QSFP 2021 – Experimental Neutrino Physics

Lecture 1

September 14, 2021

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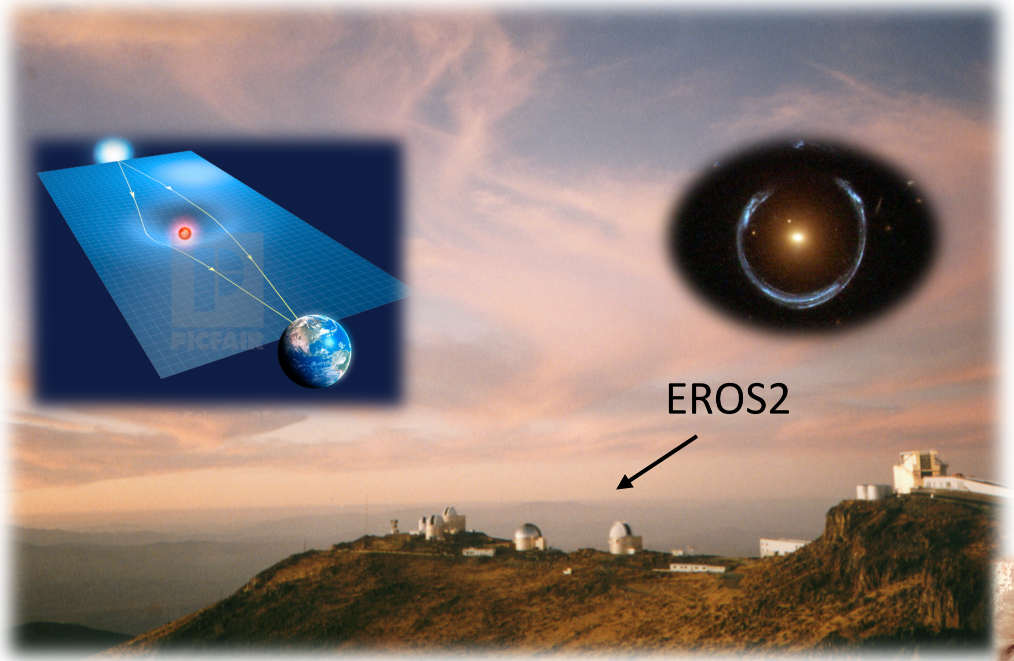
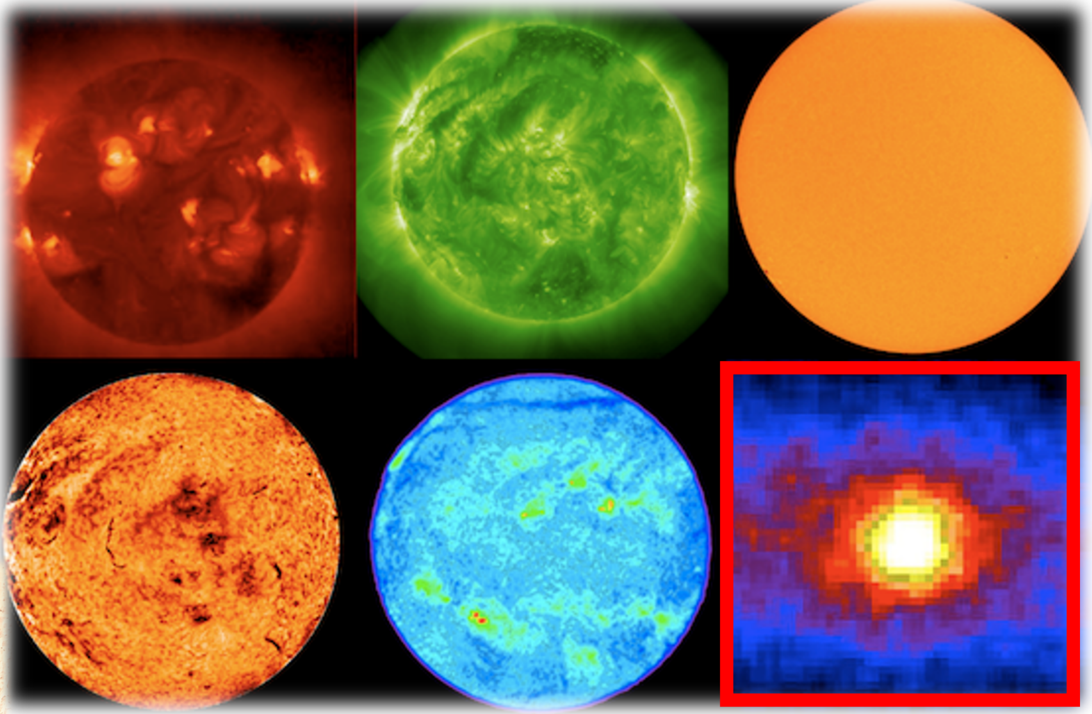
some organizational matters

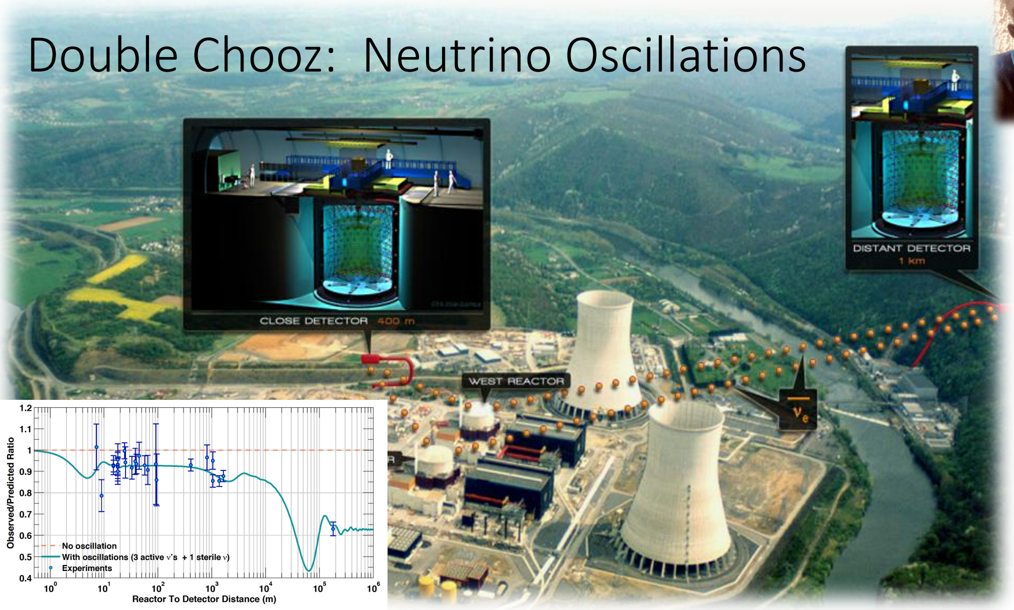
Ph.D: (baryonic) dark matter



Post-Doc: Solar Neutrinos

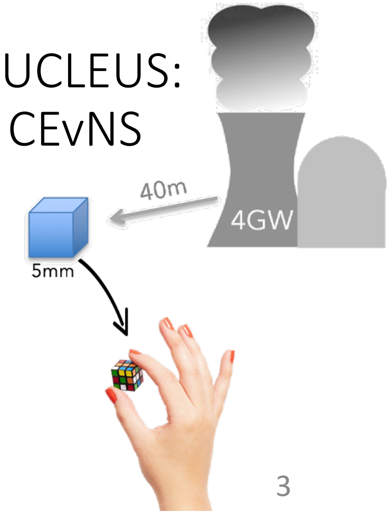


Double Chooz: Neutrino Oscillations



KATRIN: Neutrino Mass

NUCLEUS: CEvNS



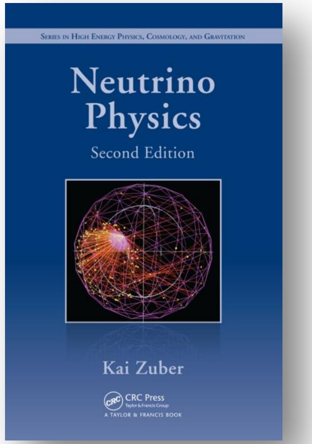
General Info

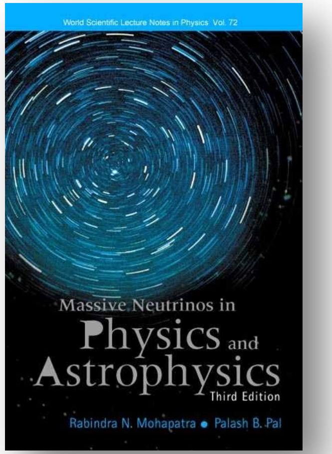
- Lectures/Tutorials: 13/09/2021 - 16/09/2021 - 17/09/2021

