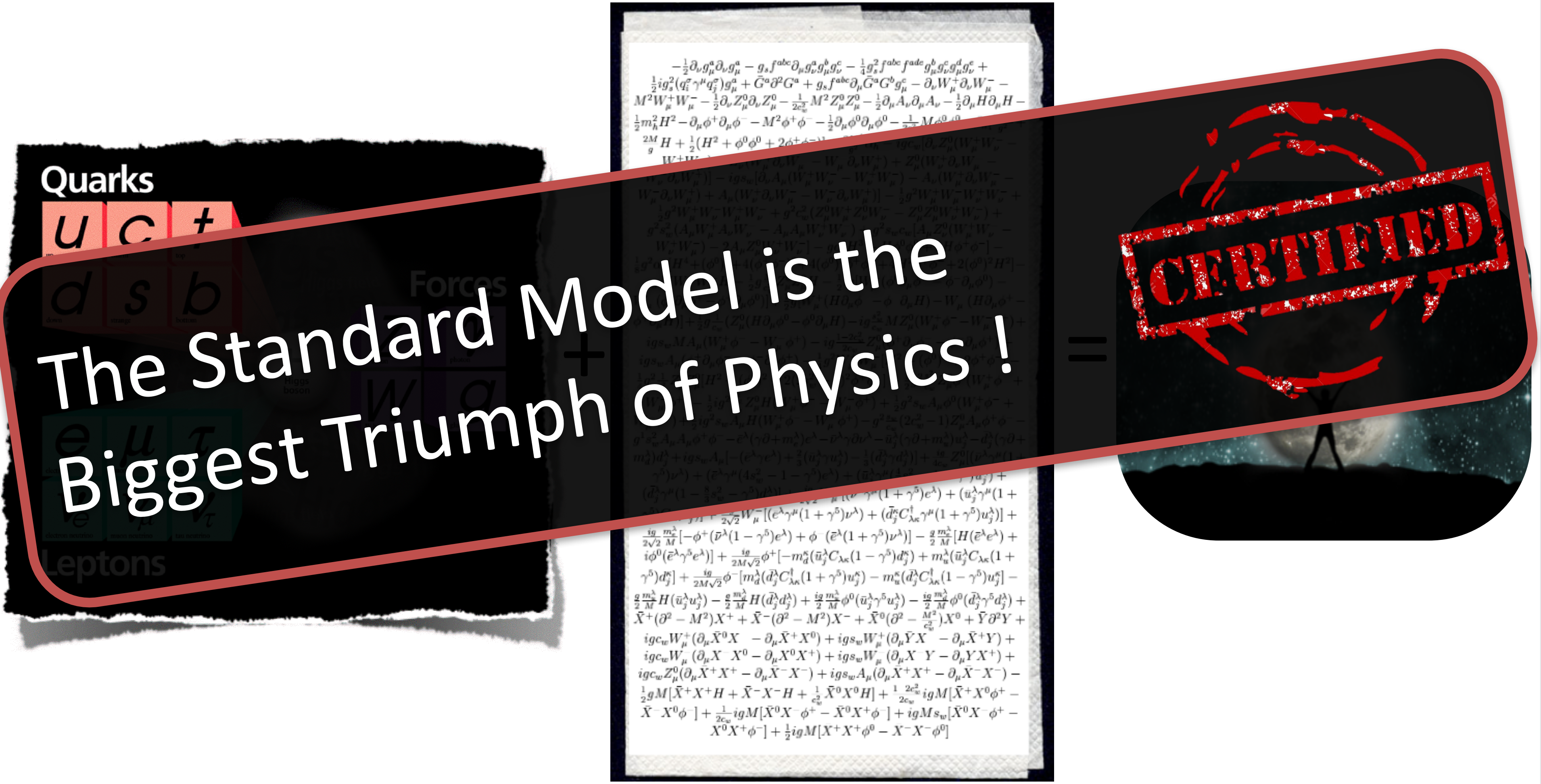

The Standard Model is the Biggest Triumph of Physics !

The Standard Model

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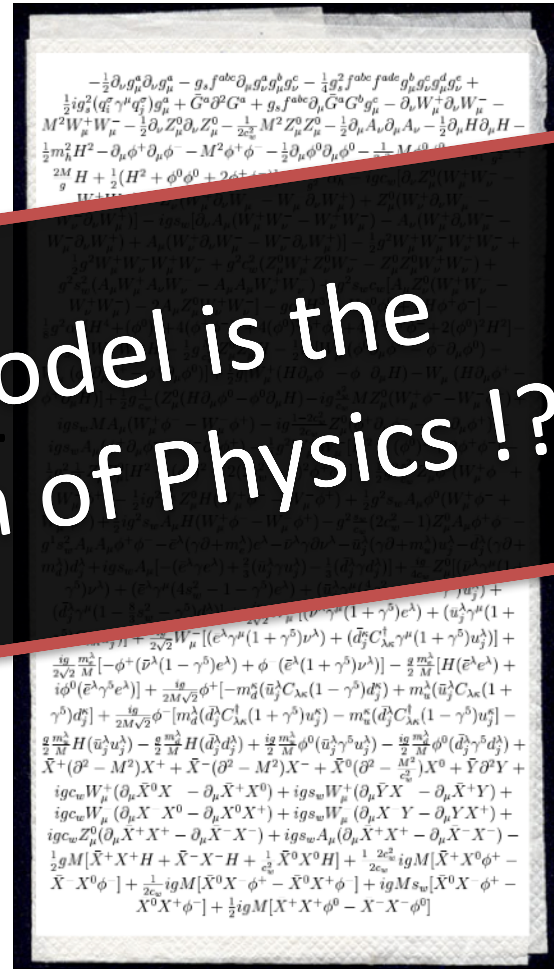

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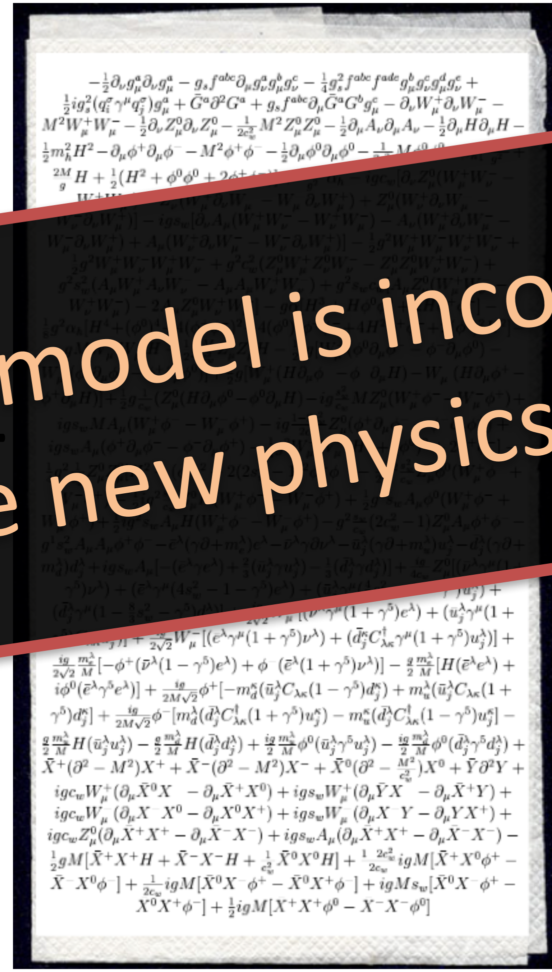
The Standard Model is the Biggest Triumph of Physics !?

But….. We still don't know Matter Anti-Matter Asymmetry, Dark Matter, Dark Energy, Black Holes, Gravity, ….

The Standard Model

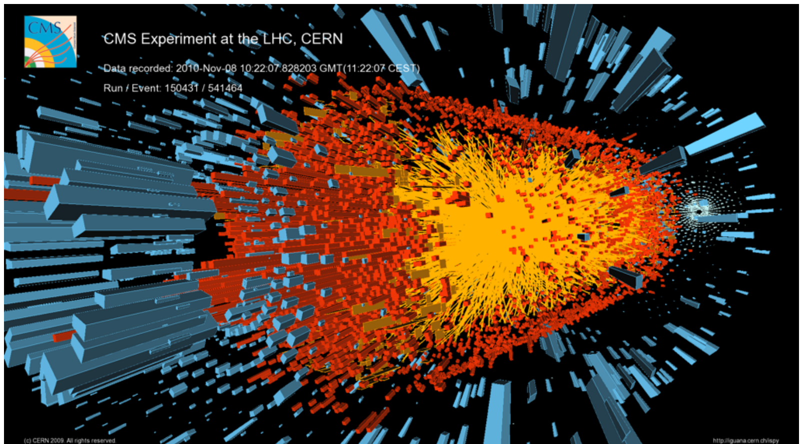


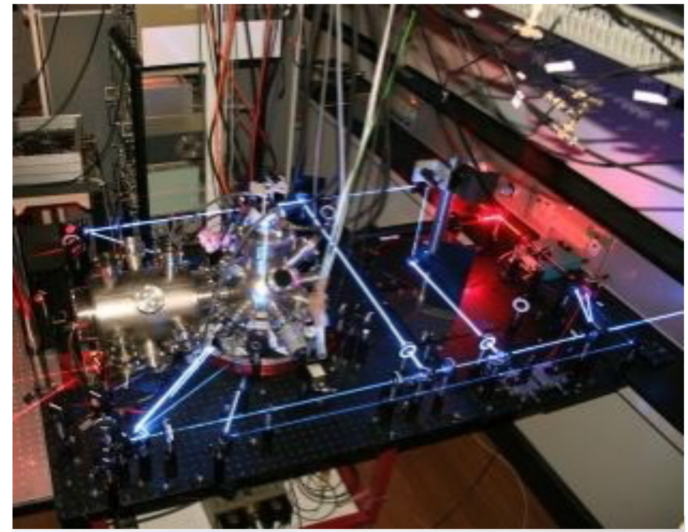
The standard model is incomplete so there **MUST** be new physics out there…

But….. We still don't know Matter Anti-Matter Asymmetry, Dark Matter, Dark Energy, Black Holes, Gravity, ….

Looking for New Physics

High Energy Vs. High Precision



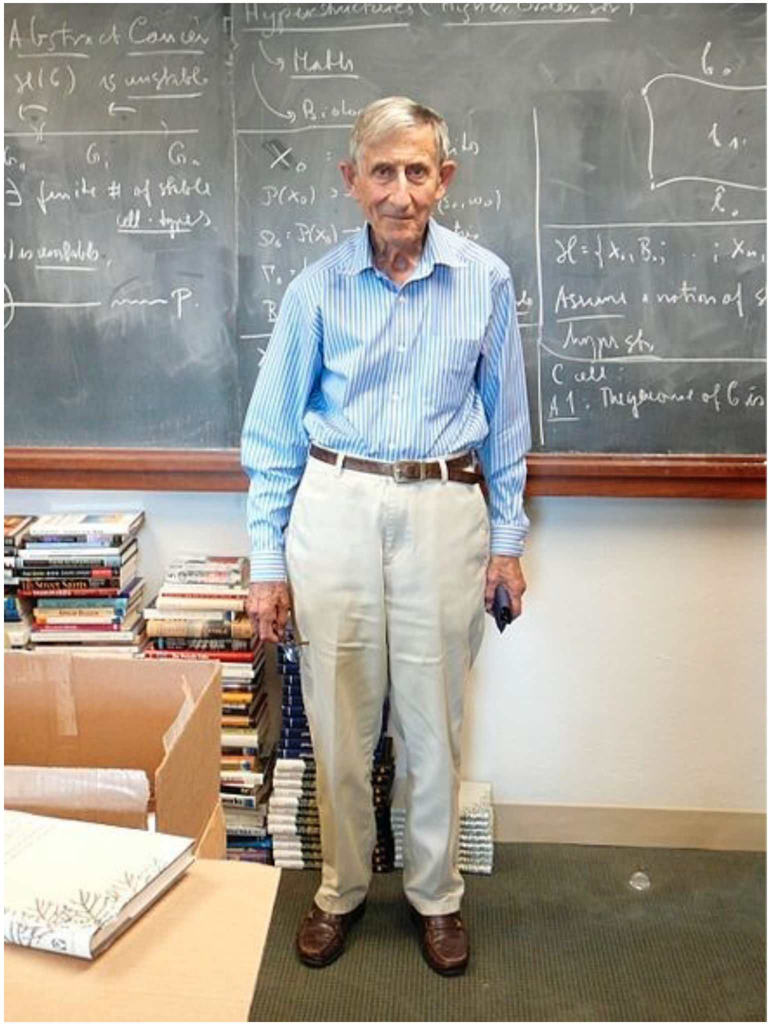


*Random people that DON'T do physics ☺

Looking for New Physics

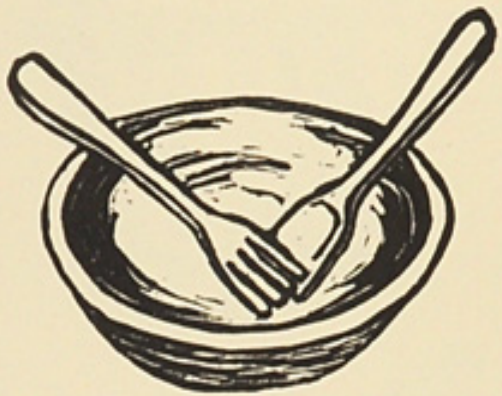
Freeman Dyson on 16 discoveries awarded the Nobel Prize between 1945 and 2008:

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.

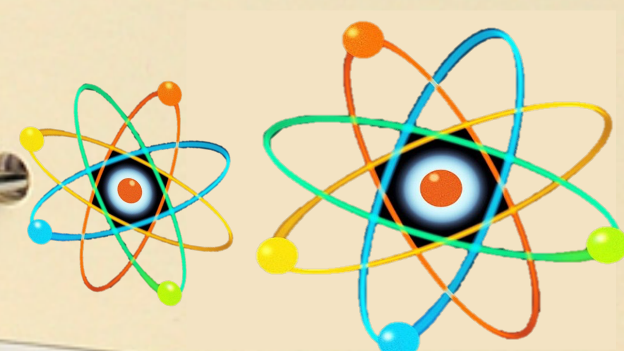


BSM Physics Searches @ Low Energy

1. Start with a process we know very (very) well.



2. Consider general new physics (by introducing new operators).
3. Look at the effect of the new physics on well defined observables.
4. Measured with high precision.
5. ***Look for (small) deviations.***



BSM Physics Searches @ Low Energy

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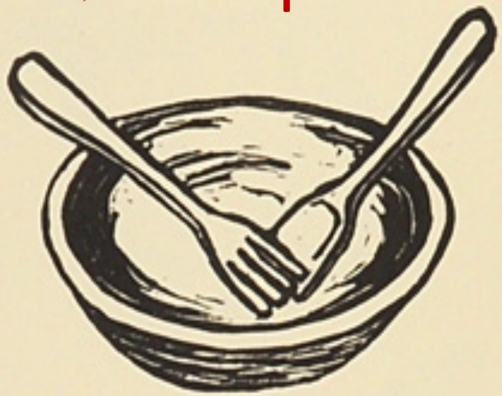
   => ^{8}Li β-Decay



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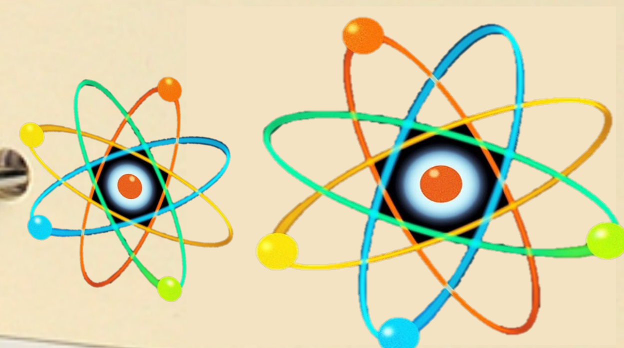

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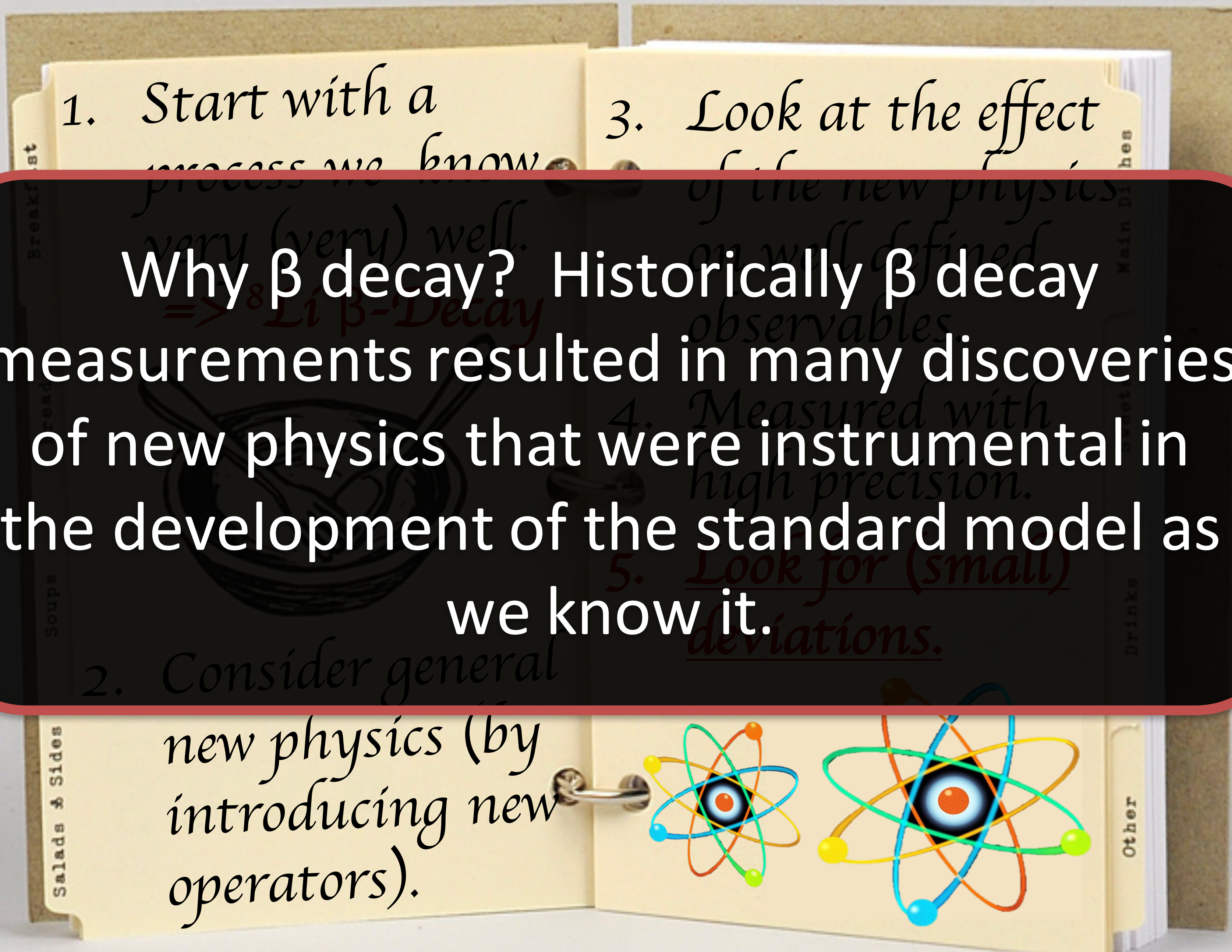


Why β decay? Historically β decay measurements resulted in many discoveries of new physics that were instrumental in the development of the standard model as we know it.