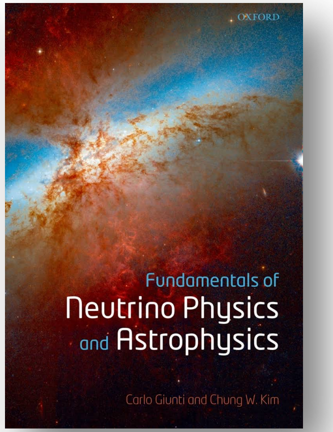
- Tutorial Organizers:
  - Patrick Foldenauer
  - Salvador Rosauro Alcaraz
  - Arsenii Titov

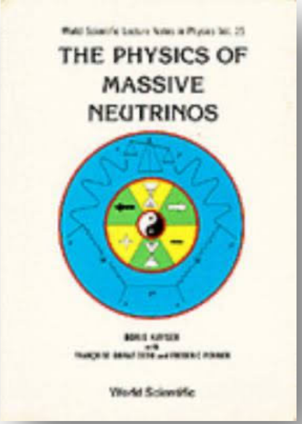
- Zoom links:
  - Mo, 13. Sep 2021 9 am (BST): https://durhamuniversity.zoom.us/j/91712717207?pwd=eEF0TXhTUWR0OWxIUmpVNTRWcmkwQT09
  - Thur, 17. Sept 2021 9 am (BST): https://durhamuniversity.zoom.us/j/98099242507?pwd=ZjQ3U2JUOWwvV1l0VEZGQXphUUxIUT09
  - Fri, 17. Sept 2021 9 am (BST) : https://durhamuniversity.zoom.us/j/97449267072?pwd=RysyYm5tZ096REJ1ZE1uRVpnYXRNZz09

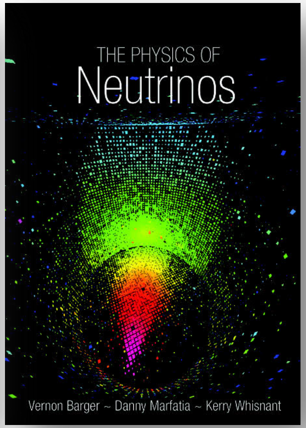
Literature on "Neutrinos"

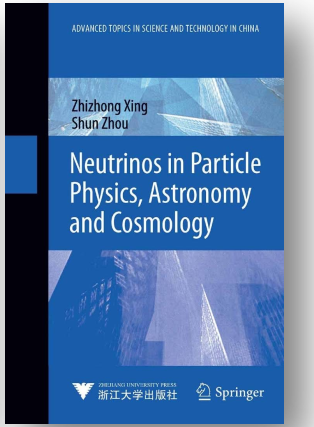








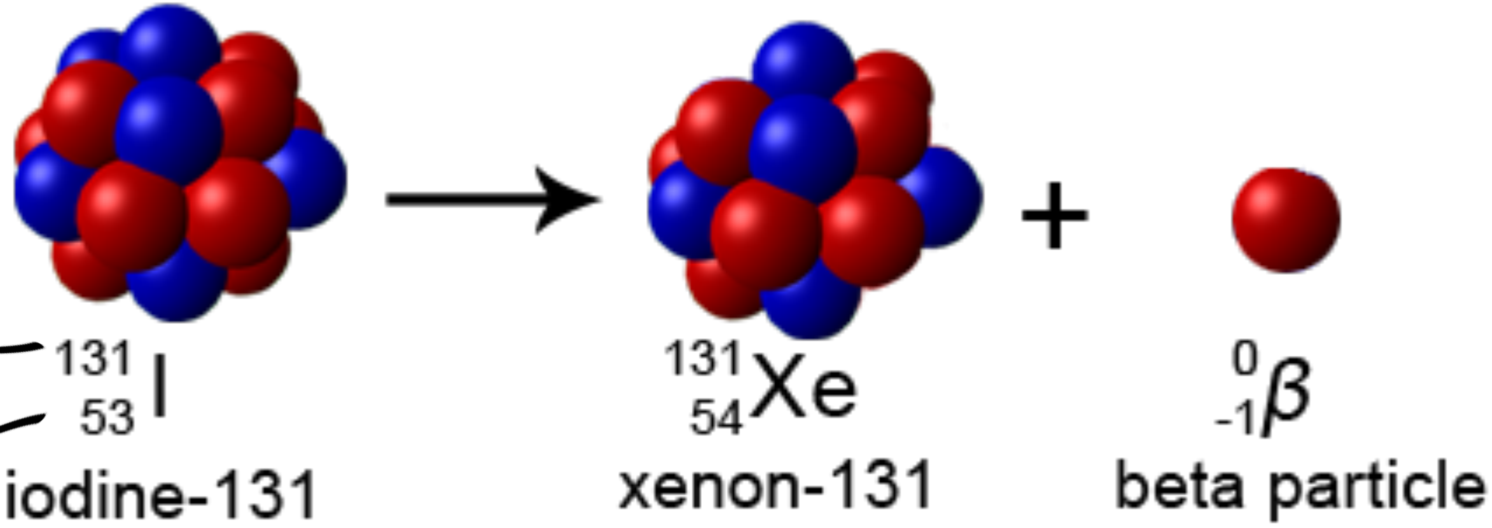




… Now physics

Characterization of the β radiation (old way)…

A = Z + N

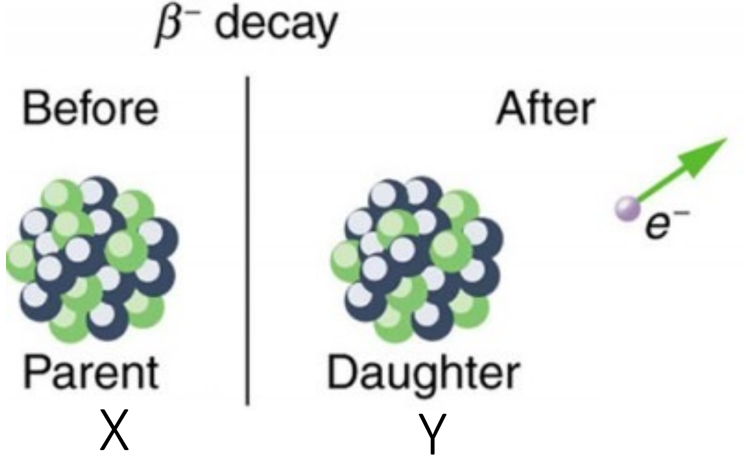


N

Experimental study: what is the energy distribution the electrons?

Expected energy distribution

Assuming: $X \rightarrow Y + e$



Energy conservation

$$E_X = E_Y + E_e \rightarrow E_e = E_X - E_Y$$

Momentum conservation
$p_X = 0$ and $p_e^2 = p_Y^2$

$$E_e = m_X - \sqrt{p_Y^2 + m_Y^2} = m_X - \sqrt{p_e^2 + m_Y^2} = m_X - \sqrt{E_e^2 - m_e^2 + m_Y^2}$$

rearranging

$$E_e^2 - 2E_e m_X + m_X^2 = m_Y^2 + E_e^2 - m_e^2$$

$$E_e = \frac{m_X^2 - m_Y^2 + m_e^2}{2m_X}$$

$$E^2 = p^2 + m^2$$

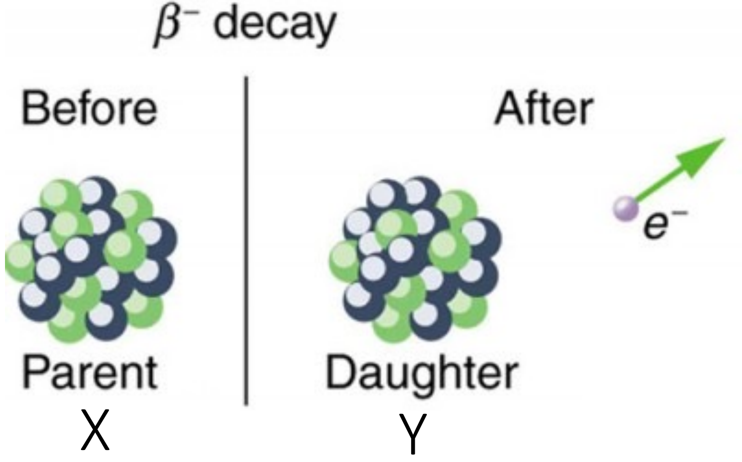
Total energy

Momentum

Rest mass

Expected energy distribution

Assuming: $X \rightarrow Y + e$



Energy conservation

$$E_X = E_Y + E_e \rightarrow E_e = E_X - E_Y$$

Momentum conservation
$p_X = 0$ and $p_e^2 = p_Y^2$

$$E_e = m_X - \sqrt{p_Y^2 + m_Y^2} = m_X - \sqrt{p_e^2 + m_Y^2} = m_X - \sqrt{E_e^2 - m_e^2 + m_Y^2}$$

$$E_e - m_X = -\sqrt{m_Y^2 + E_e^2 - m_e^2}$$

rearranging

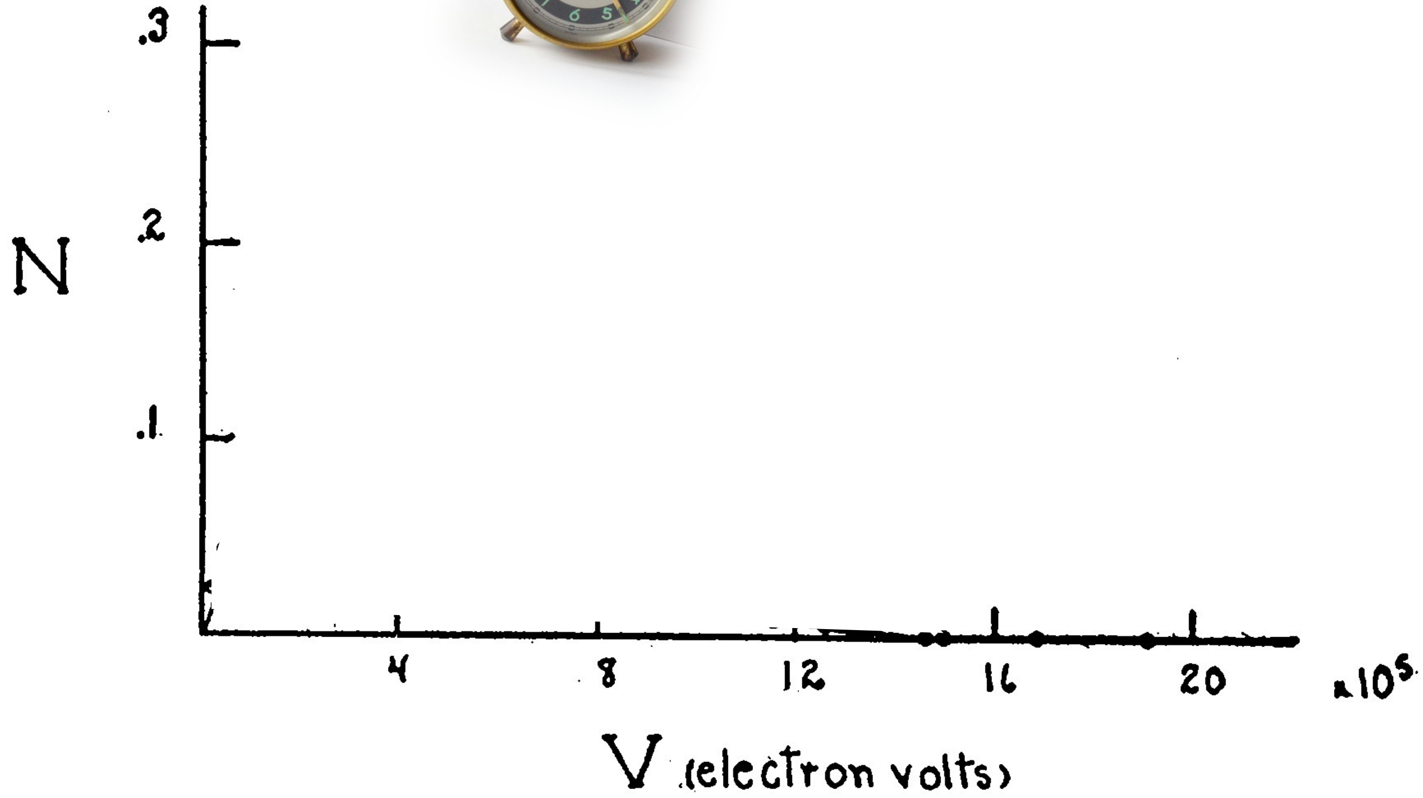
$$E_e^2 - 2E_e m_X + m_X^2 = m_Y^2 + E_e^2 - m_e^2$$

$$-2E_e m_X + m_X^2 = m_Y^2 - m_e^2$$

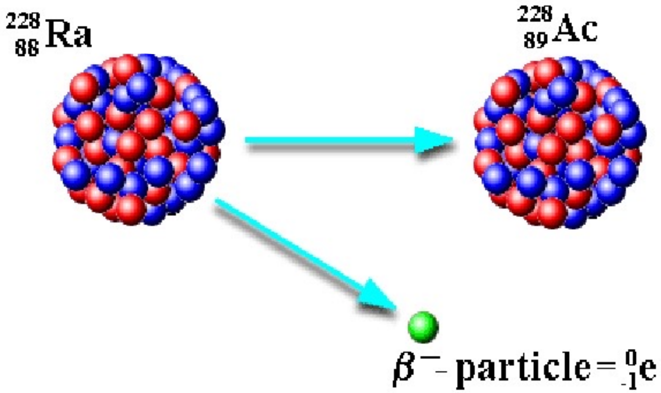
$$E_e = \frac{m_X^2 - m_Y^2 + m_e^2}{2m_X}$$

- In a 2-body decay the electron energy would be fixed

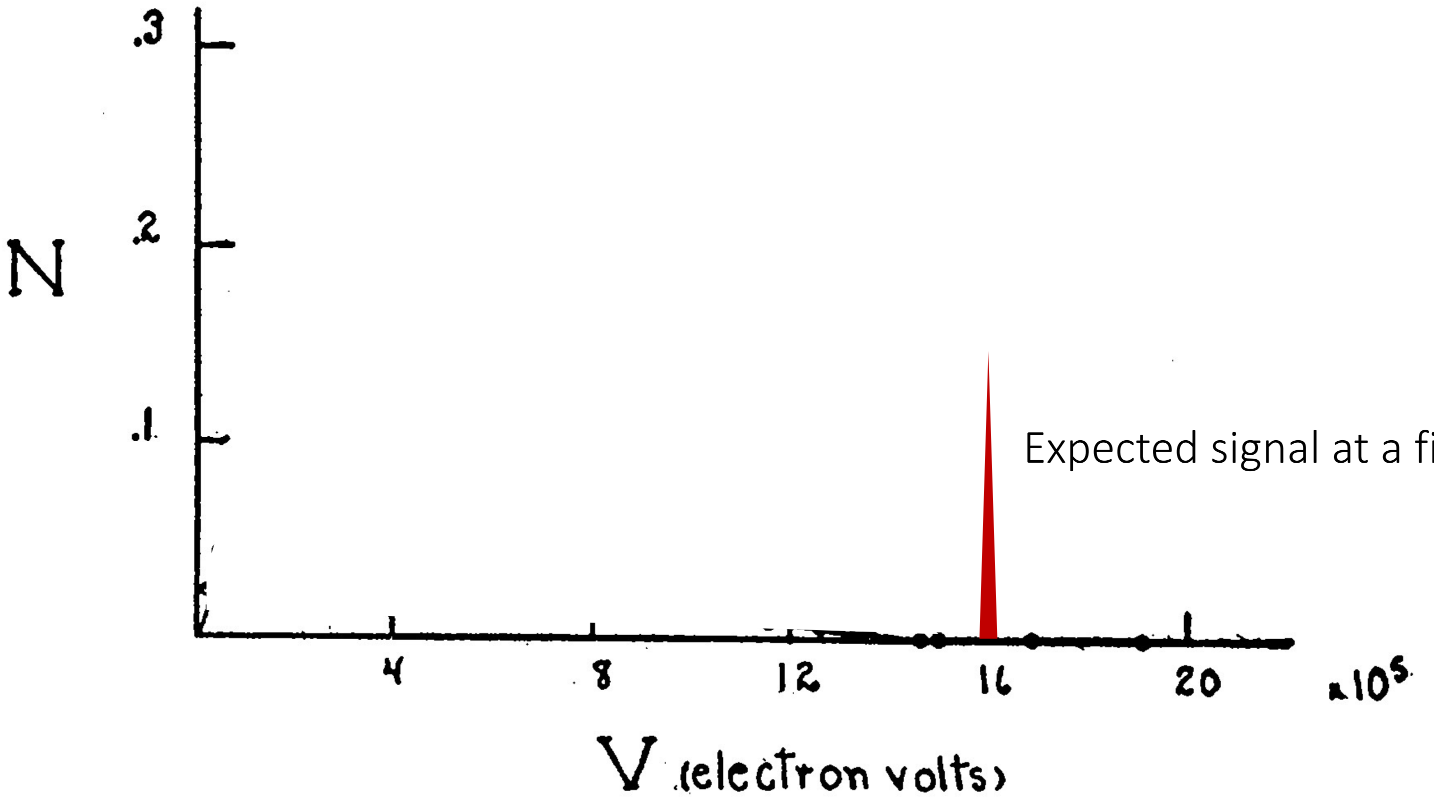
β-decay of radium: Expected Signal



(energy of electron)