β Decay History

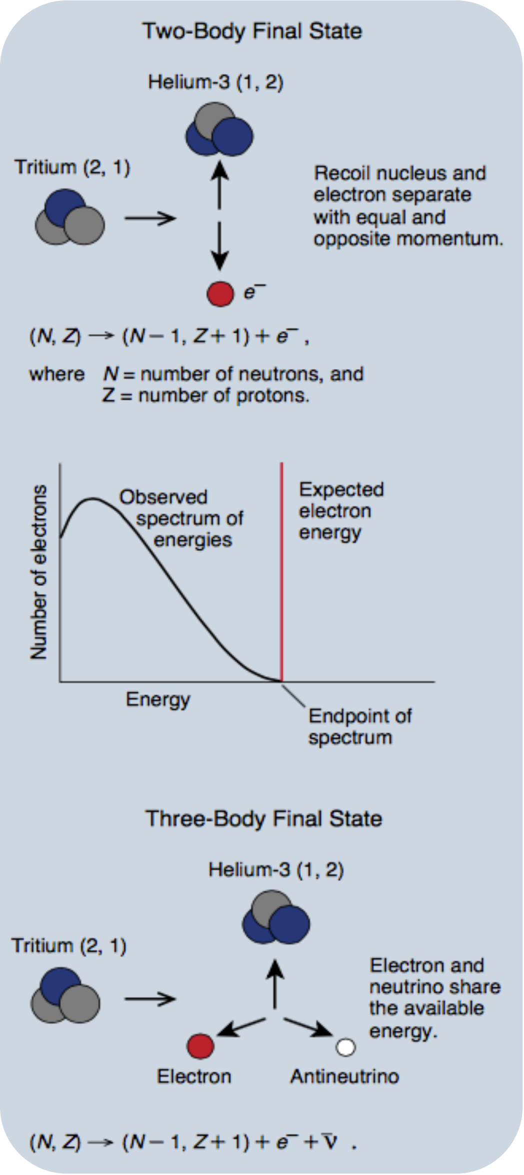
1911 – 1927: β energy spectrum measurement in nuclear β decay.

- Expectation: Discrete spectrum (≈ Q-Value)
- Observation: Continues spectrum with a clear endpoint (≈ Q-Value)

1930: Pauli's proposal: Existence of a light neutral 'neutron' like particle emitted in the β decay process

1931: Fermi changes Pauli's 'neutron' to 'neutrino' and formulate a 'contact interaction' model for beta decay.

- QED analogy; assuming vector interactions



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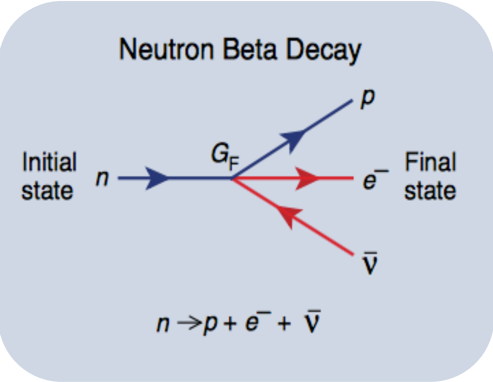
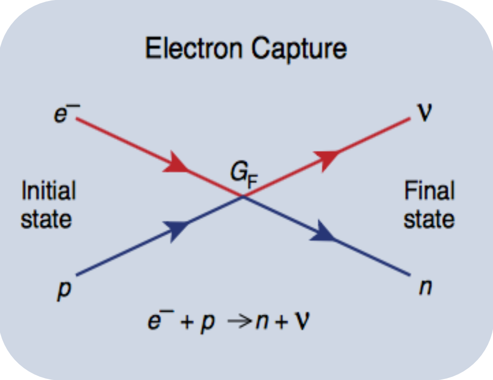
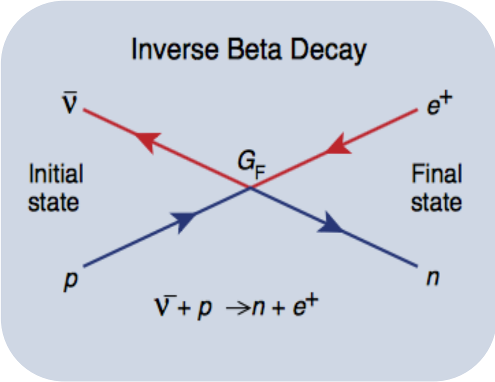




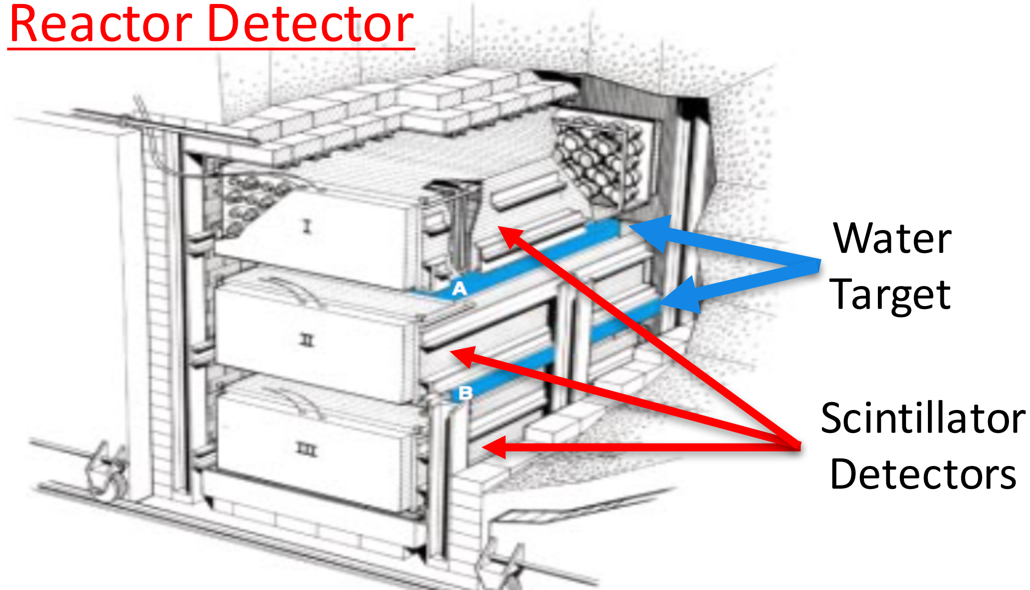


Observing the Neutrino

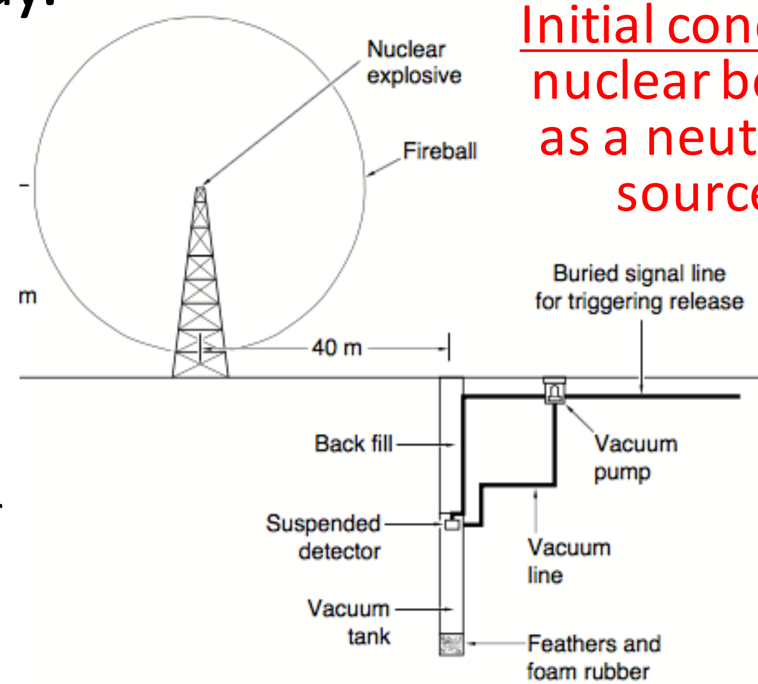
1956: Cowan-Reines observe reactor anti-neutrinos.

- Use nuclear reactors as a high-flux anti-neutrino source.
- Water target for inverse beta decay: $\bar{\nu}_e + p \rightarrow n + e^+$
- Add ^{108}Cd to capture the neutron ($\tau \approx 5$ μsec).
- Use liquid scintillator to measure gammas from positron annihilation and ^{109m}Cd decay.

Reactor Detector



Initial concept: nuclear bomb as a neutrino source

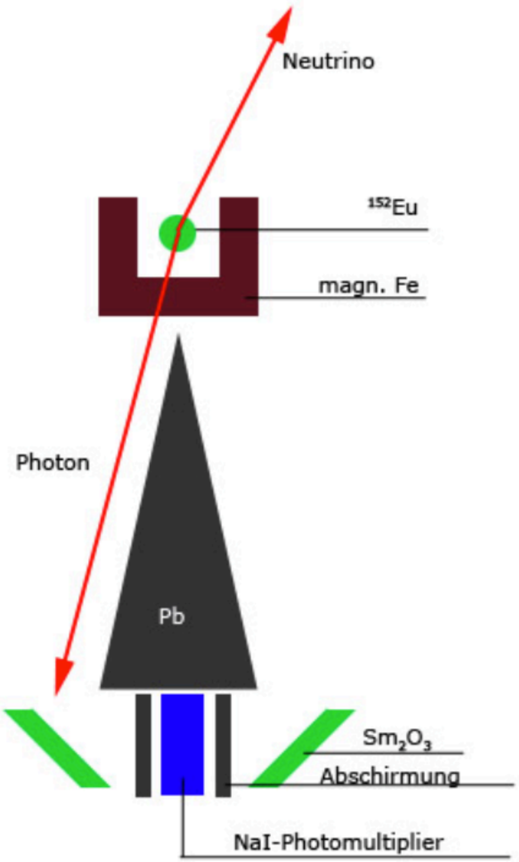


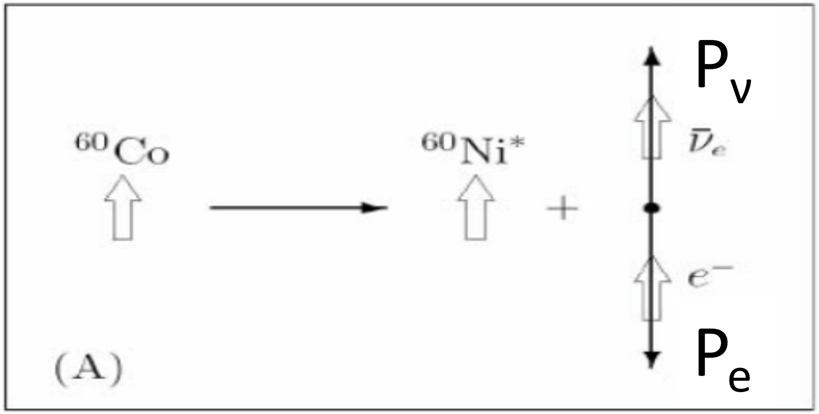
P Violation and V-A nature

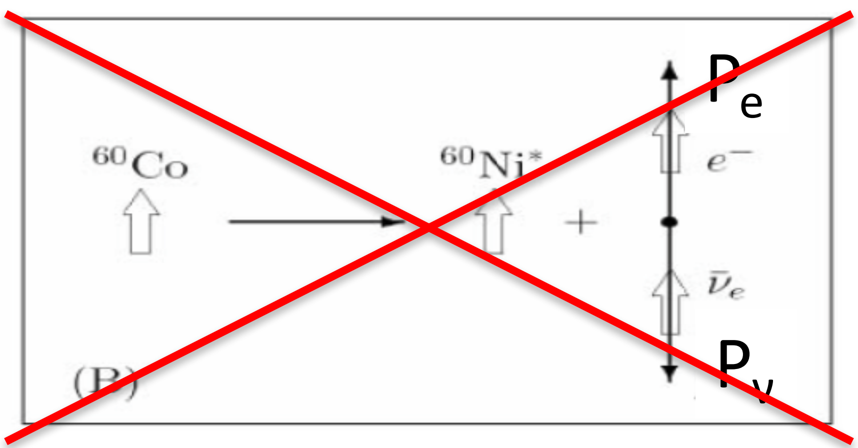
1957: Wu et al. observes parity violation in ^{60}Co decay.

Goldhaber measures the neutrino helicity.

=> Neutrinos are left handed. Weak Interaction is V-A







Searching Under the Lamppost …

Measuring Everything we can:

- Energy Spectra
- Angular Correlations
- Half-Lives
- Polarizations
- …

… Constraining New Physics

Comparing to Theory and Probing:

- Non V-A Contribution (S, T, P).
- Right-handed Currents (V+A).
- Massive Neutrinos.
- CKM Unitary.
- ….

+ Many open questions in ‘standard’ nuclear physics

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Standard Model Formalism

- General Hamiltonian:

$$H_{int} = \sum_{X=\{V,A,T,S,P\}} (\bar{\psi}_P O_X \psi_n)\left(C_X \bar{\psi}_e O_X \psi_v + C'_X \bar{\psi}_e O_X \gamma^5 \psi_v\right)$$

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- Standard Model V-A assumption:

$$C_V = -C'_V = 1\,; C_A = -C'_A = -1.27$$

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- Decay Rate:

$$\Gamma dE_e d\Omega_e d\Omega_v \propto \left[1 + \alpha_{\beta v} \frac{\vec{P}_e \cdot \vec{P}_v}{E_e E_v} + b \frac{m_e}{E_e} + \frac{\langle \vec{I} \rangle}{I} \cdot \left(A_\beta \frac{\vec{P}_e}{E_e} + B_v \frac{\vec{P}_v}{E_v} + D \frac{\vec{P}_e \times \vec{P}_v}{E_e E_v} \right)\right]$$

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$$\alpha_{\beta v} = \begin{bmatrix} |M_F|^2 \left(|C_V|^2 + |C'_V|^2 - |C_S|^2 - |C'_S|^2\right) \\ -\frac{1}{3} |M_{GT}|^2 \left(|C_A|^2 + |C'_A|^2 - |C_T|^2 - |C'_T|^2\right) \end{bmatrix} \xi^{-1}$$

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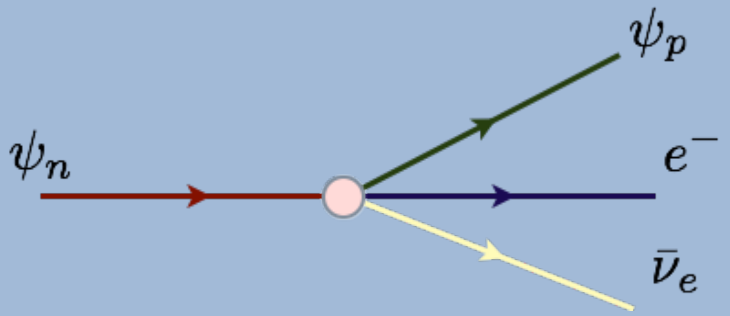
- Sensitivity to new physics: $\left(\frac{M_W}{M_{New}} \right)^2 \sim A_{CC}$

New Physics in β Decay

Standard Model:

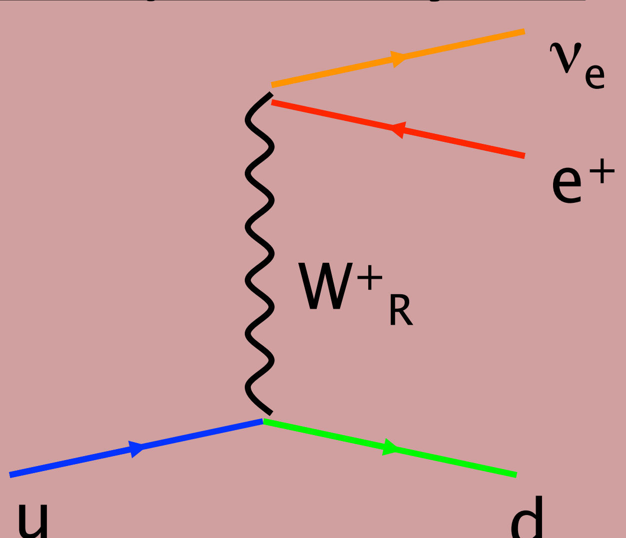


$$H_\beta = (\bar{\psi}_n \gamma_\mu \psi_p)(C_V \bar{\psi}_e \gamma^\mu \psi_\nu + C'_V \bar{\psi}_e \gamma^\mu \gamma_5 \psi_\nu) - (\bar{\psi}_n \gamma_\mu \gamma_5 \psi_p)(C_A \bar{\psi}_e \gamma^\mu \gamma_5 \psi_\nu + C'_A \bar{\psi}_e \gamma^\mu \psi_\nu)$$

$$C_V = C'_V = 1$$

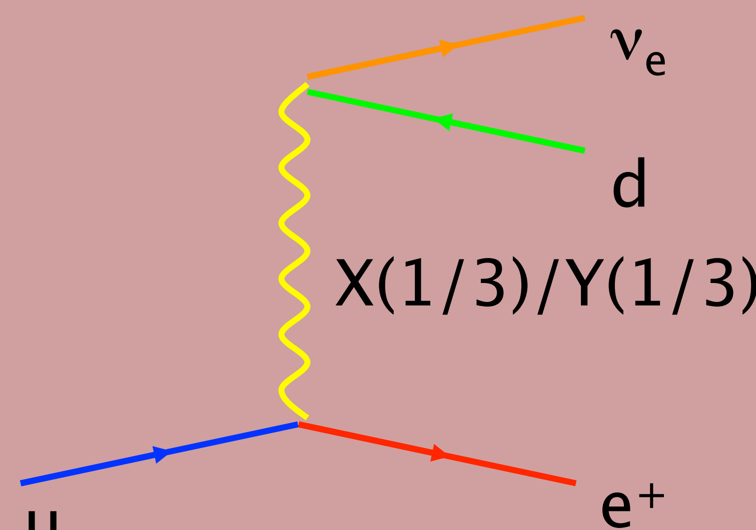
$$C_A = C'_A = 1.26$$

(Some) New Physics:



Right Handed Bosons

(C≠C')



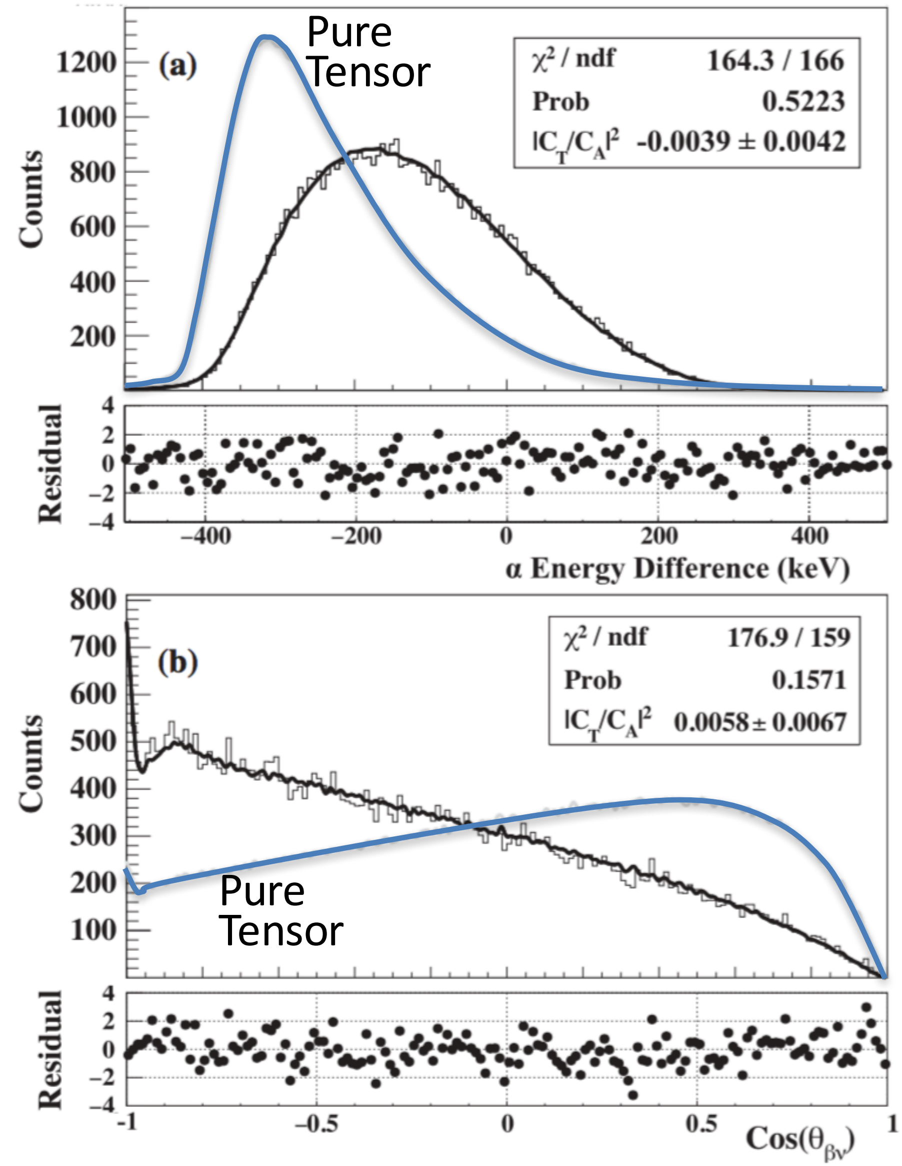
Scalar / Tensor Leptoquarks

($C_{S,T}$≠0)

A-V vs. Tensor Currents

Kinematical distributions sensitive to type of current (from a recent measurement of ^{8}Li decay):

- Energy distribution of recoiling ion (from two alpha measurement).
- Angle between neutrino and electron.



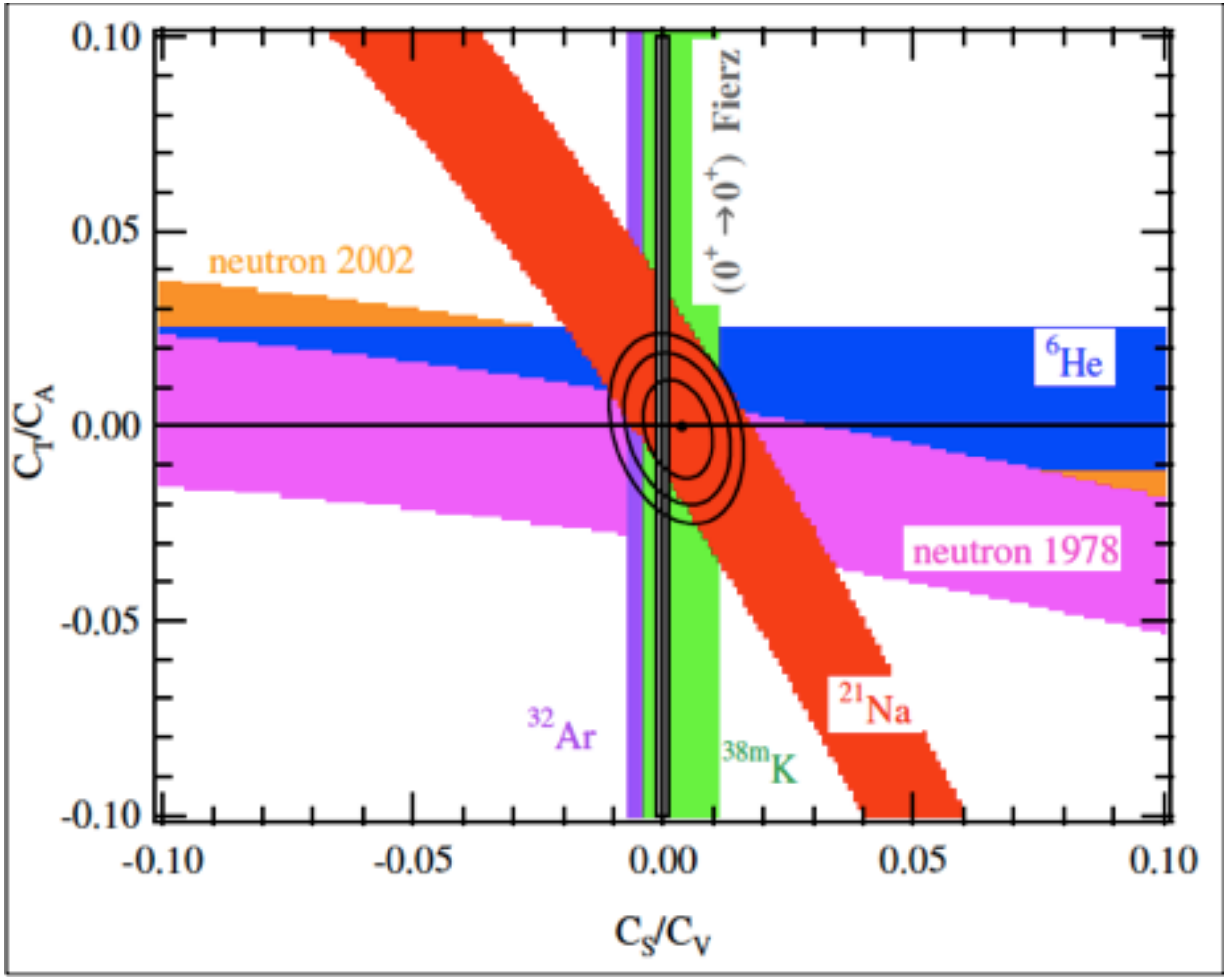
Resulting Constrain:

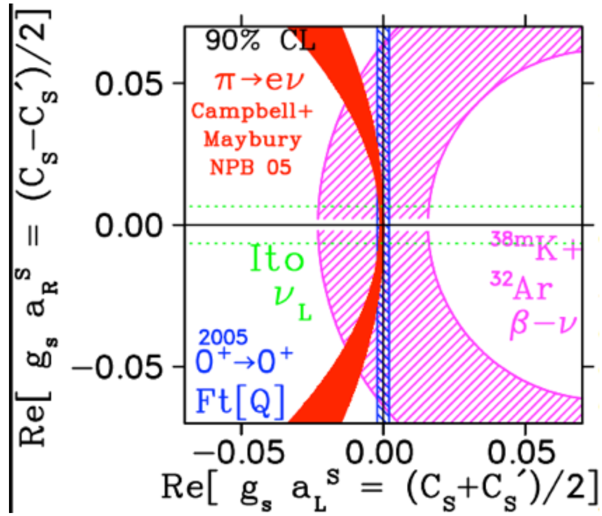
$C_T/C_A < 10\%$ (95% C.L.)

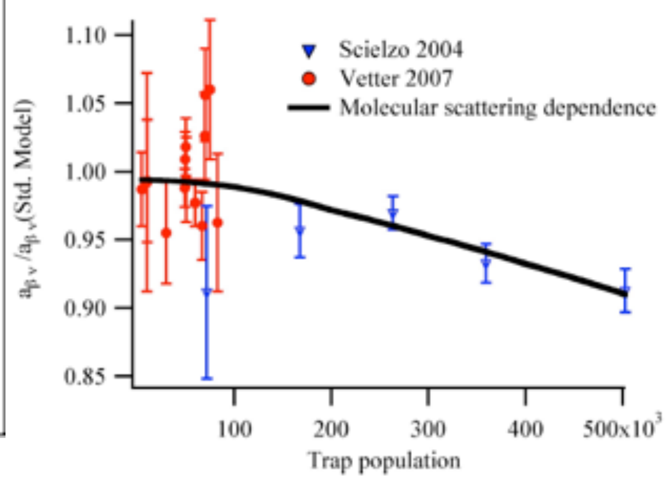
Sternberg et al., PRL **115**, 182501 (2015)

A-V vs. Tensor Currents

Combined Constraint:







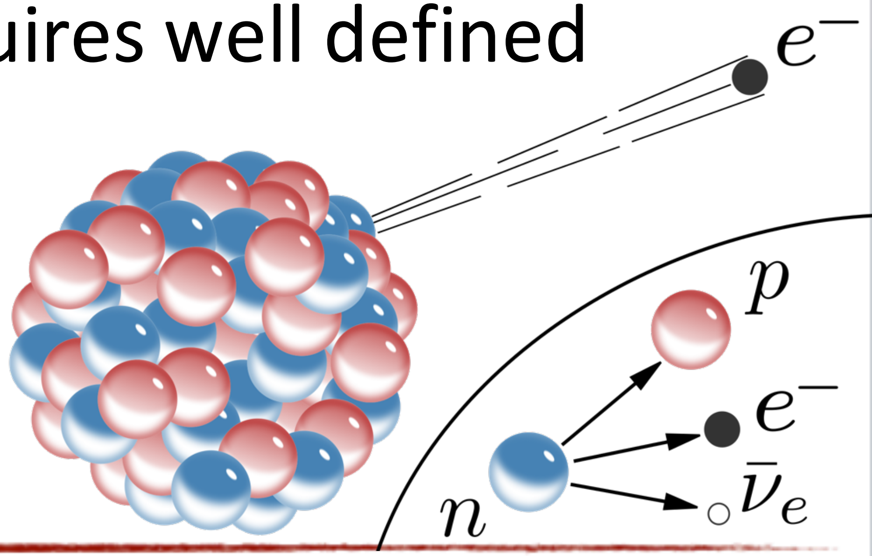
The β Decay Challenge

One sentence summery: **measuring heavy particles with low energy in very very hard!**

- (anti)Neutrino reconstructed from the measured momenta of the recoil system and beta particle.
- Recoil system is heavy and has low energy.
- Angular reconstruction requires well defined vertex

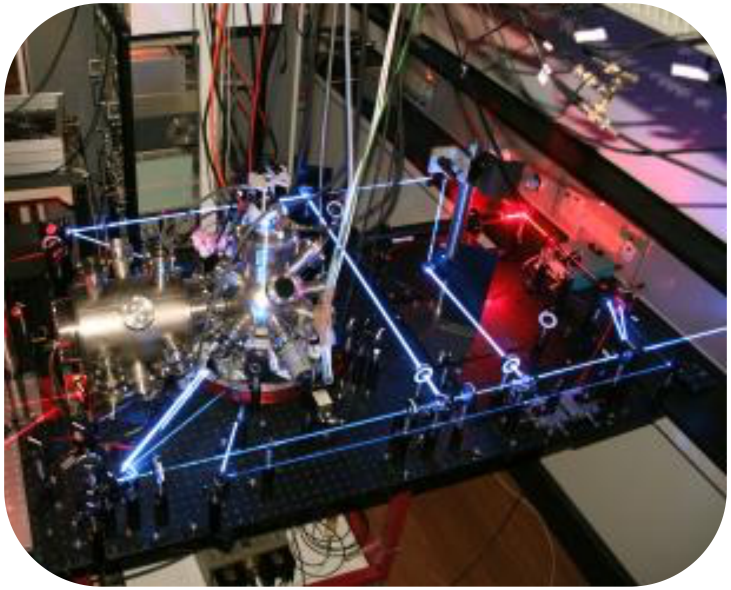
=> Must use traps!

+ Nuclear Uncertainties



Standard β Decay Experiment

Produce Radioactive Atoms
(Produce, Transport, Neutralize)

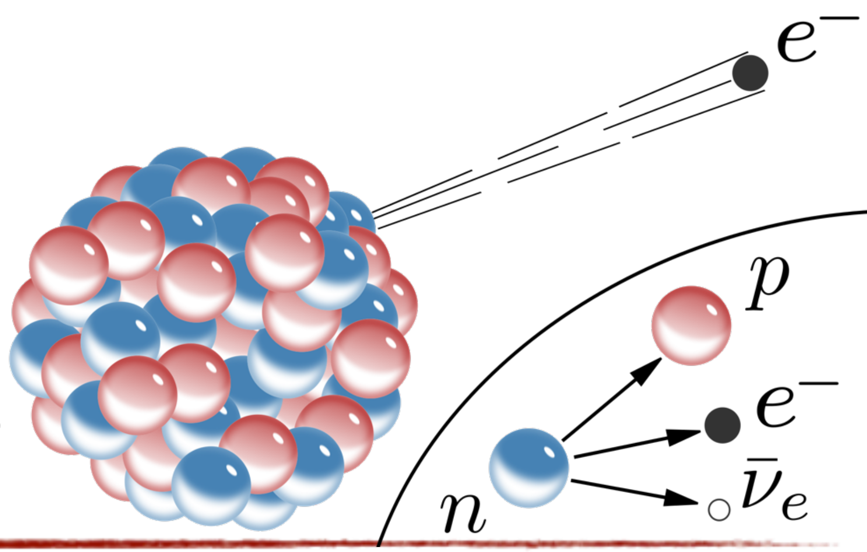


Trap
(MOT, Dipole, Ion, Electrostatic, …)

Wait…

Measure Decay Products
(β , ion ; Scintillators, MCP, …)

Analyze the Data and Compare to SM Prediction



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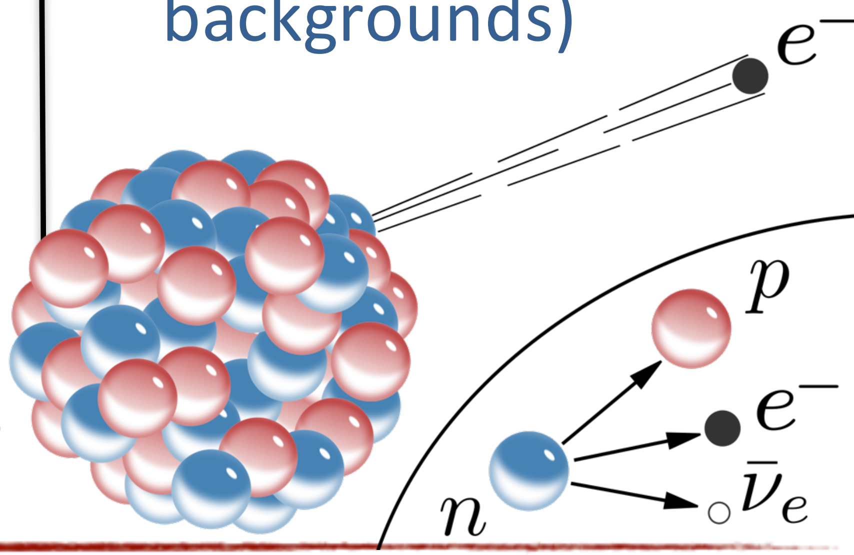
- Cold and Dilute:
  - No ‘smearing’ of the ion
  - Less interactions
- Well localized vertex
- Isotope selectivity (low backgrounds)



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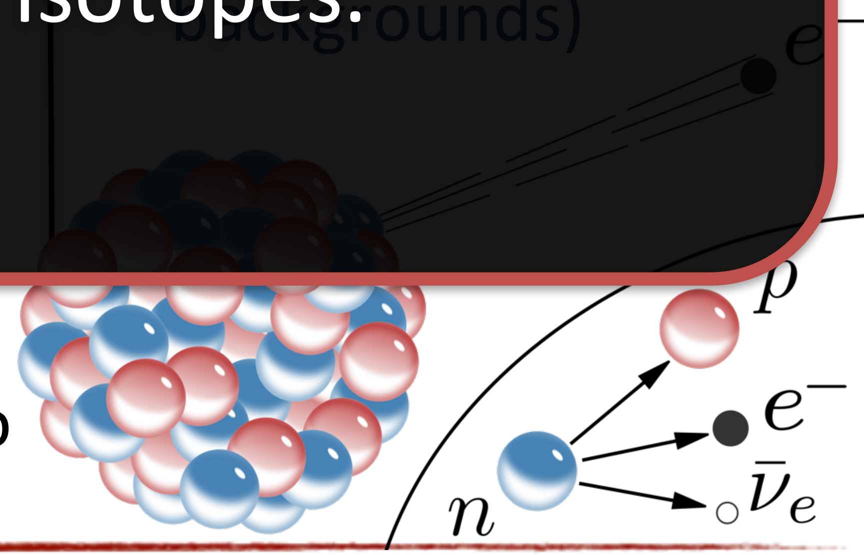

Downside of Trapping:

- Complicated experimental setup.
- Limited number of Isotopes.
- Low Statistics.