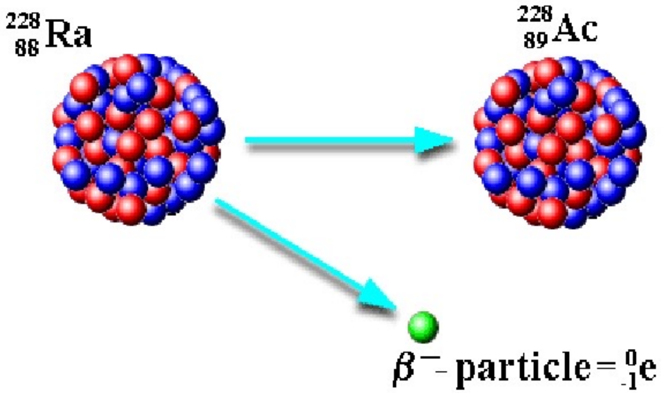


β-decay of radium: Expected signal

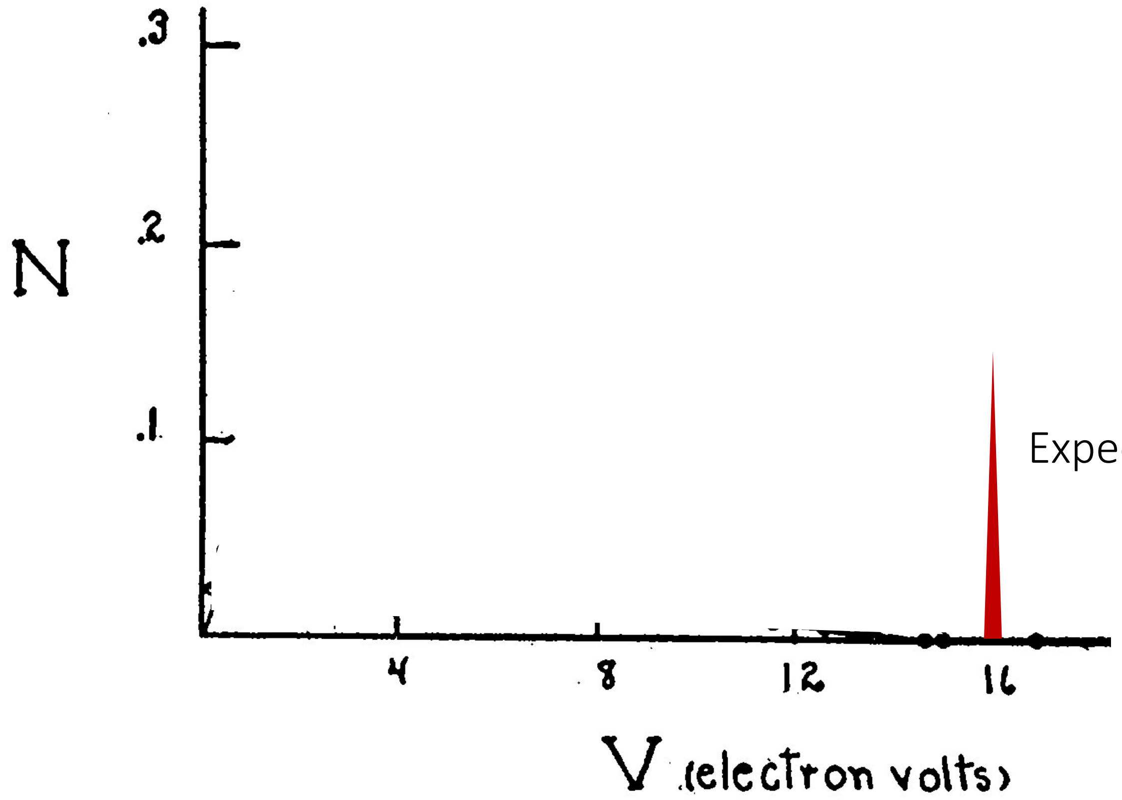


(energy of electron)

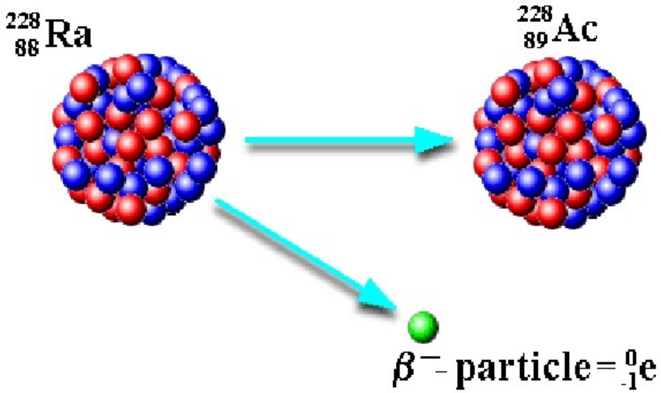
Expected signal at a fixed energy



β-decay of radium: Expected signal



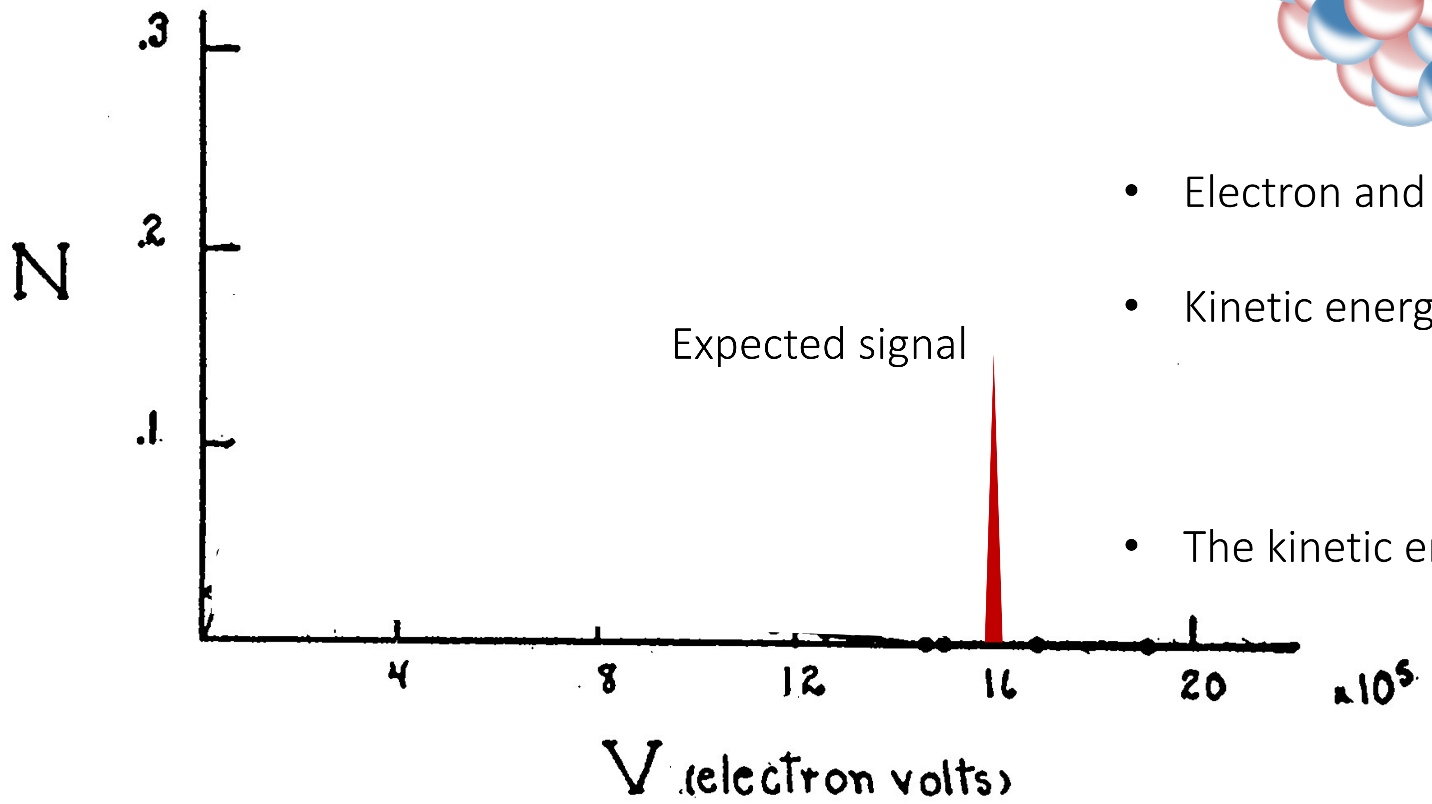
(energy of electron)



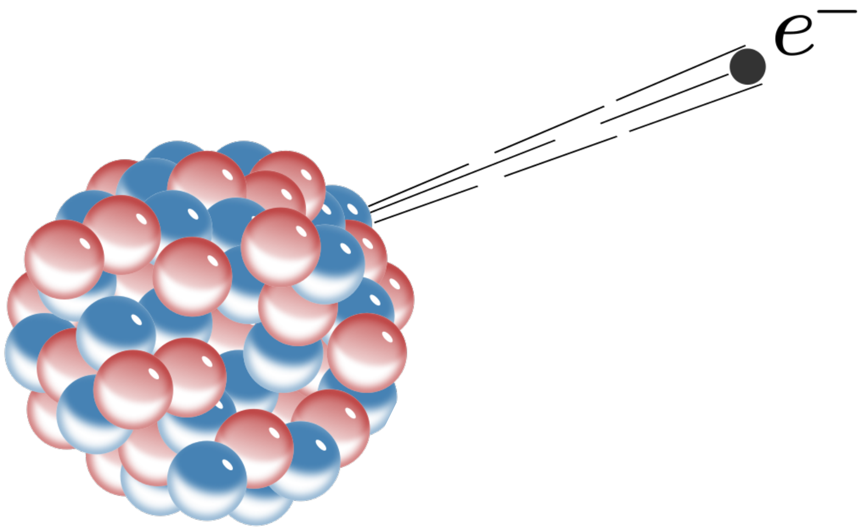
Expected signal

- Fixed energy
- $E_e \approx E_0$
- E_0 : **endpoint energy** = energy available from the decay (after creation of all decay products)
- Why does the electron get all the extra kinetic energy?