Standard β Decay Experiment

Produce Radioactive Atoms
(Produce, Transport, Neutralize)

↓

Trap
(MOT, Dipole, Ion, Electrostatic, …)

↓

Wait…

↓

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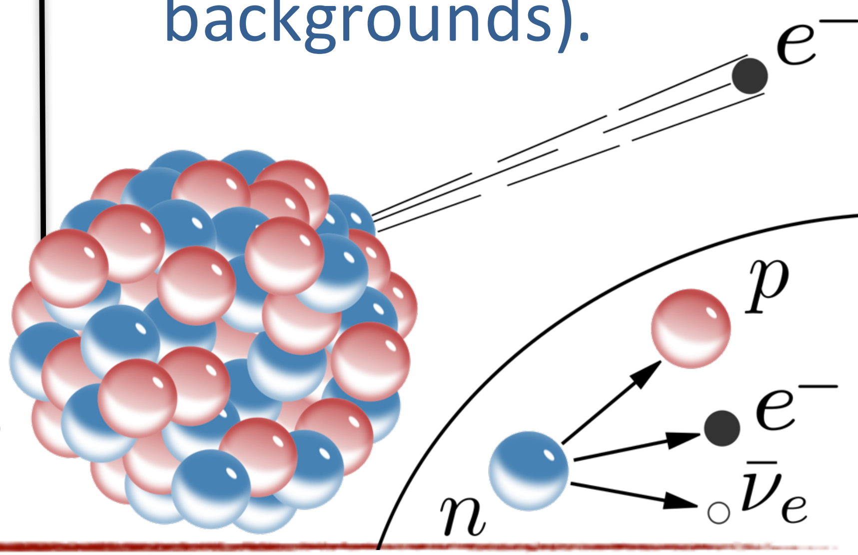
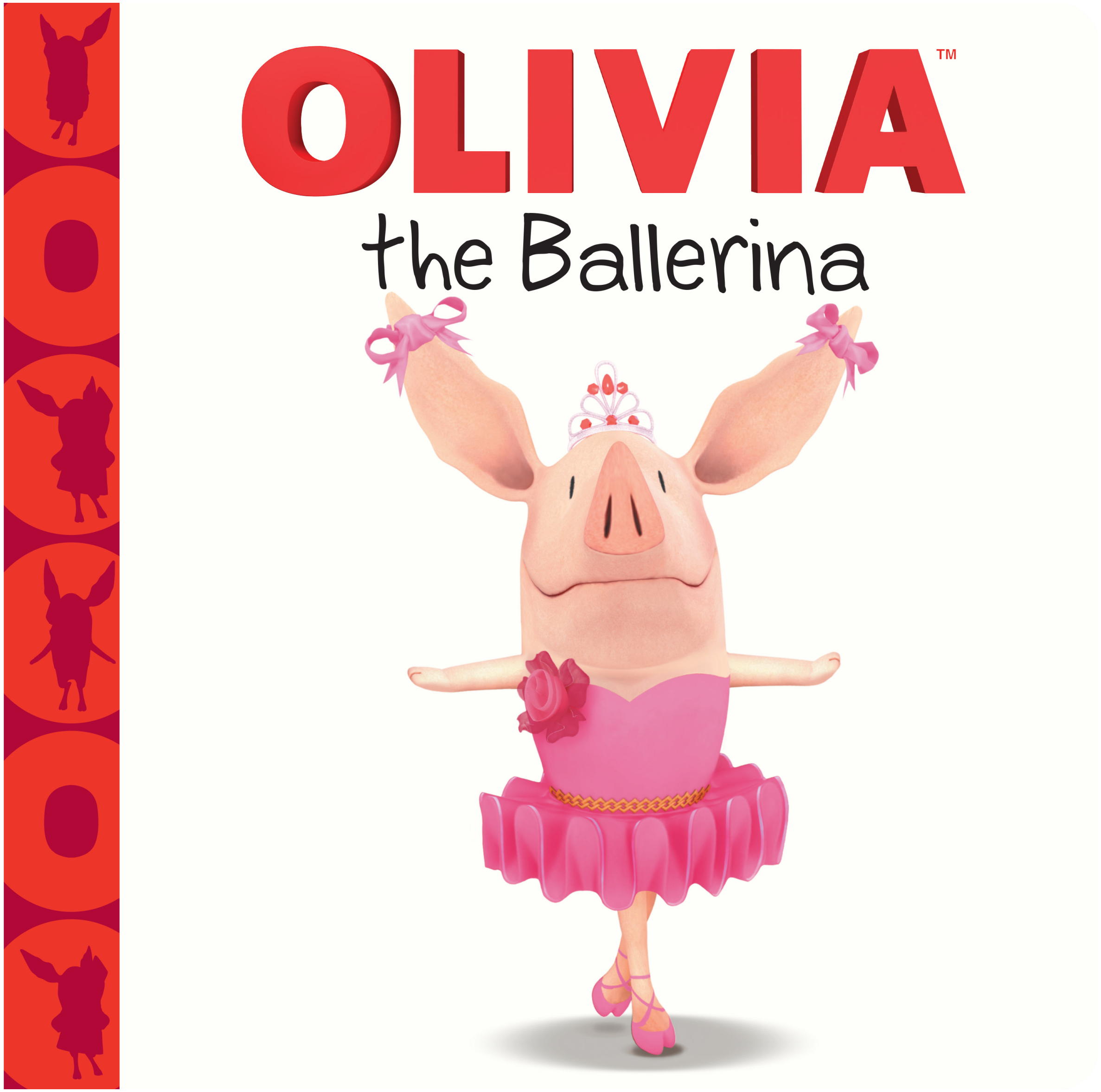
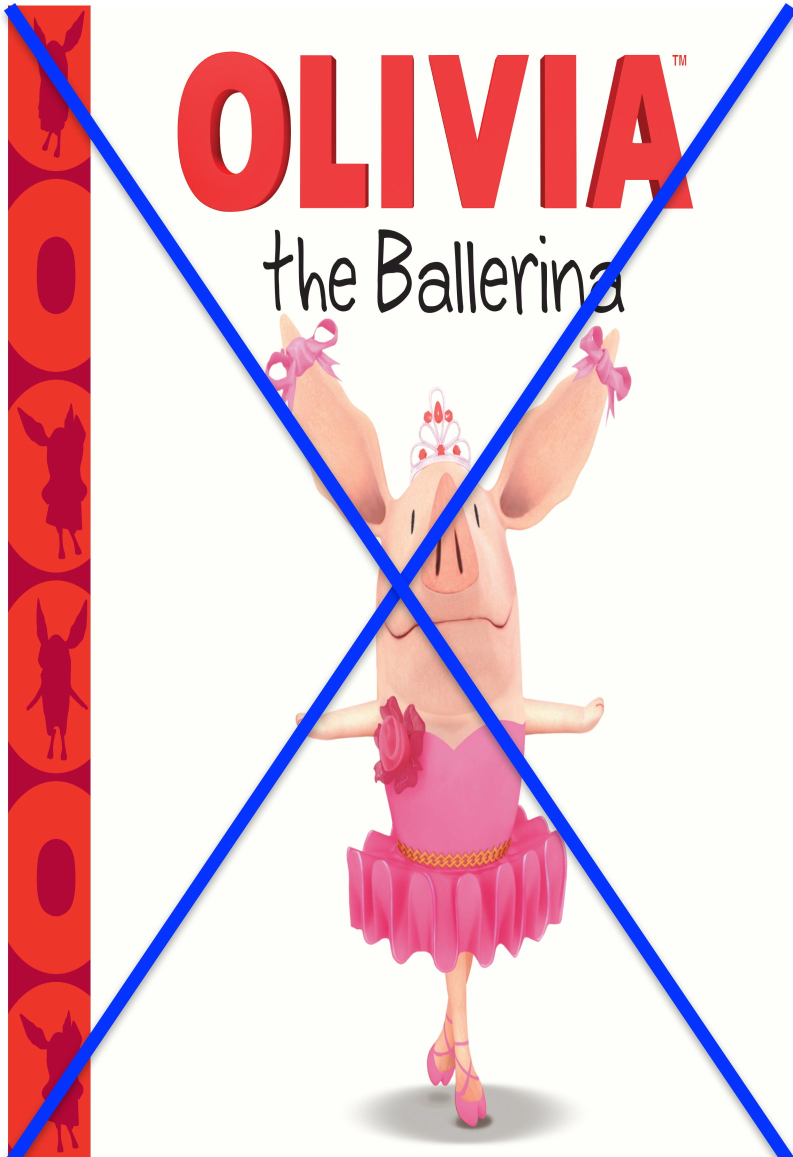


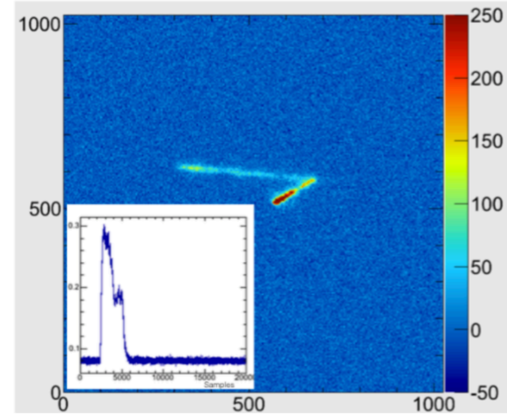
The OLIVIA Experiment

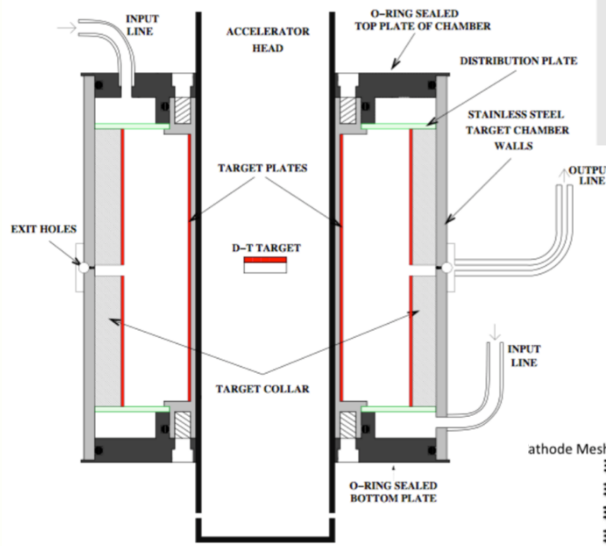


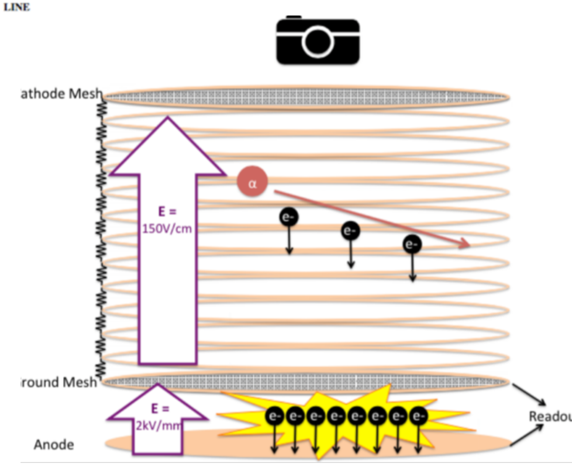
The OLIVIA Experiment

Optical LIthium V-mInus-A Experiment









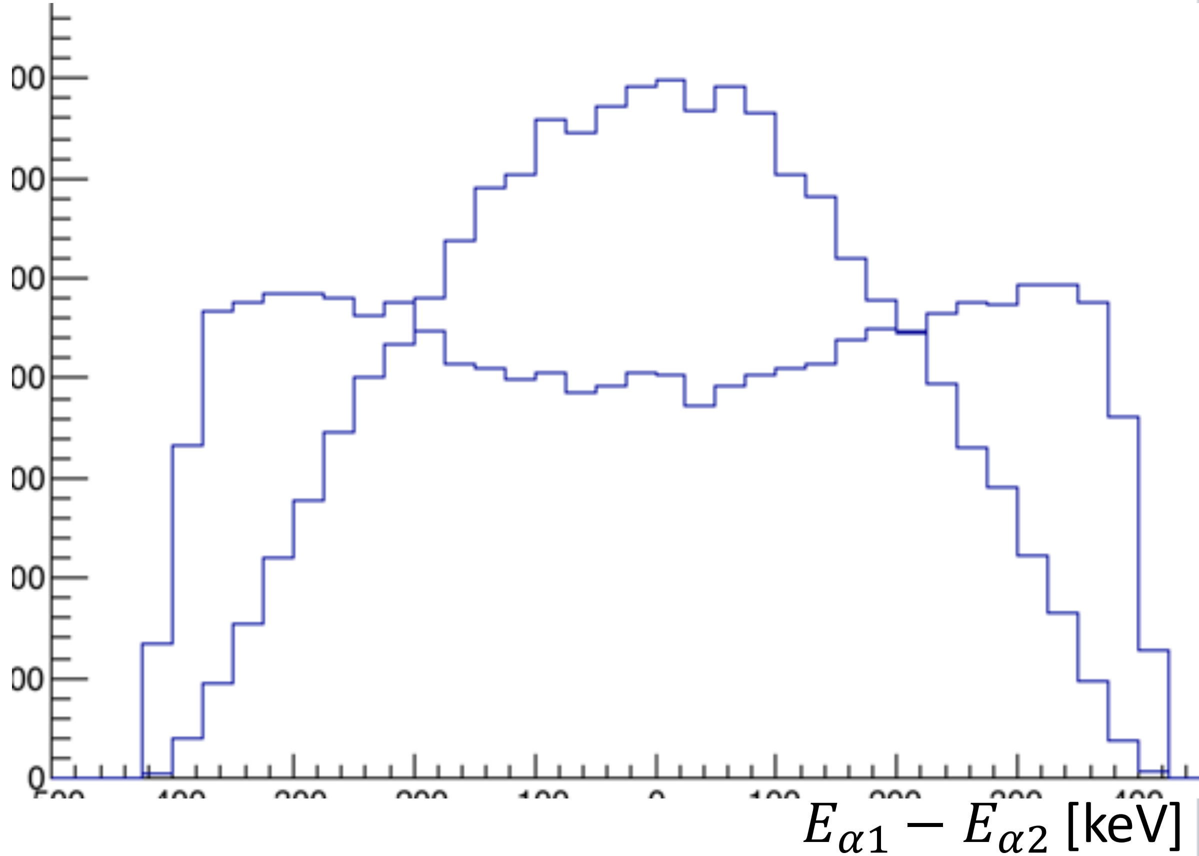
The Case for ^{8}Li

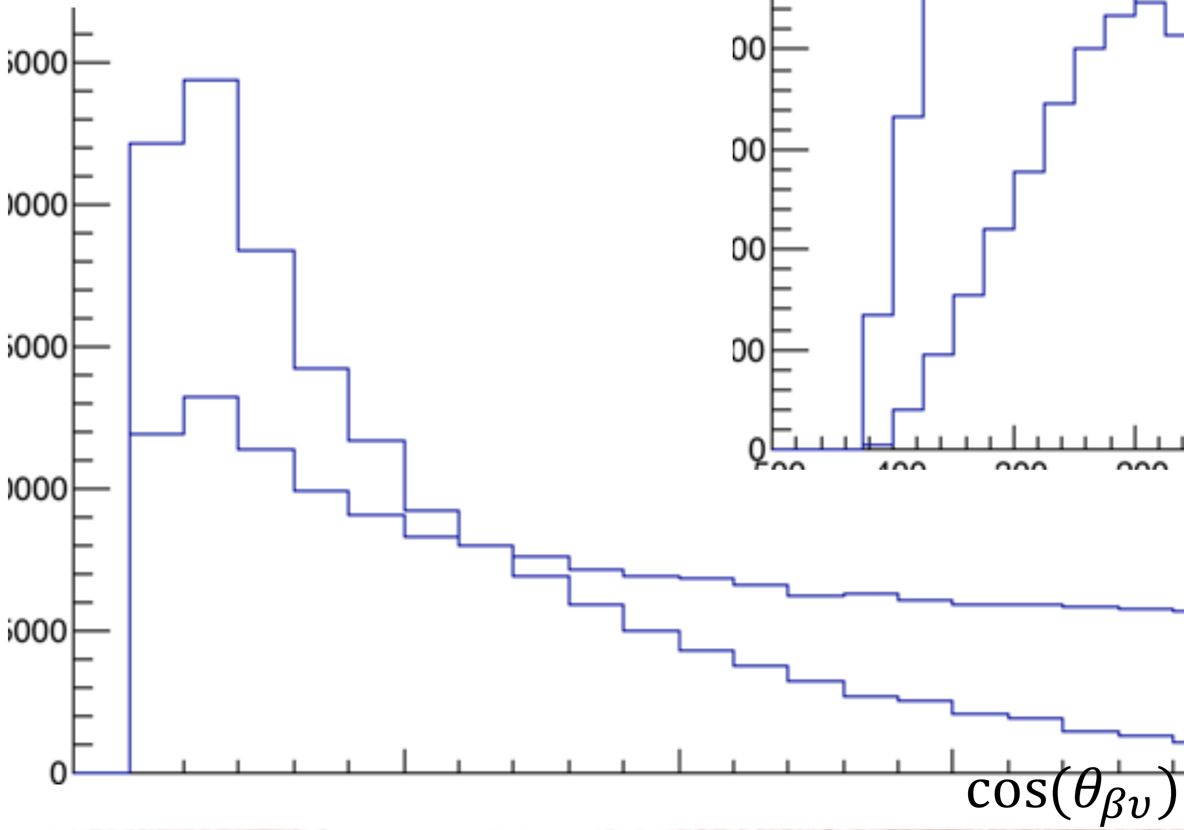
$$^{8}Li \rightarrow e^{-} + \bar{\nu}_e + {}^{8}B(\rightarrow \alpha + \alpha)$$

- Good for theory:
  - Almost pure GT.
  - Light nucleus – 'exact' calculations possible.
- Excellent for experiment:
  - Easy to produce using proton / neutron induced reactions.
  - 0.8 sec lifetime.
  - Very high Q-value.
  - Two ~3.5 MeV alphas in the final state.