β-decay of radium



(Kinetic energy of electron)

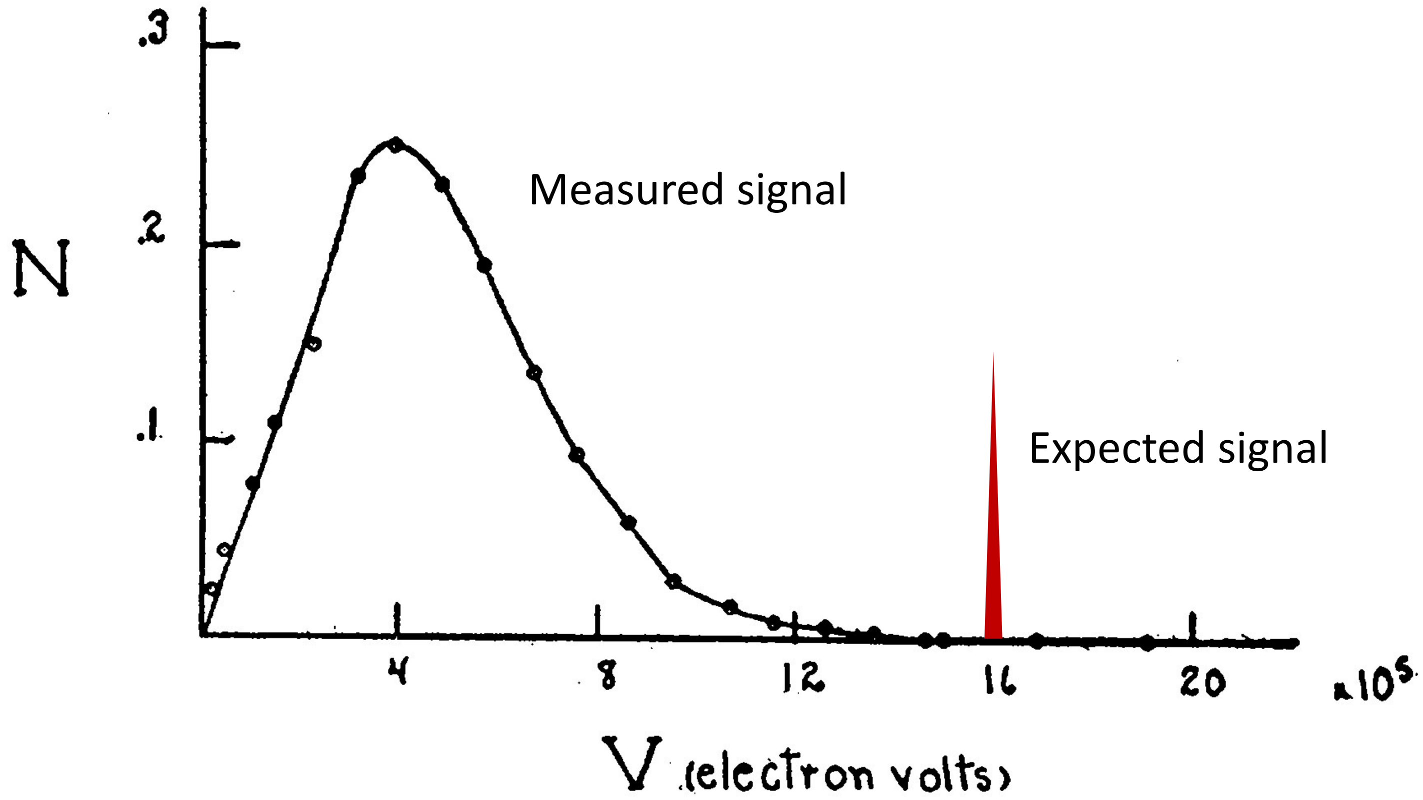


- Electron and daughter have the same momentum
- Kinetic energy:

$$E_{kin}^{Y} = \frac{p^2}{2m_Y} \text{ and } E_{kin}^{e} \gg E_{kin}^{Y}$$

- The kinetic energy of the heavy daughter nuclei is small

β-decay of radium: Measured signal

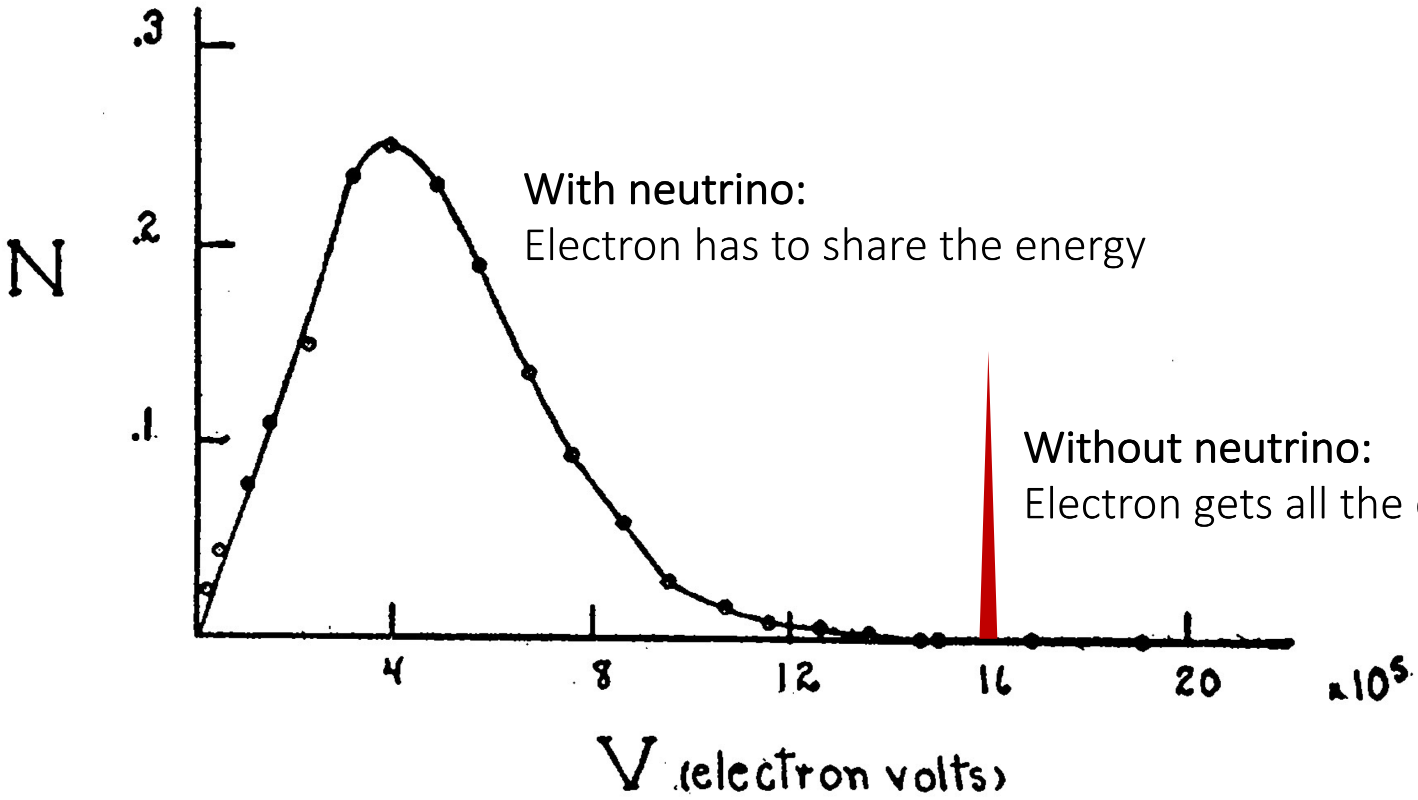


(Kinetic energy of electron)

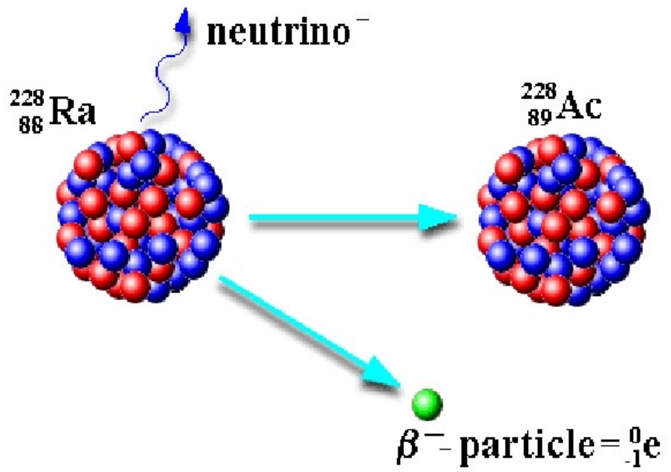
β-decay of radium: Interpretation

β⁻ - decay

$$\boxed{{}^{228}_{88}\mathrm{Ra} \rightarrow {}^{228}_{89}\mathrm{Ac} + e + \bar{\nu}_e}$$

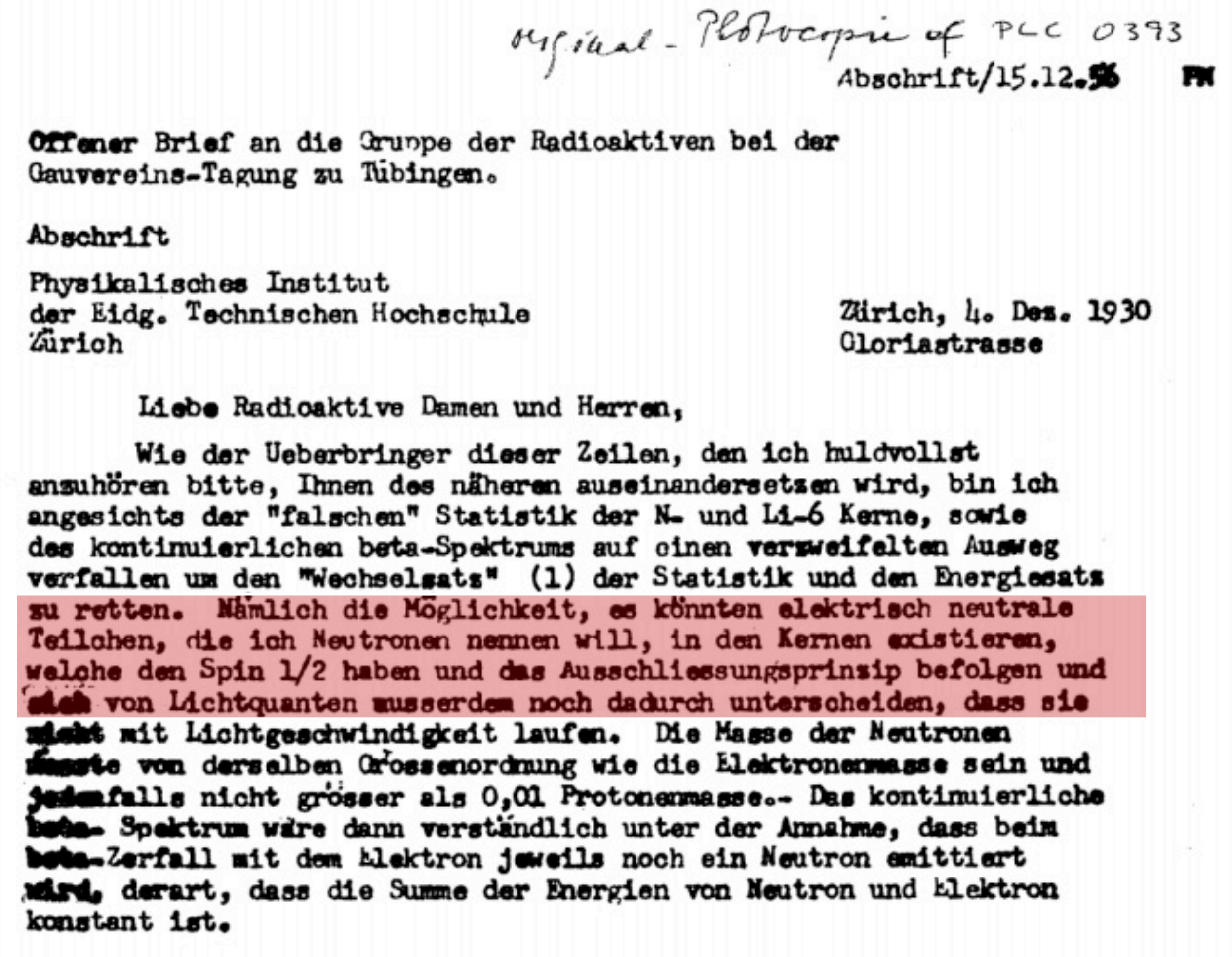


(Kinetic energy of electron)



The (electron) neutrino postulate

1930: Postulation of „Neutron“ by Pauli



Original - Photocopie of PLC 0393

Abschrift/15.12.56 FM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

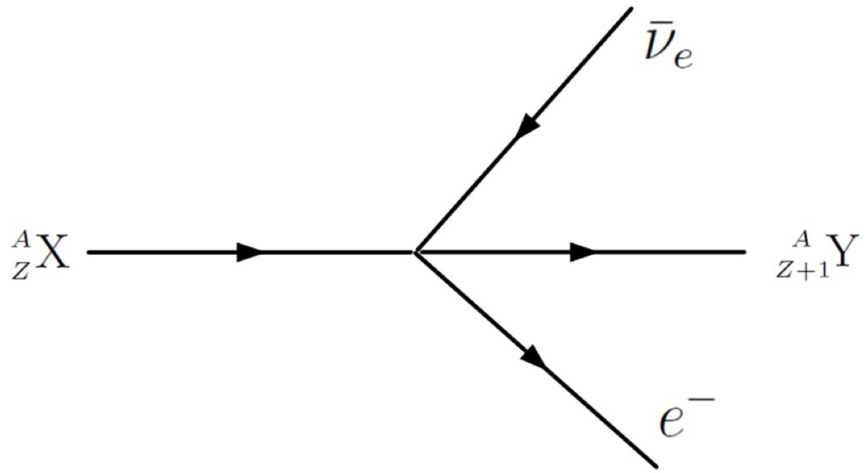
Zürich, 4. Dez. 1930
Gloriastrasse

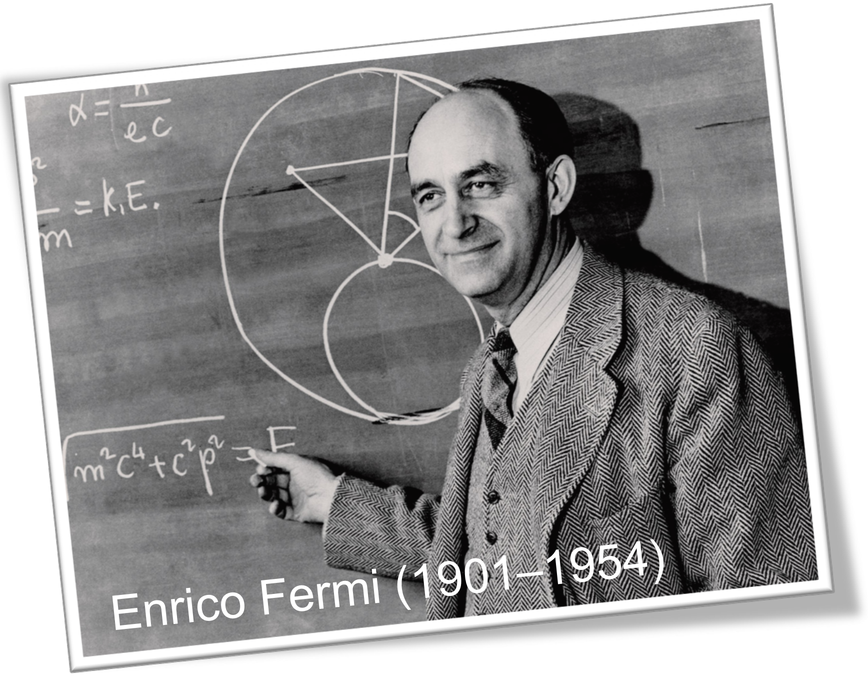
Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

1933: Fermi's Theory

- Description of β-decay by four-point interaction with coupling constant G_F (G_F = 1.2 10^{-5} GeV^{-2} for $c = \hbar = 1$)





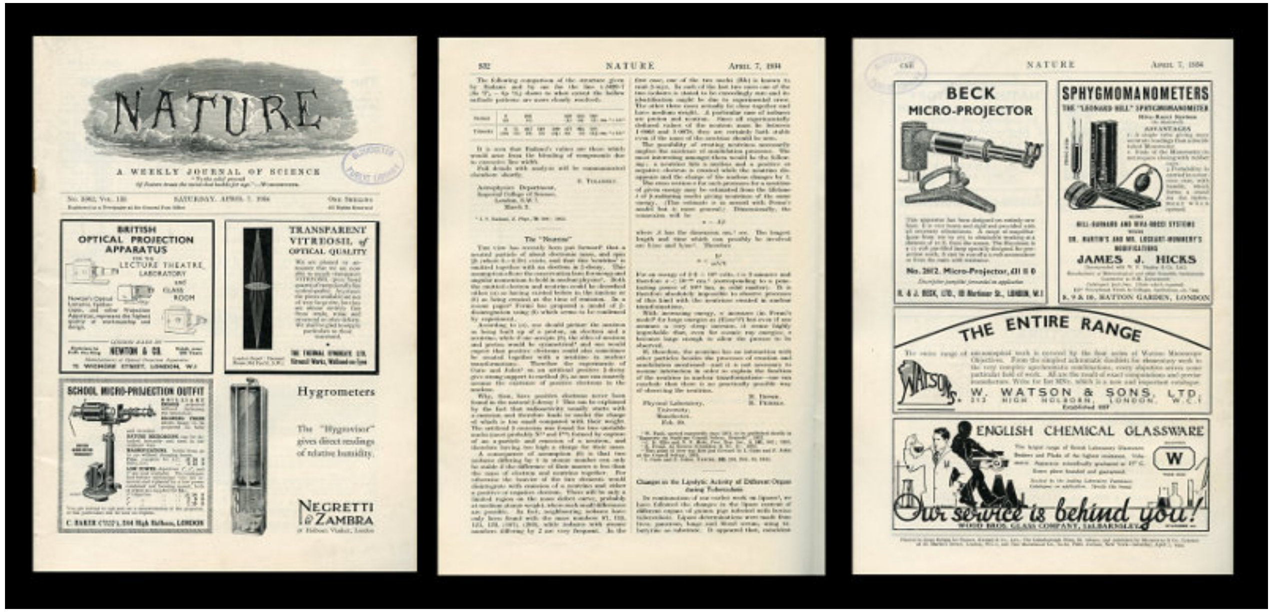
- Fermi's theory was the precursor of the theory of weak interaction