The Case for ^{8}Li

Tensor Vs. V-A





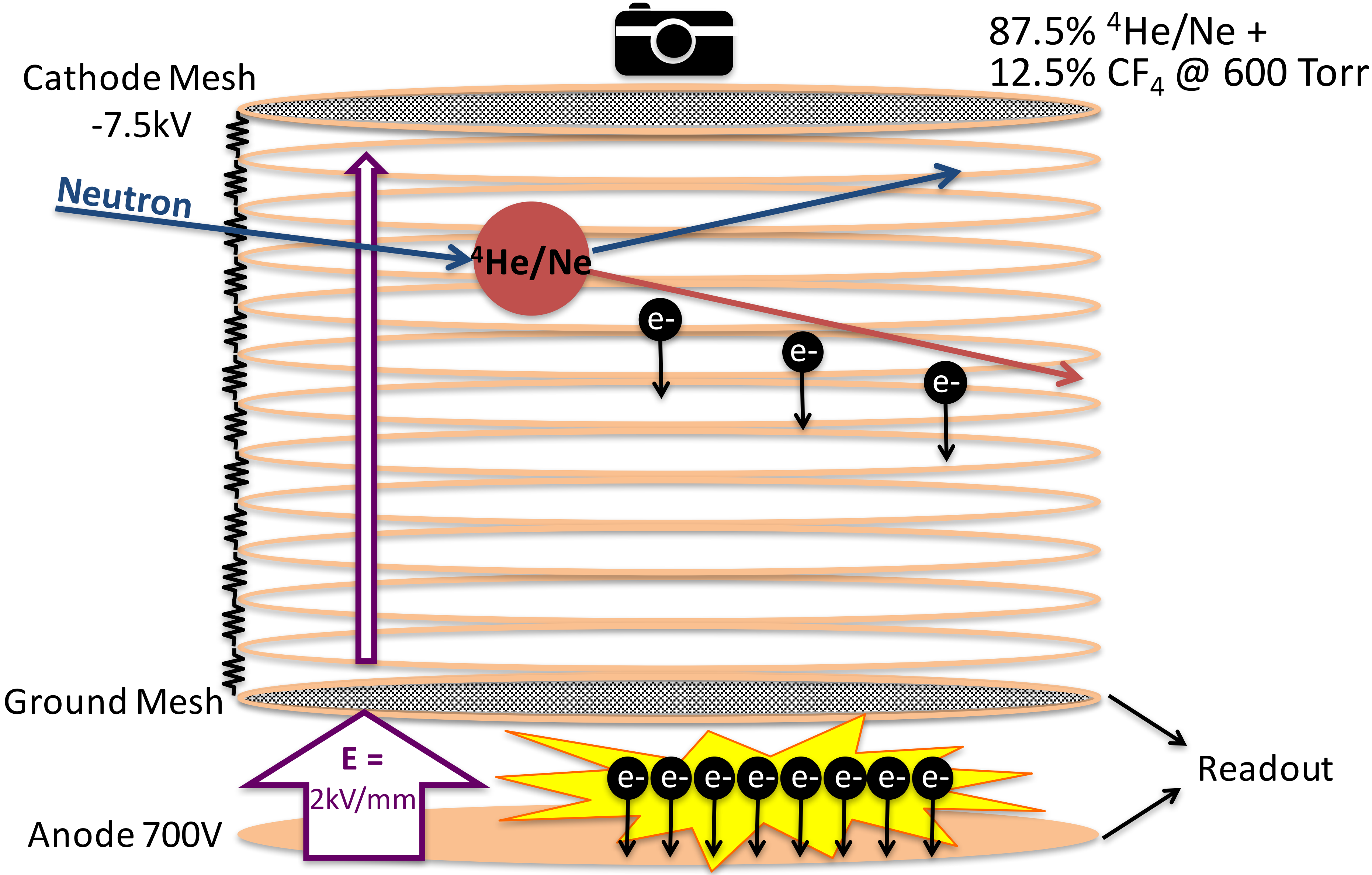
OLIVIA Experiment

Goal: High-Statistics High-Precision Measurement of ^{8}Li beta decay using a **TPC instead of a trap**

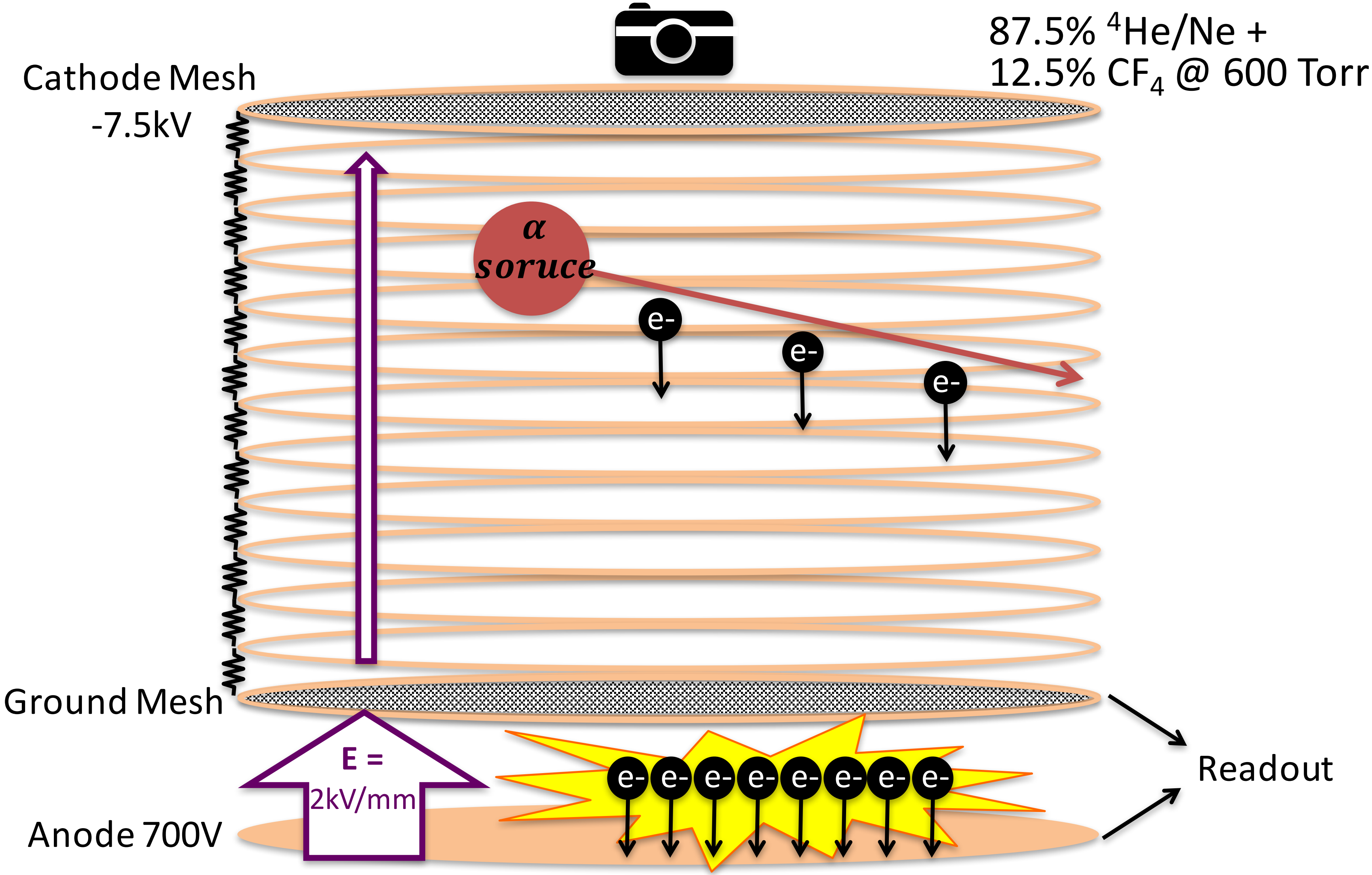
- Reminder: $^{8}Li \rightarrow \boldsymbol{e^{-}} + \bar{\upsilon}_e + {}^{8}Be(\rightarrow \boldsymbol{\alpha} + \boldsymbol{\alpha})$

- Steps:
  - Build a TPC with sensitivity to 1 – 5 MeV Alphas and 1 – 16 MeV electrons.
  - Setup a ^{8}Li production scheme.
  - Build a ^{8}Li Transport system to the TPC.
  - Perform the measurement ☺

MITPC


87.5% $^4He/Ne$ +
12.5% CF_4 @ 600 Torr
Cathode Mesh
-7.5kV
Neutron
$^4He/Ne$
e-
e-
e-
Ground Mesh
E =
2kV/mm
e- e- e- e- e- e- e- e-
Readout
Anode 700V

MITPC



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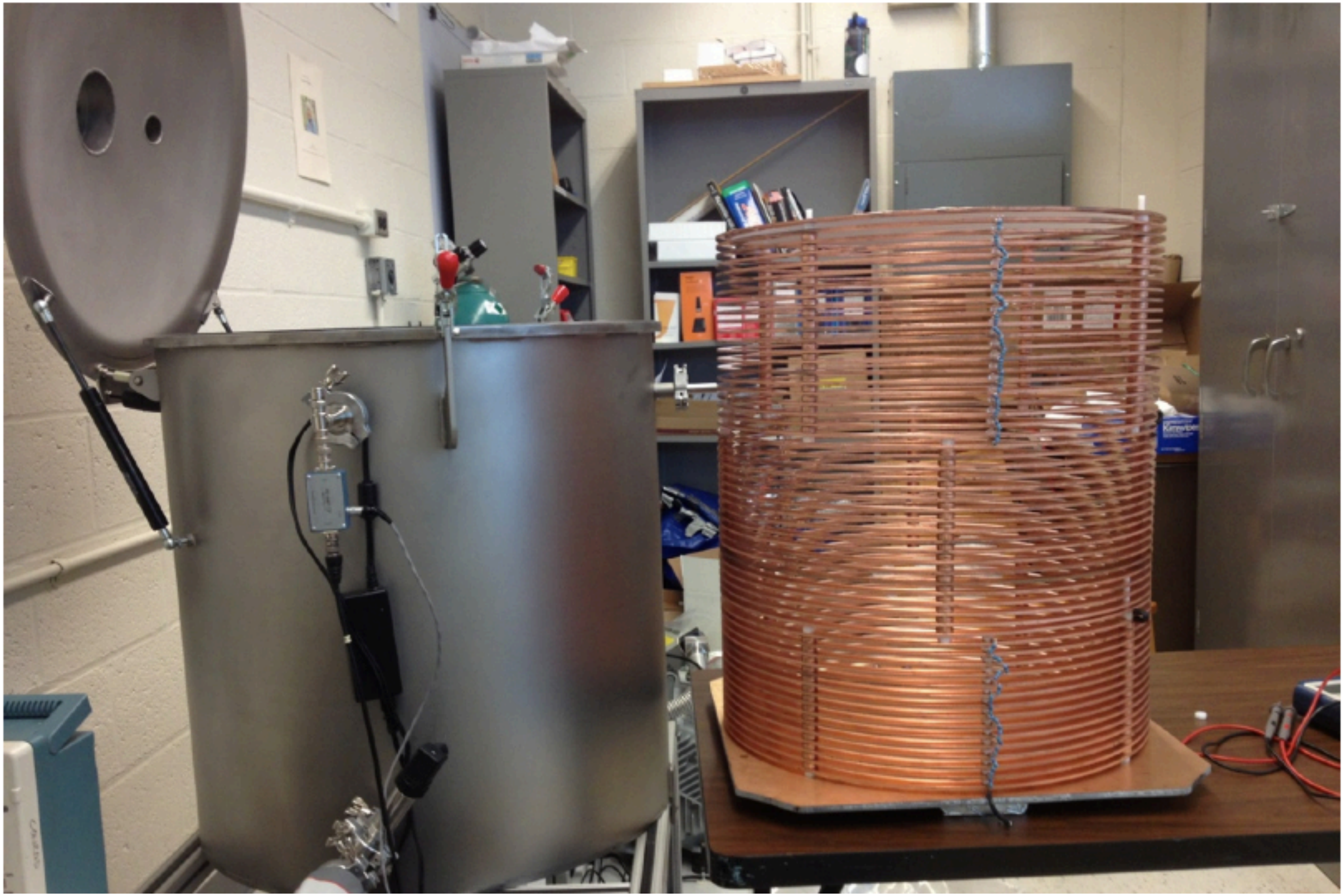
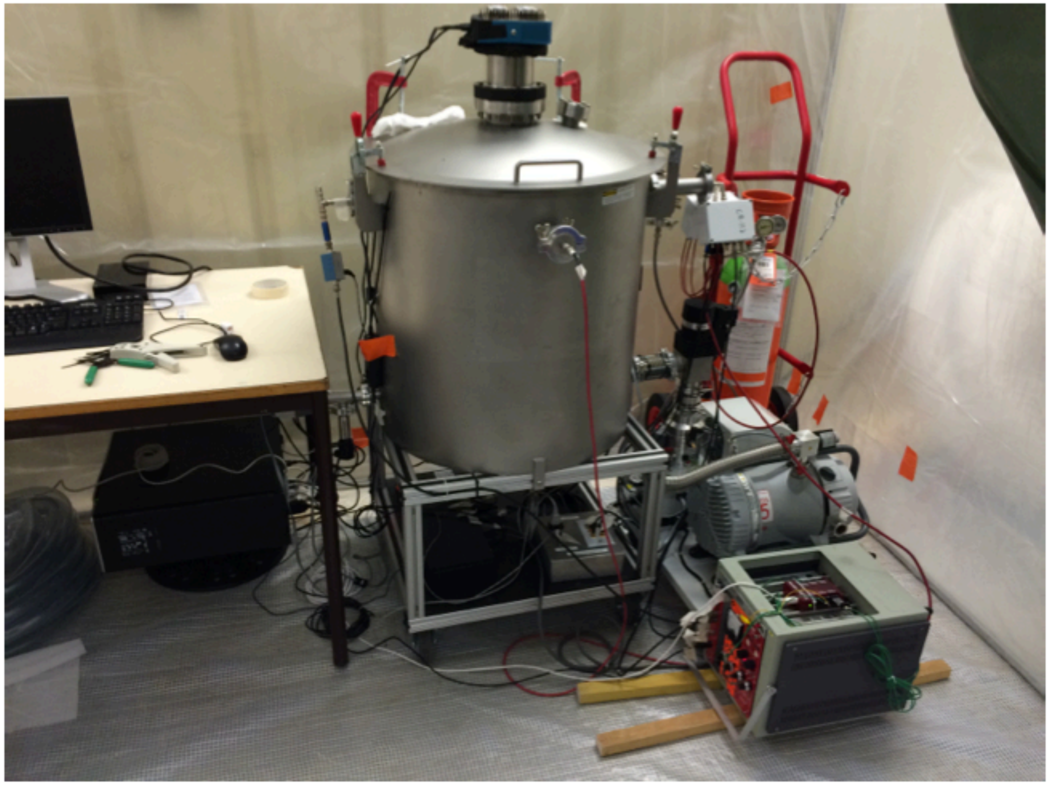


MITPC

Little MITPC

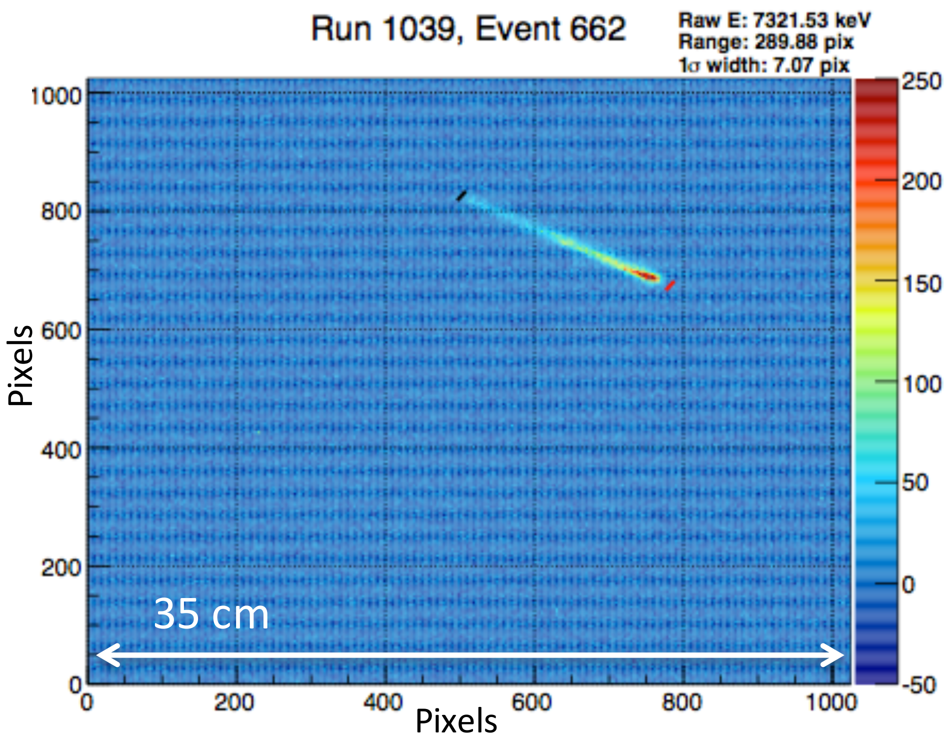
- 2.8L
- 0.2 – 10 MeV nuclear recoil
- 4 months of data at Double Chooz far hall
- Now at MIT for OLIVIA



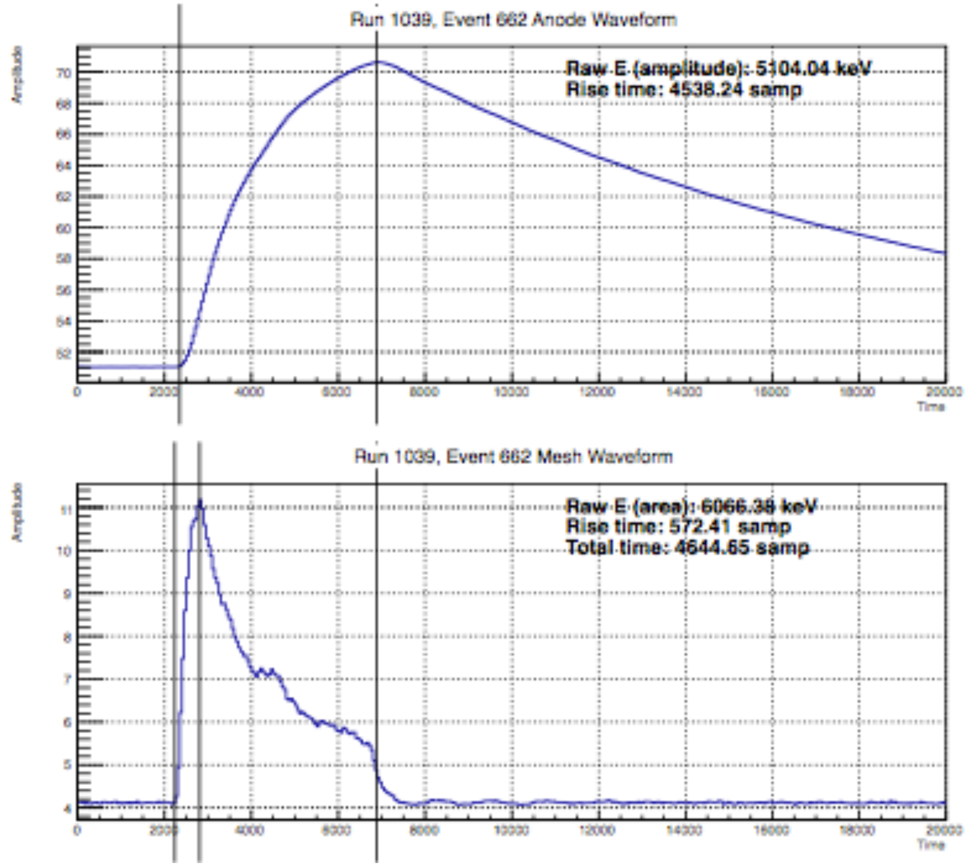
Big MITPC

- 60L
- 0.3 – 20 MeV nuclear recoil
- 7 months of data at Double Chooz near hall
- Now taking data at FNAL