- Neutrinos have no electric charge, but still interact

1934: Notion of Cross Section

- Cross section refers to probability for an interaction to occur
- The cross section is noted σ. It has the unit af an area (cm^2)
- In nuclear physics, typical cross section are of the order of 10^{-24} cm^2 (1 barn)
- The number of neutrino you expect in a detector is proportional to:
  - the neutrino flux, f, in neutrino/sec/cm^2
  - the cross section of neutrino interaction σ, in cm^2
  - the number of target (e.g. protons, N_p) in your detector
- Usage: $\#\text{interactions/sec} \sim f \,.\, \sigma \,.\, N_p$

1934: Cross Section for Neutrino Interaction

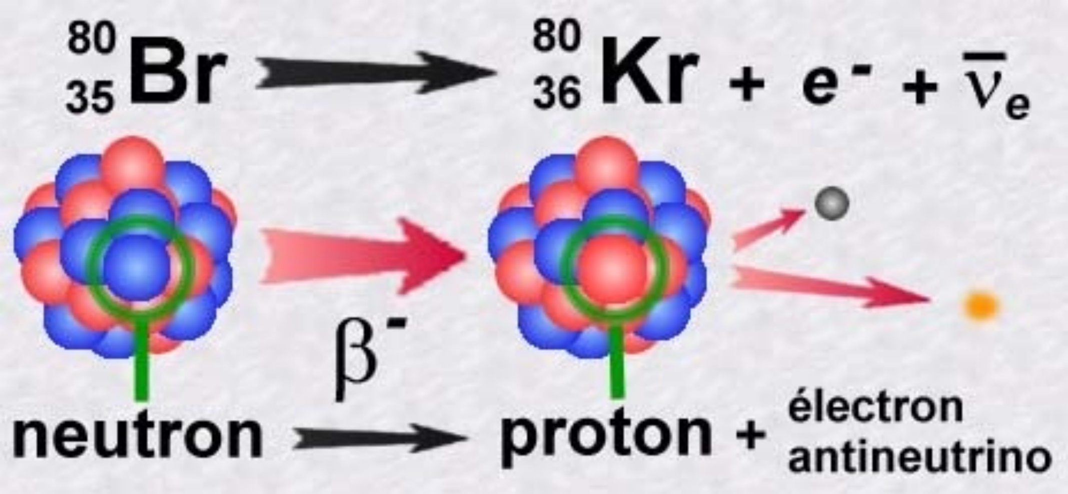


The Neutrino in Nature 133, No. 3362, April 7, 1934, p.532. H. A. Bethe, R. E. Peierls.

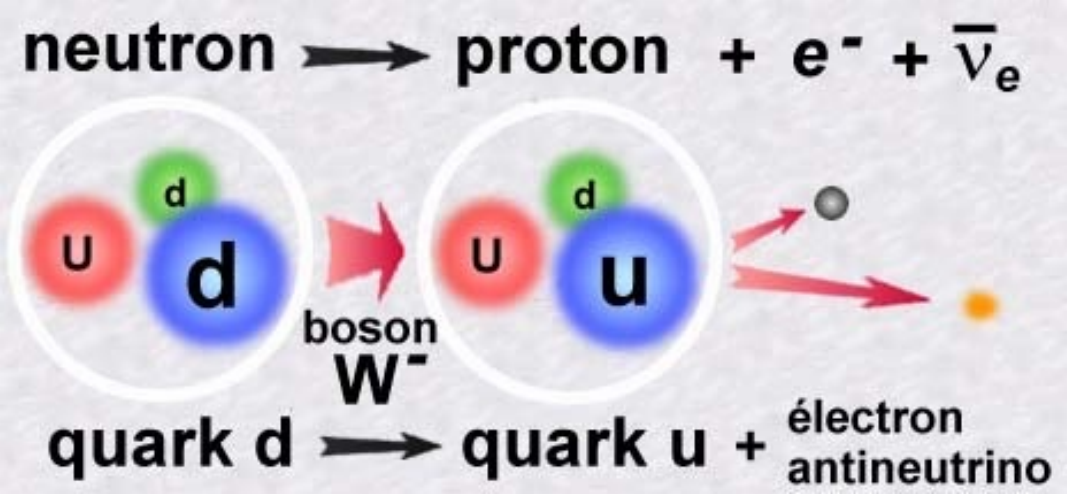
- Use Fermi theory
- Apply to radioactive β-decays (neutrino energy of a few MeV)
- Estimation: $\sigma < 10^{-44}\ cm^2$
- Penetration power of 10^{16} km in solid matter (1 l.y. = 10^{13} km) !
- « It is therefore absolutely impossible to observe processes of this kind with the neutrinos created in nuclear transformations »

Modern view on β-decays

Nuclear physics

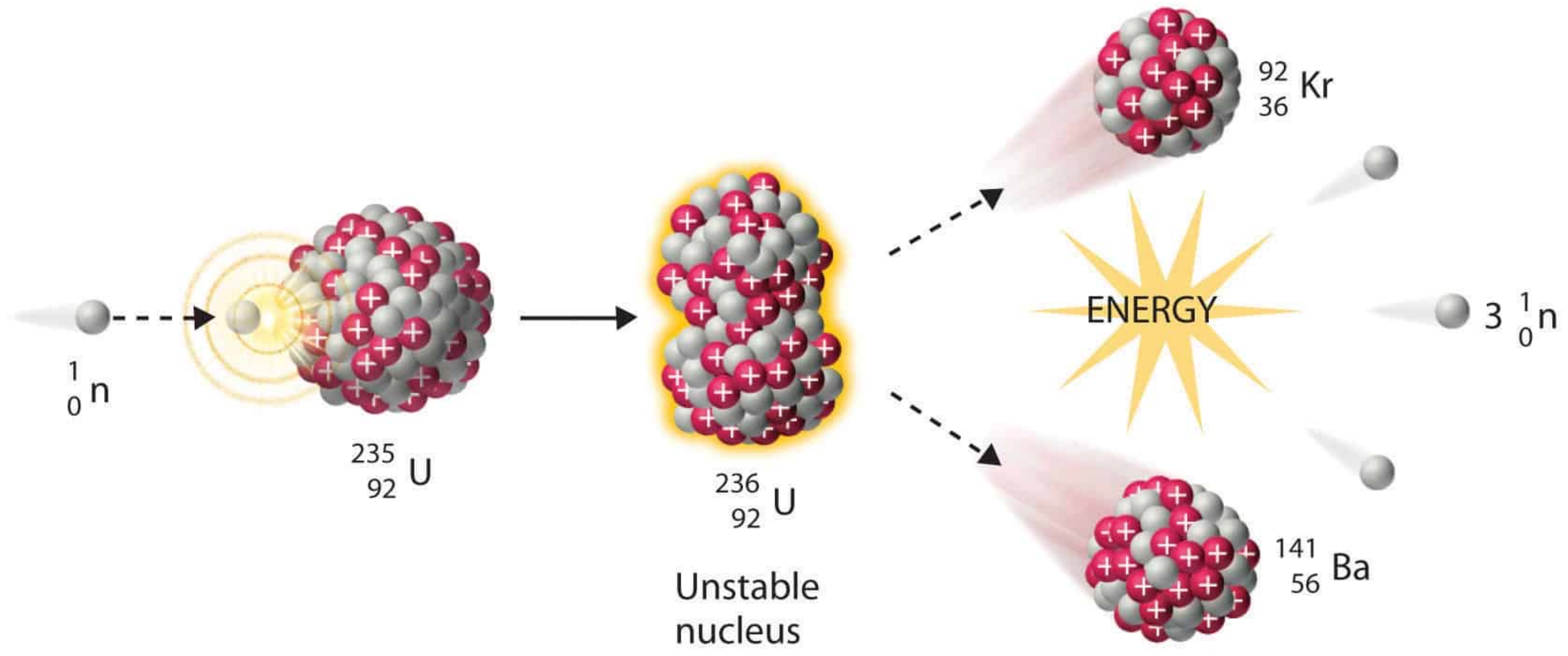


Particle physics



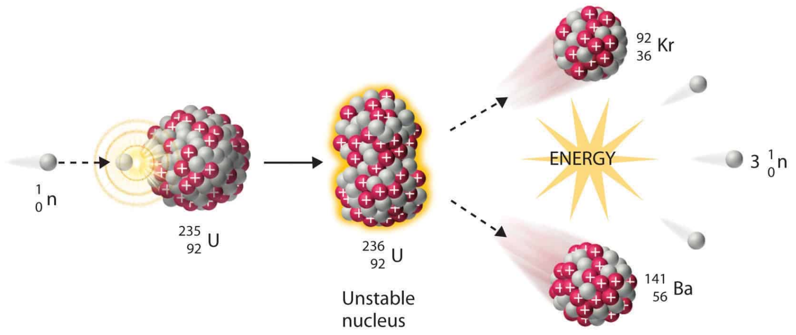
The first abundant neutrino source: nuclear fission