Event Readout for Alpha Track



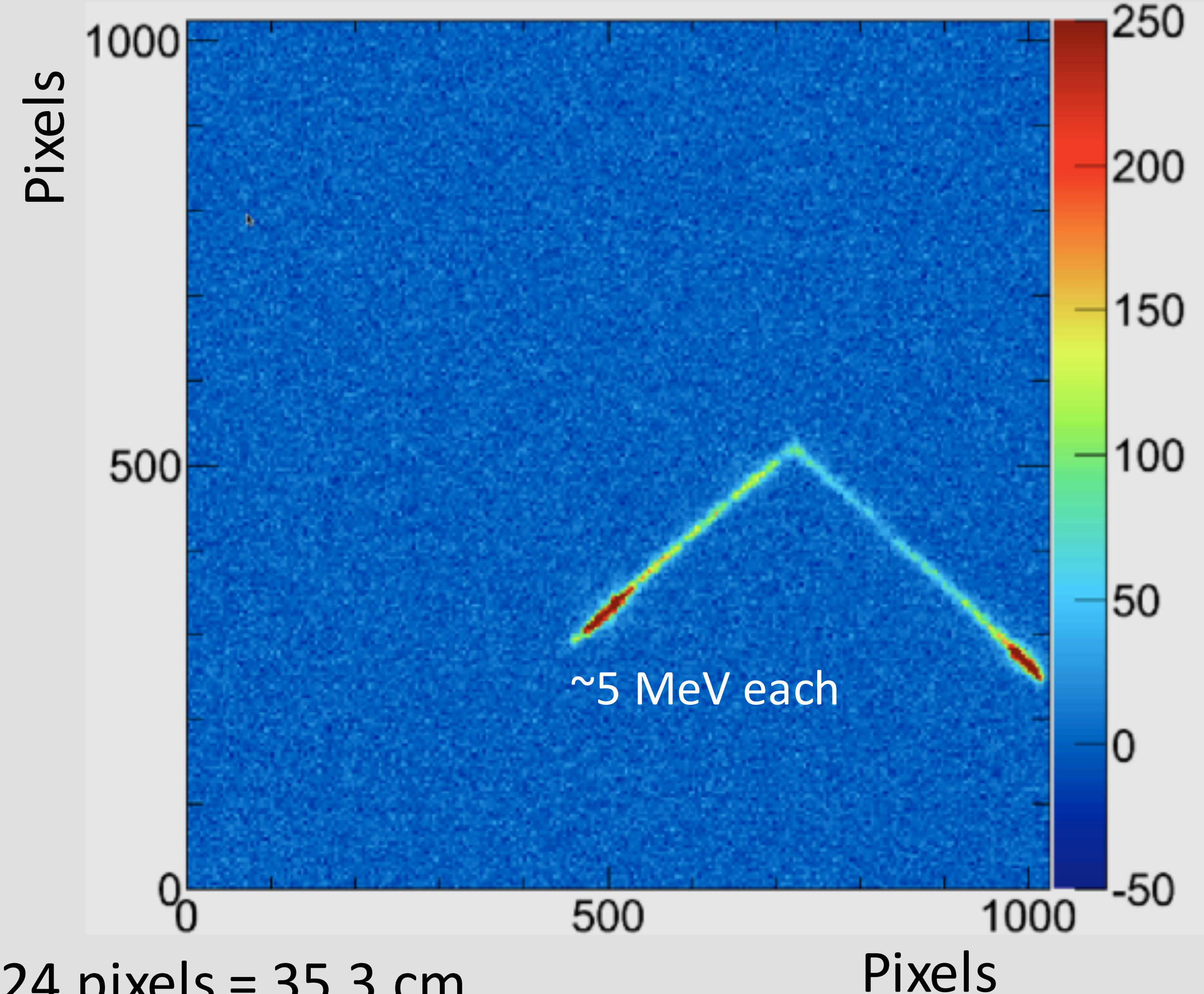
CCD readout



Waveform readouts: anode (top); mesh (bottom)

Two Alpha Event

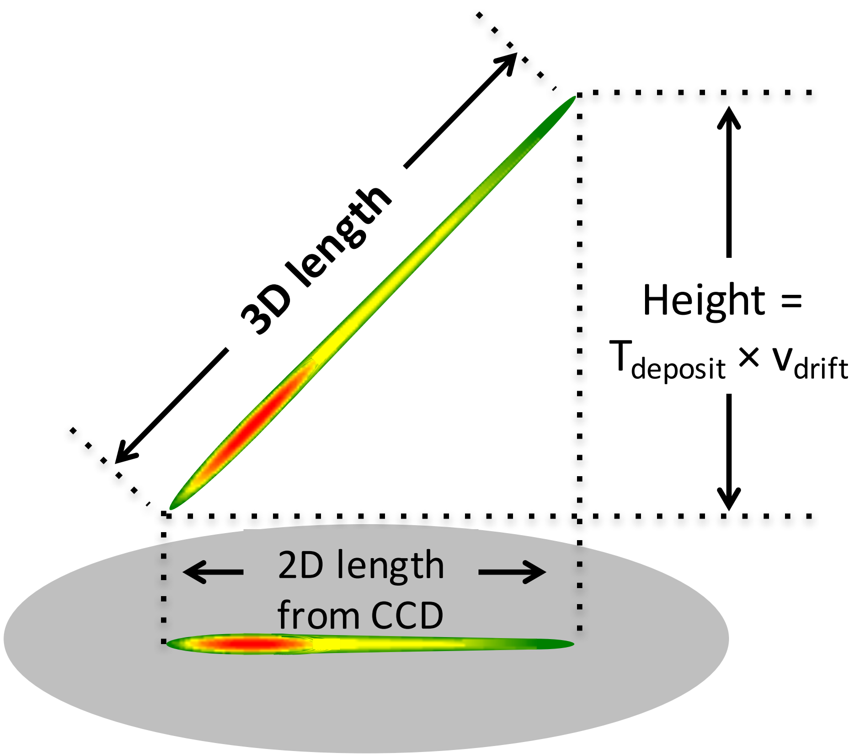
$$^{220}\text{Rn} \rightarrow \, ^{216}\text{Po} \rightarrow \, ^{212}\text{Pb}$$



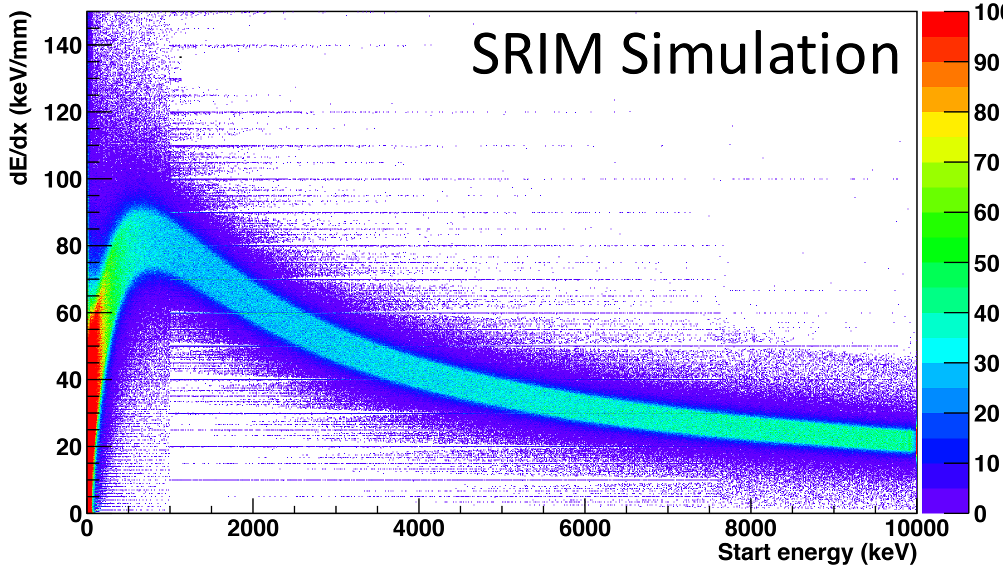
1024 pixels = 35.3 cm

Energy Reconstruction

Energy Reconstruction from 3D track length



Energy loss of alpha particles in $^4He/CF_4$



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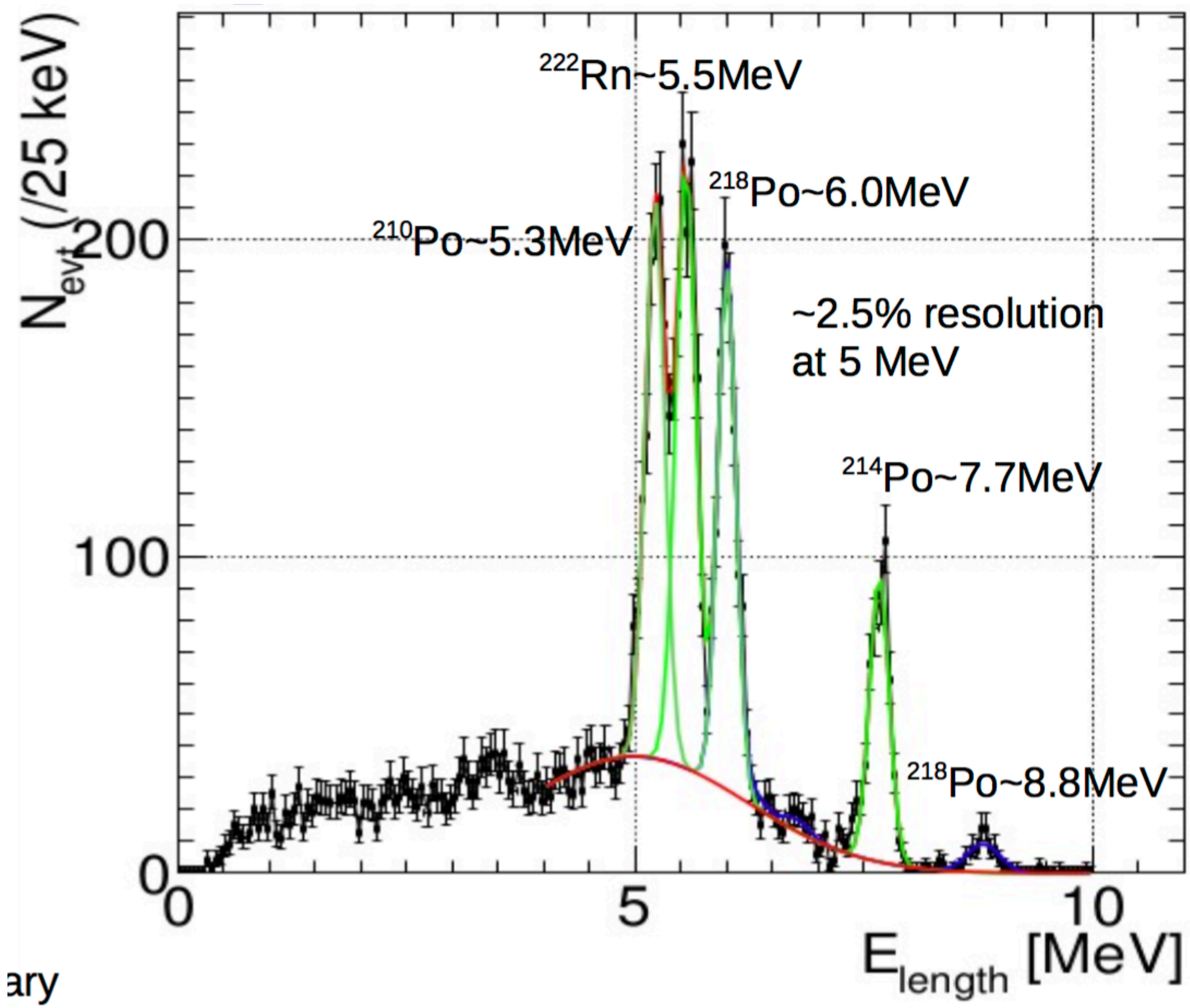
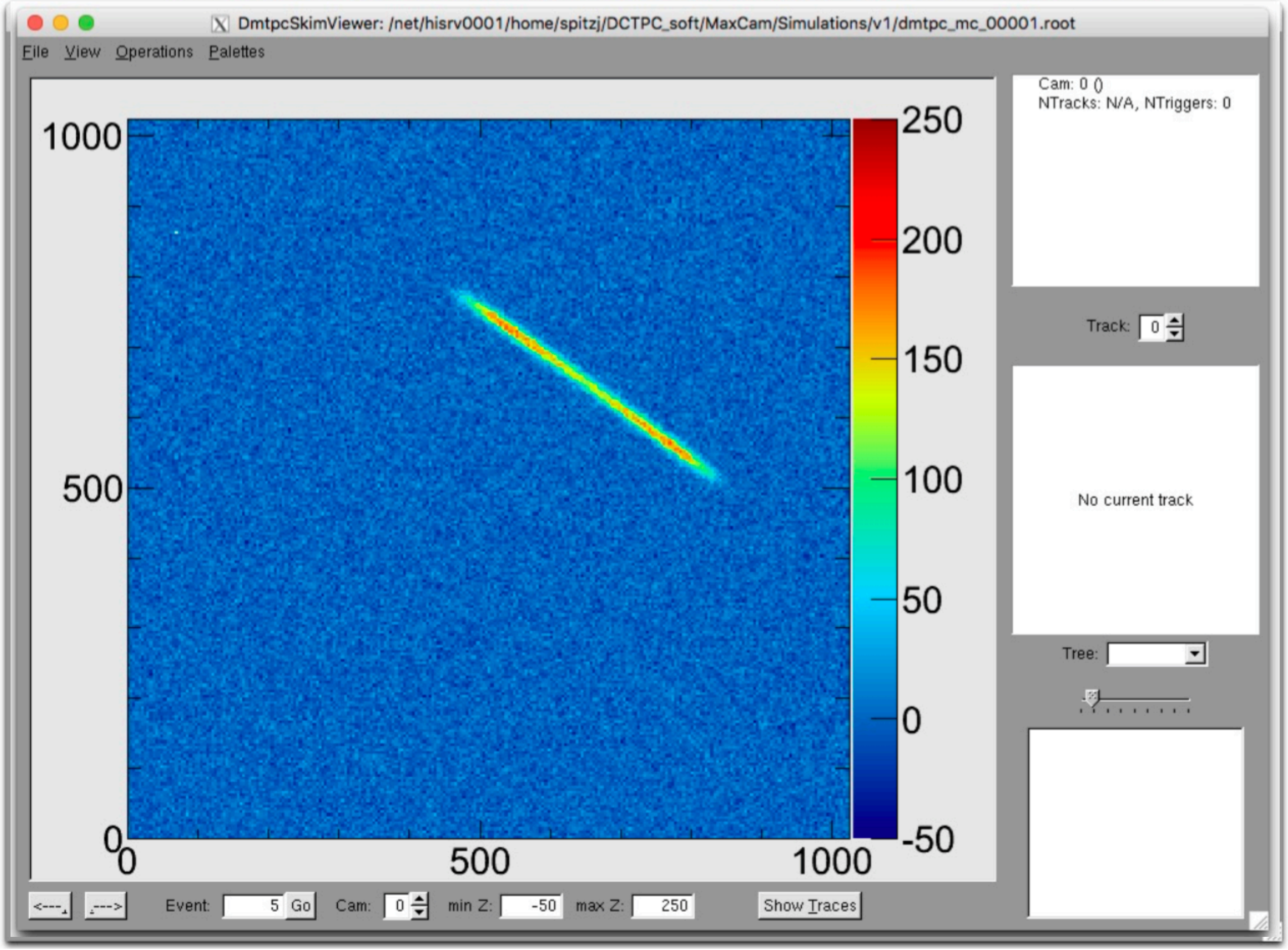


Sensitivity to ^{8}Li decay Alphas

'Typical' simulated events @ 200 Torr



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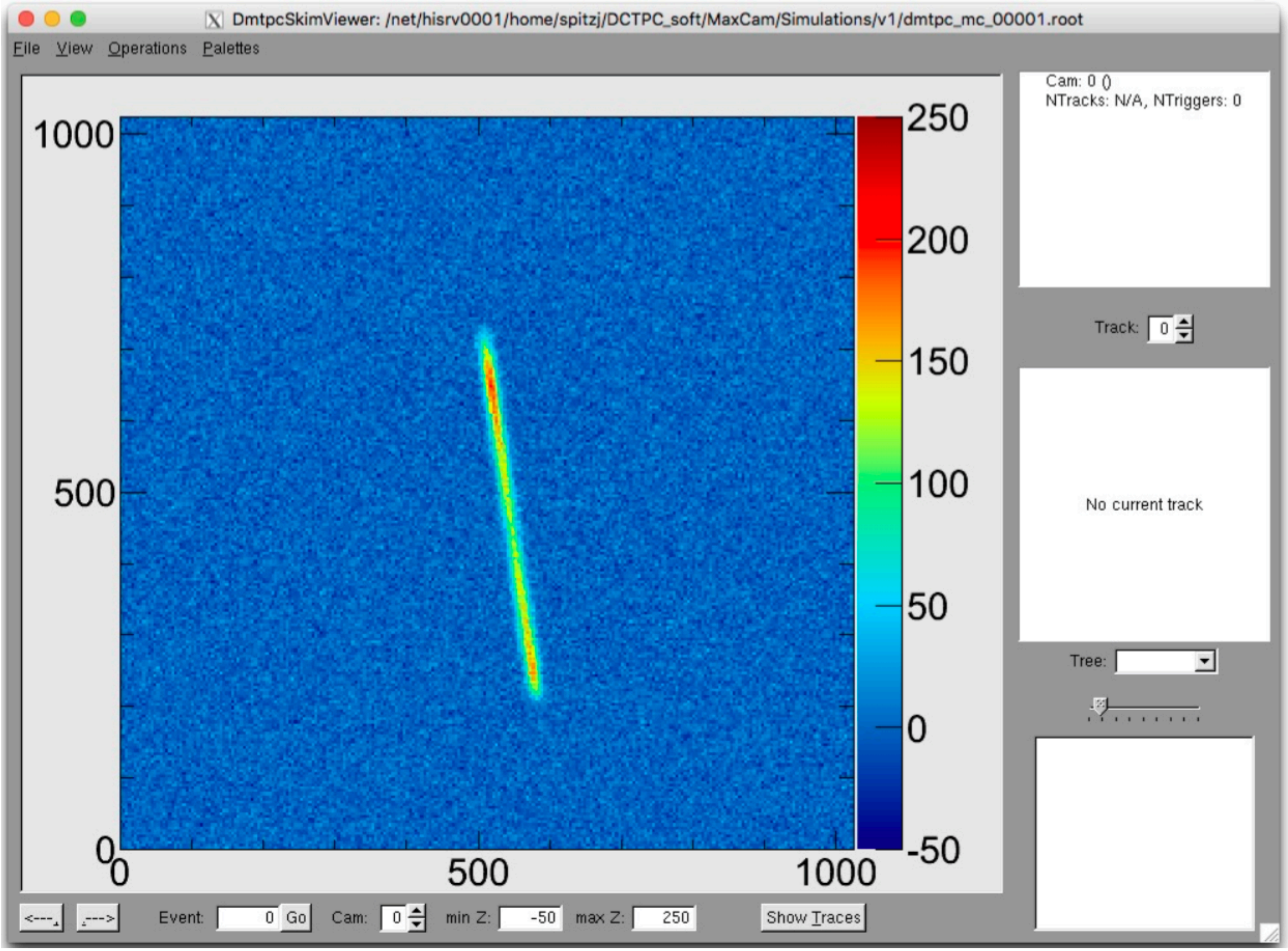

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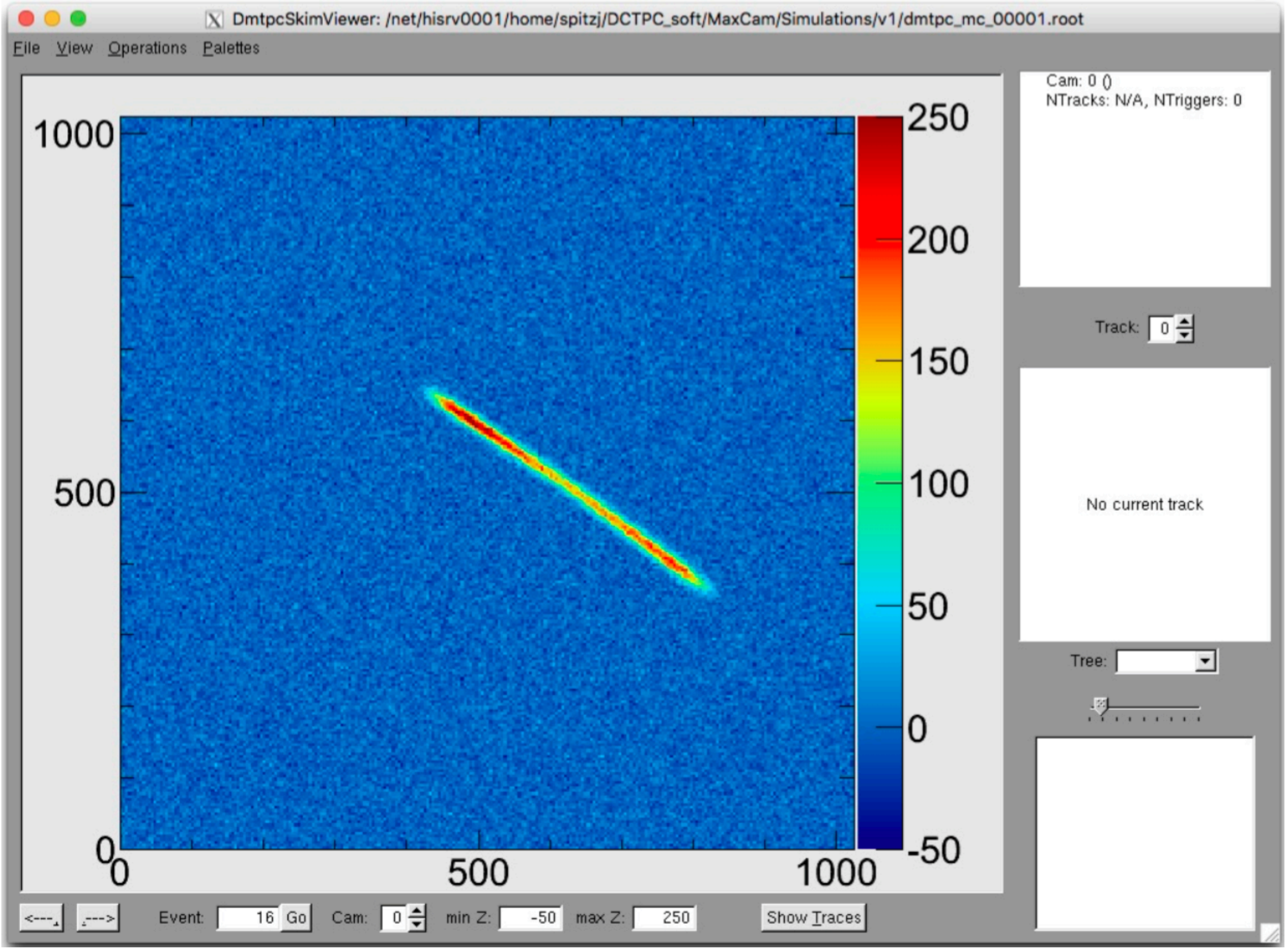

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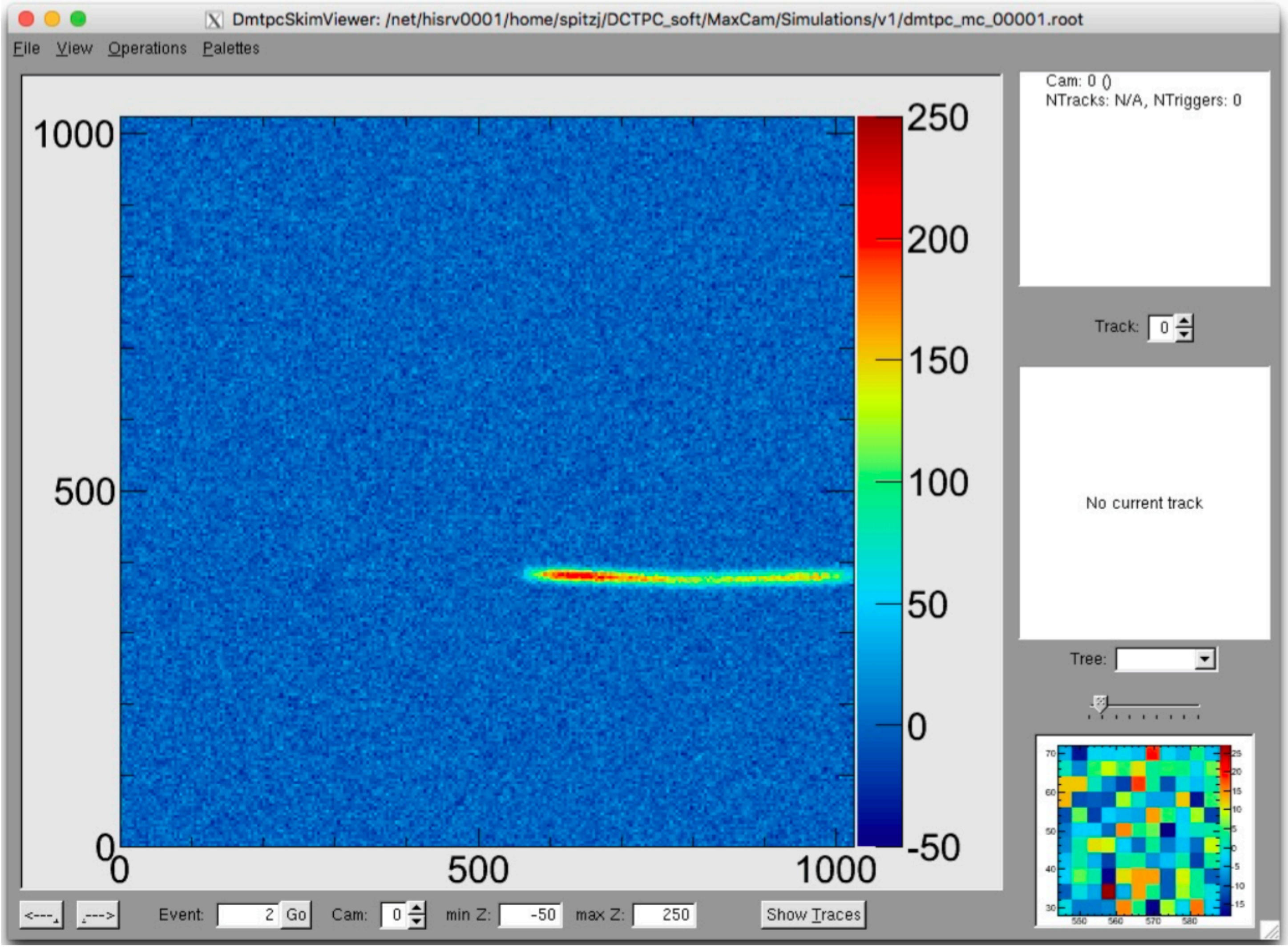

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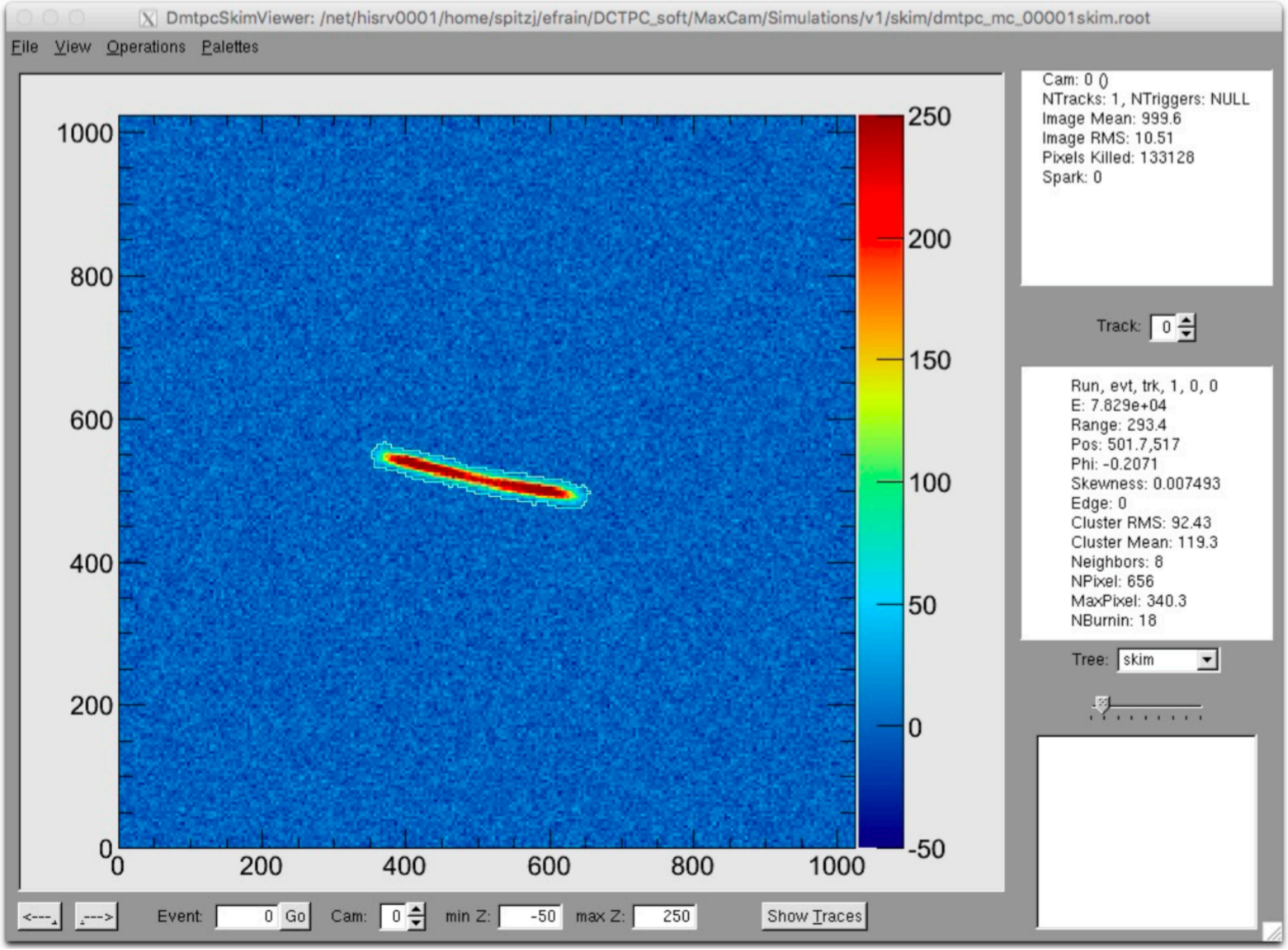

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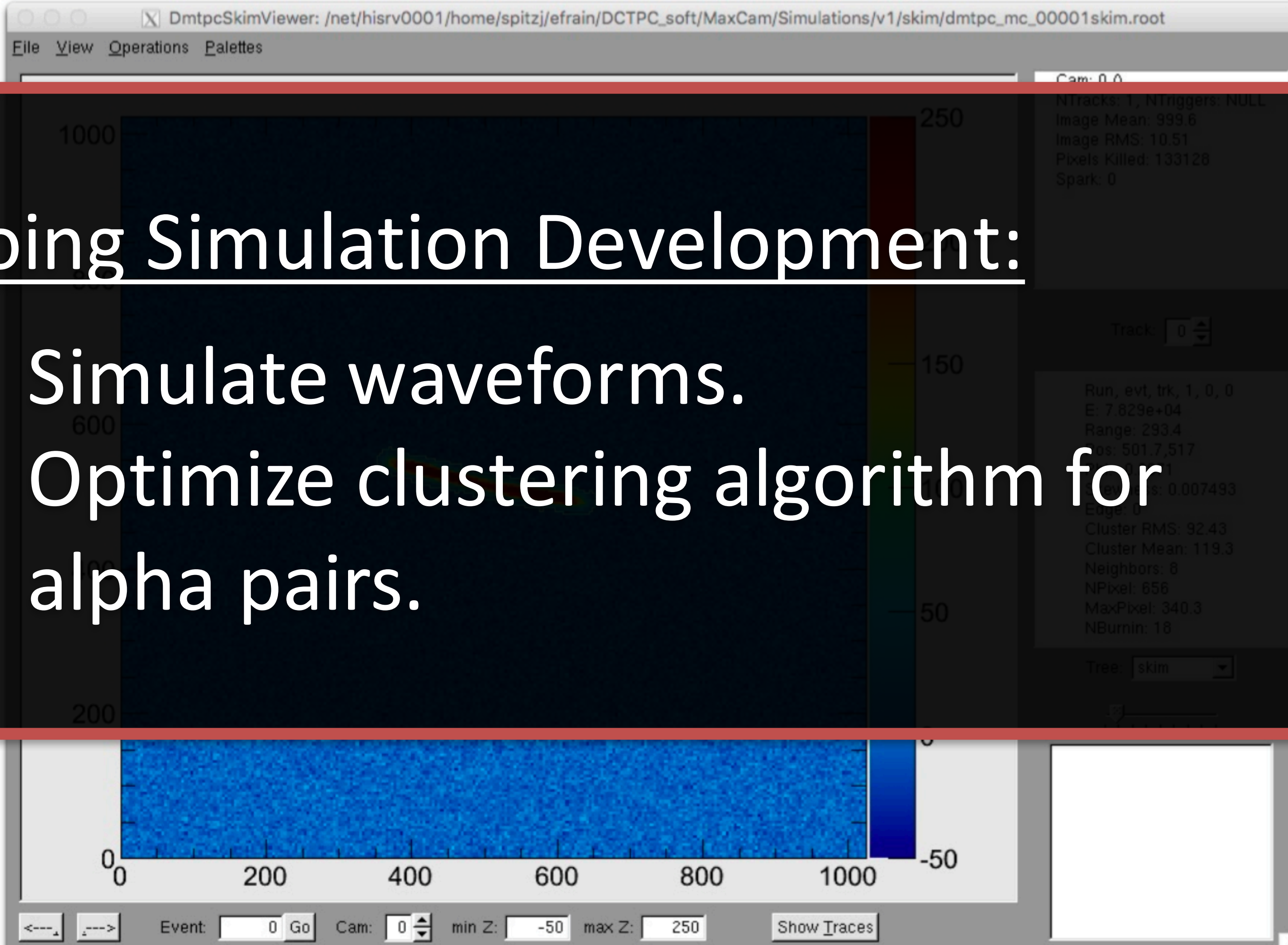
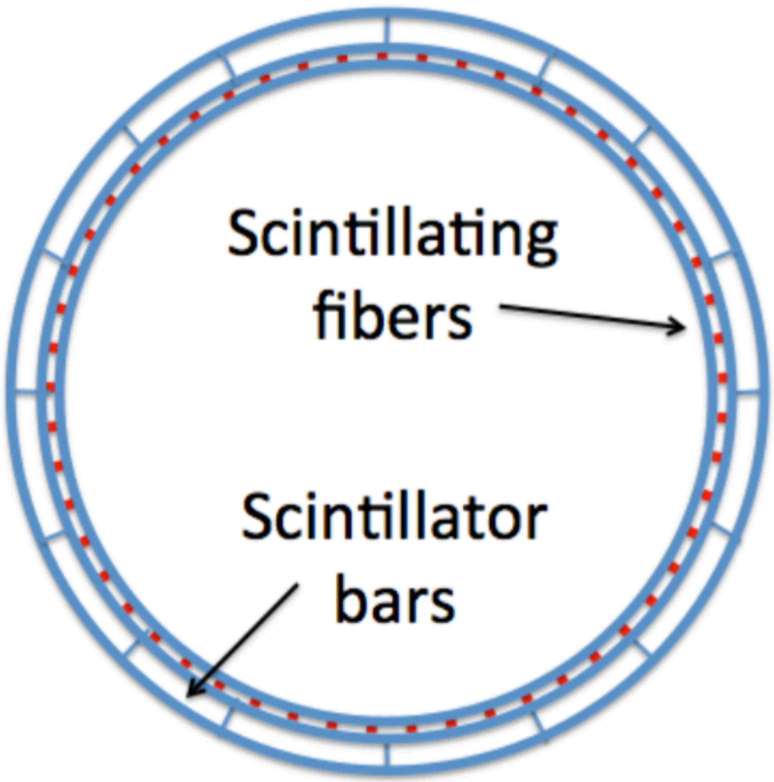


<u>Ongoing Simulation Development:</u>

- Simulate waveforms.
- Optimize clustering algorithm for alpha pairs.

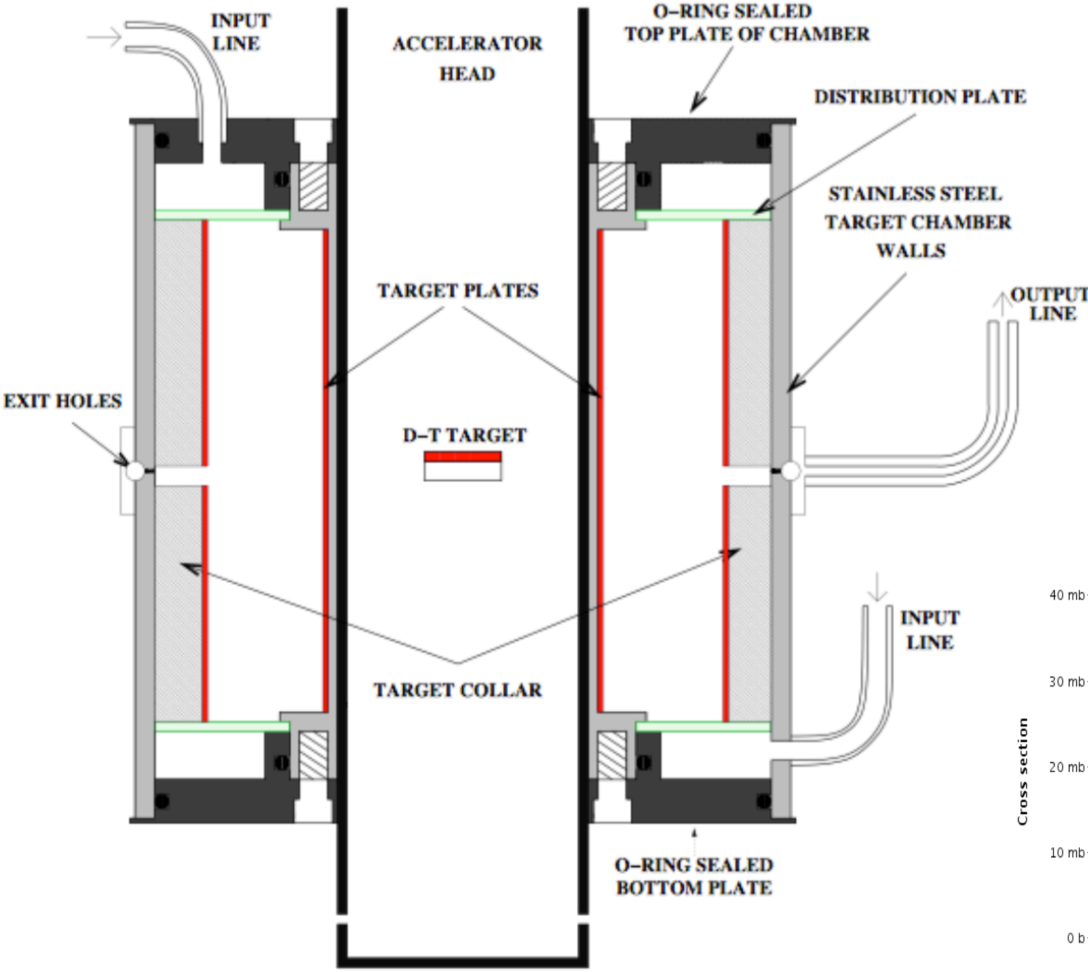
Electron Detection

Adding scintillators to the side of the field cage:

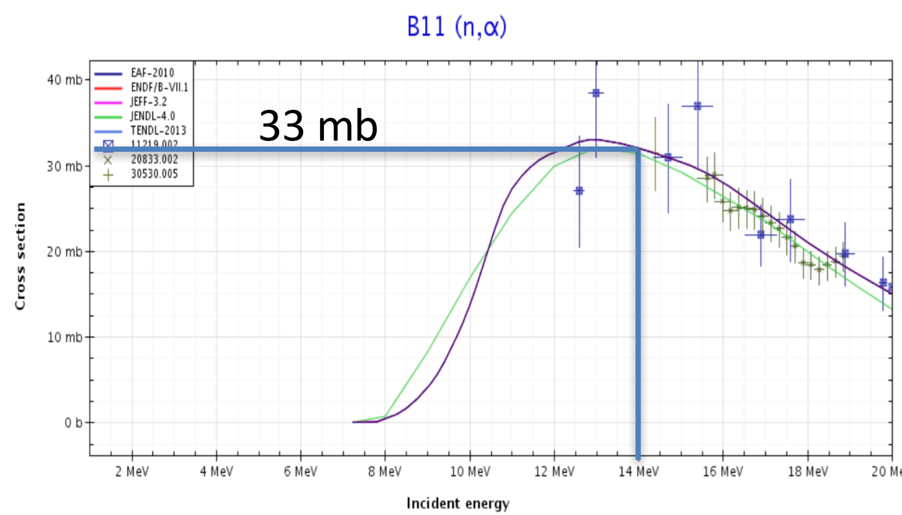


^{8}Li Production

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



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



Based on the SNO ^{8}Li calibration system

arXiv: 0202024 (2002)

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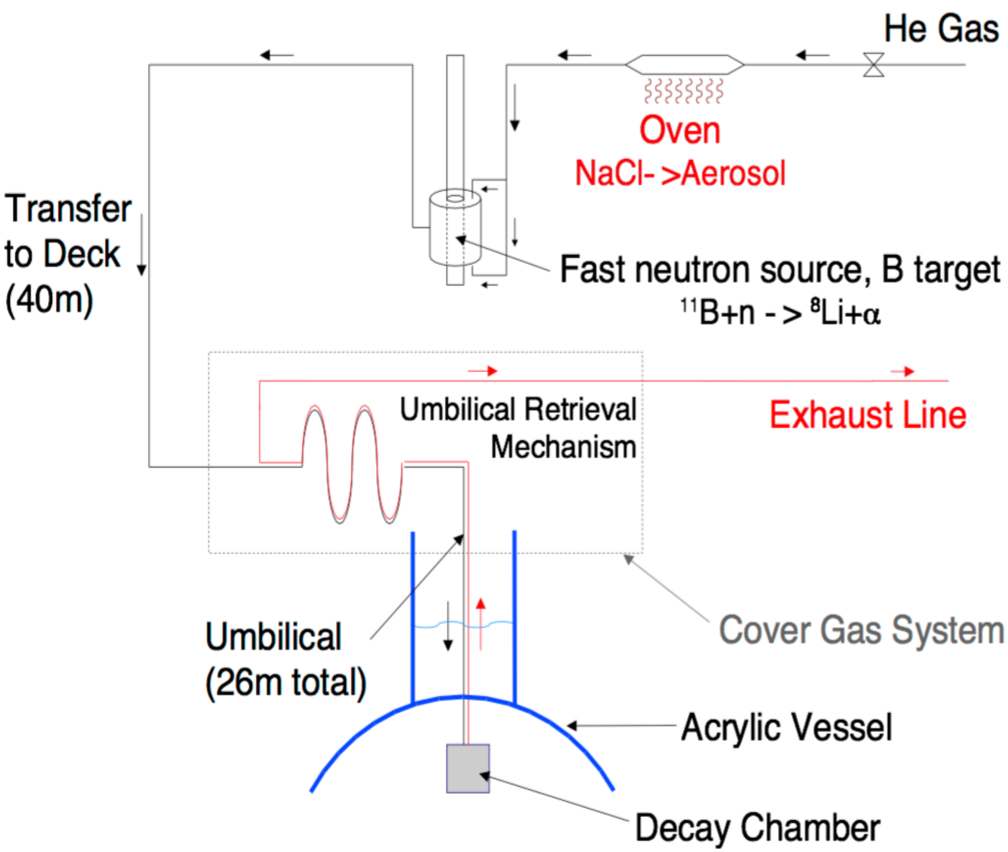

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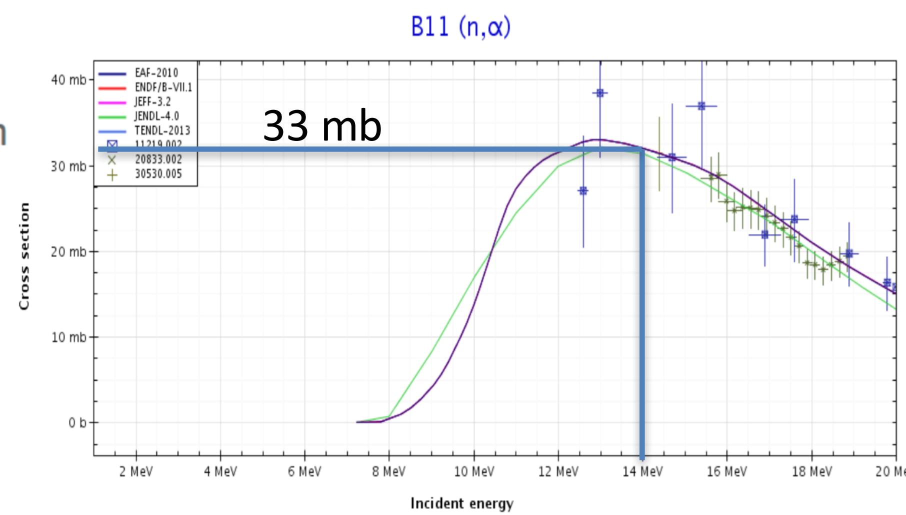

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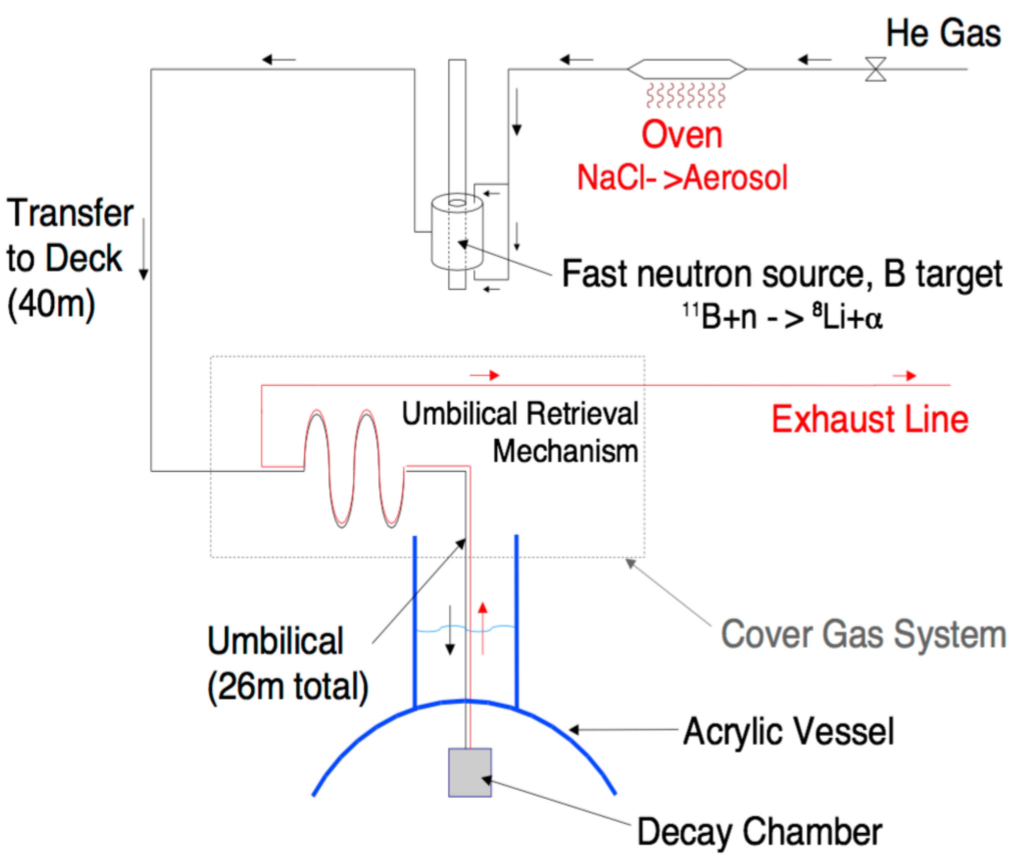

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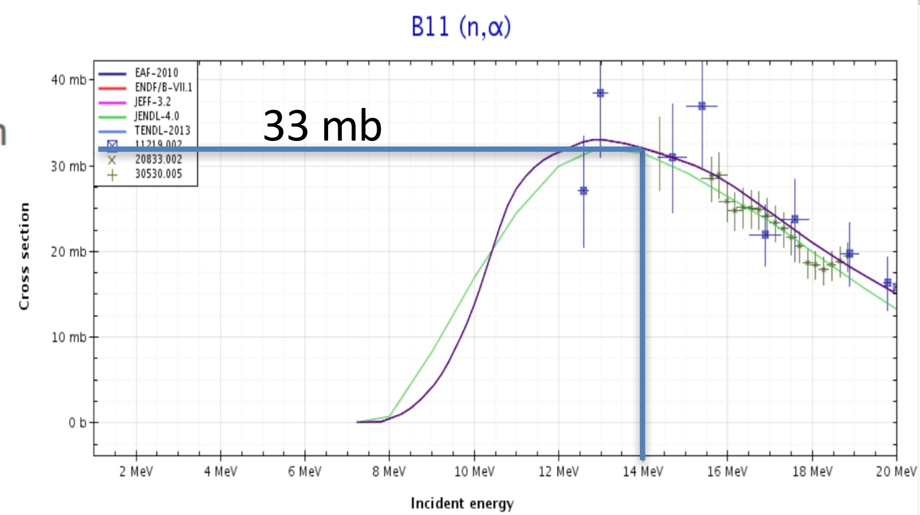
Expected Statistics: 3.6×10^{7}



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Resolution Effects

<u>Nominal resolutions</u>:

2% - Energy,

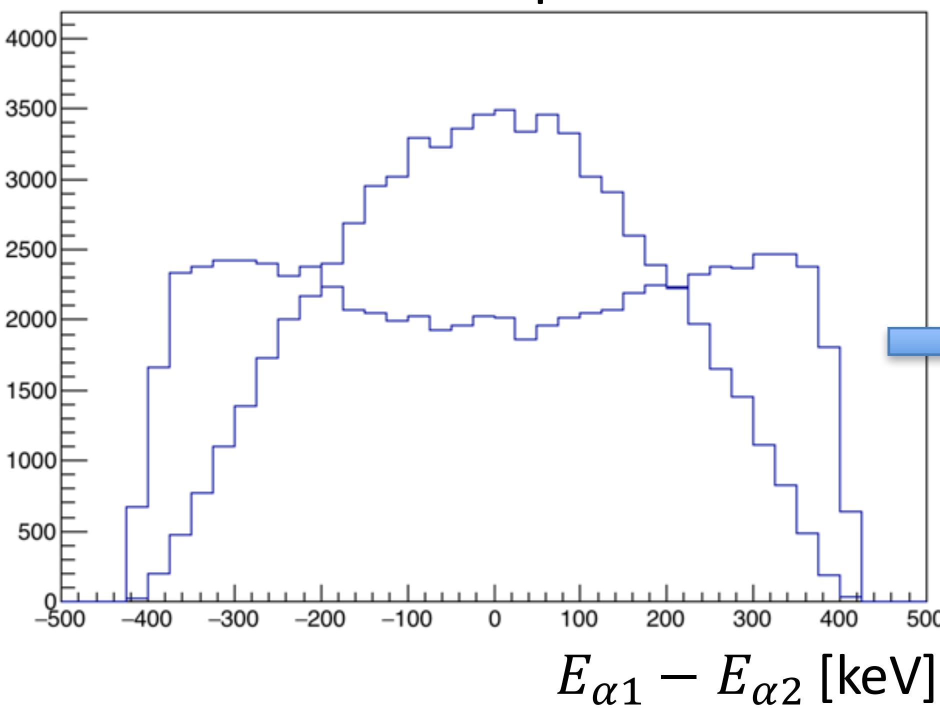
1° – In-Plane angle,

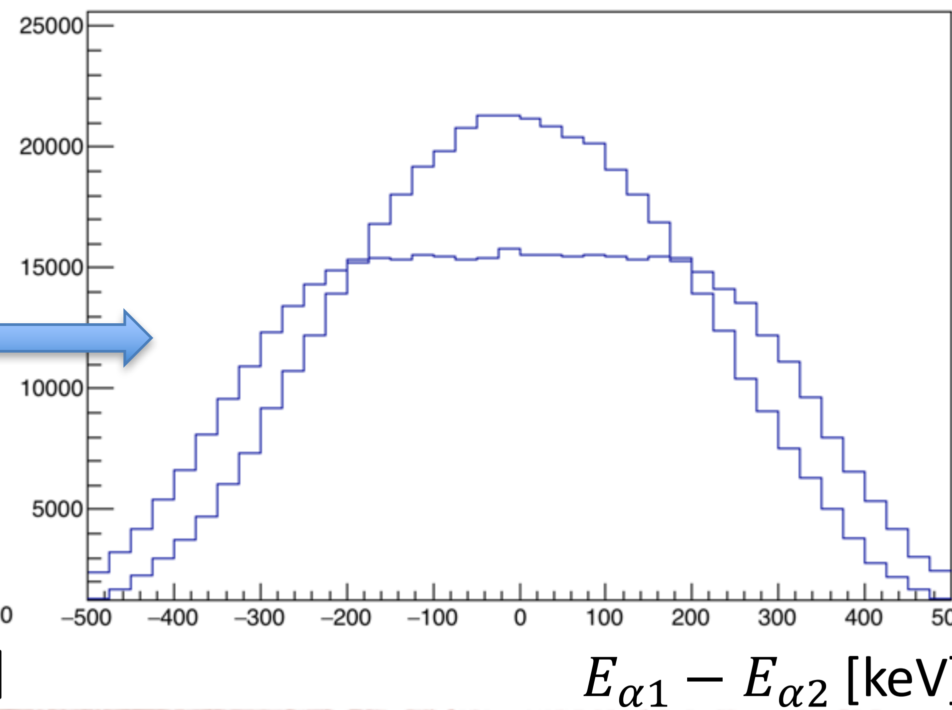
2° – out-of-plane angle.

Energy resolution is the main issue. Can be improved using:

- lower gas pressure
- larger volume TPC
- Better camera

For "back to back" alphas:





Status and Outlook

- MITPC is a great, proven, 3D alpha detector!
- Based on the reported SNO rates we can measure 10^7 decays in 2 - 3 months of data taking.
- Finalizing simulations to optimize the resolutions and extract the expected C_T/C_A sensitivity.
- Initial DT feasibility runs planed for the summer.
- Physics running planed for 2017 (2018).