Nuclear Fission



Energy Released in Nuclear Fission

- Reaction



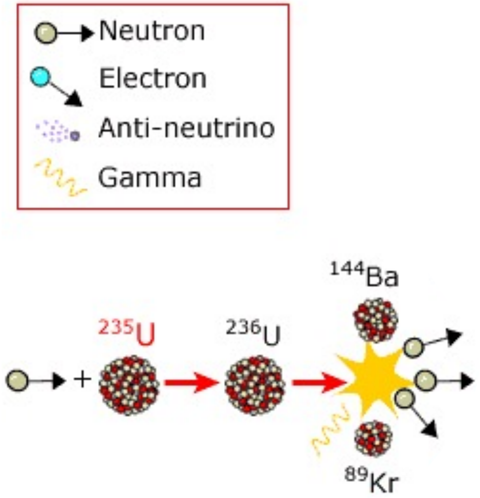
- $m(^{236}U)$ = 236.045 u
- $m(^{92}Kr)$ = 91.926 u
- $m(^{141}Ba)$ = 140.914 u
- $m(n)$ = 1.008 u

- $\Delta m = m(^{236}U) - m(^{92}Kr) - m(^{141}Ba) - 3\ m(n) = 0.179$ u $> 0 \rightarrow$ exothermic reaction

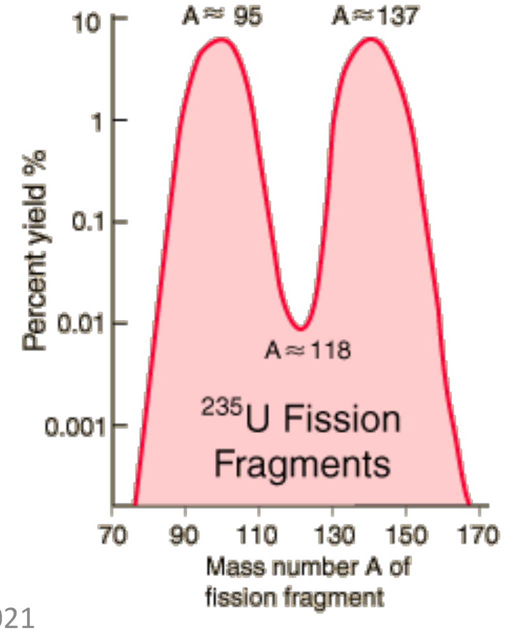
- Energy released = $\Delta m\ c^2 = 0.179 \,.\, 931.5\ MeV/c^2 \,.\, c^2 = 167\ MeV$

- Released in each fission! A lot more than energy released in chemical reactions !

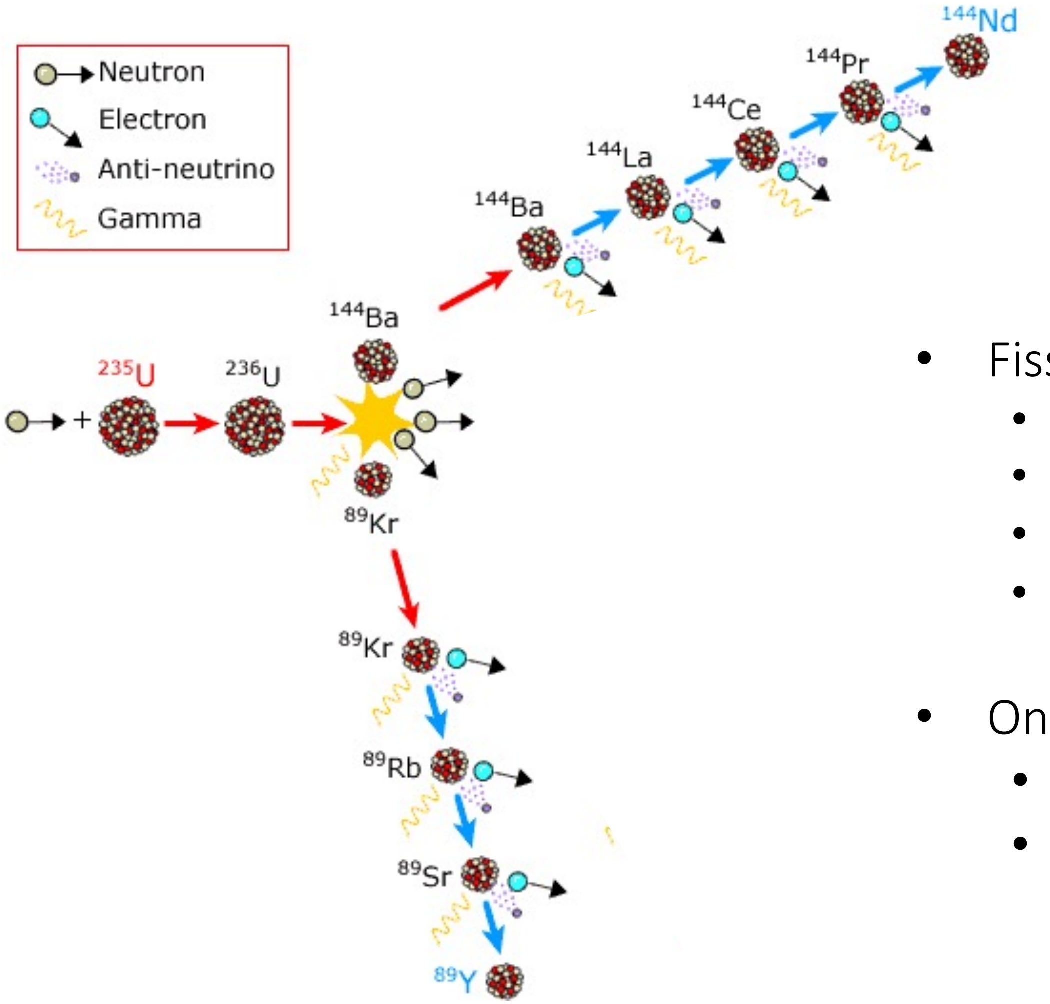
How many neutrinos are released / fission



- 2 fission fragments (or fission products)
- Here, ^{144}Ba and ^{89}Kr are the two fission products
- Many other pairs of fragment are possible



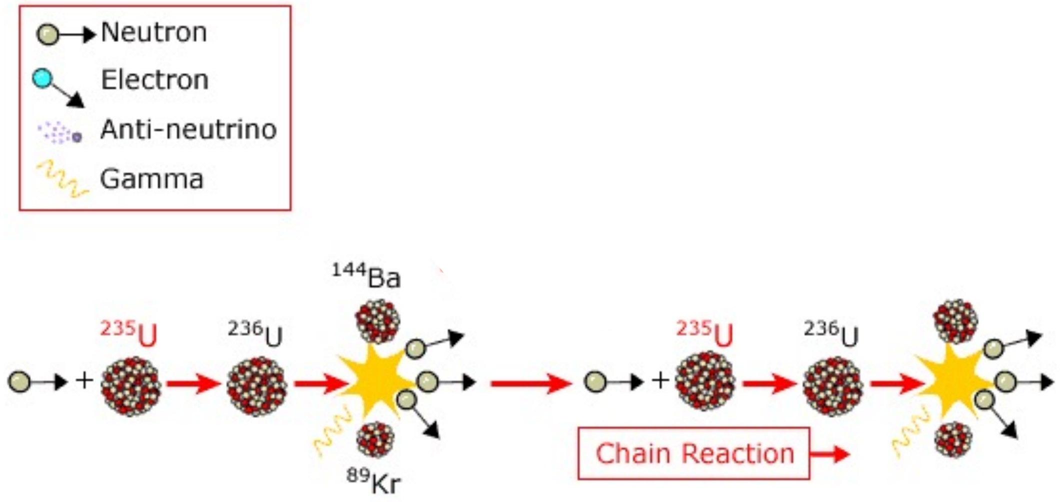
How many neutrinos are released / fission



- Fission fragments
  - Radioactive too!
  - Too large number of neutrons compared with protons
  - Get rid of their extra neutrons via β^--decays
  - Emission of electron antineutrinos

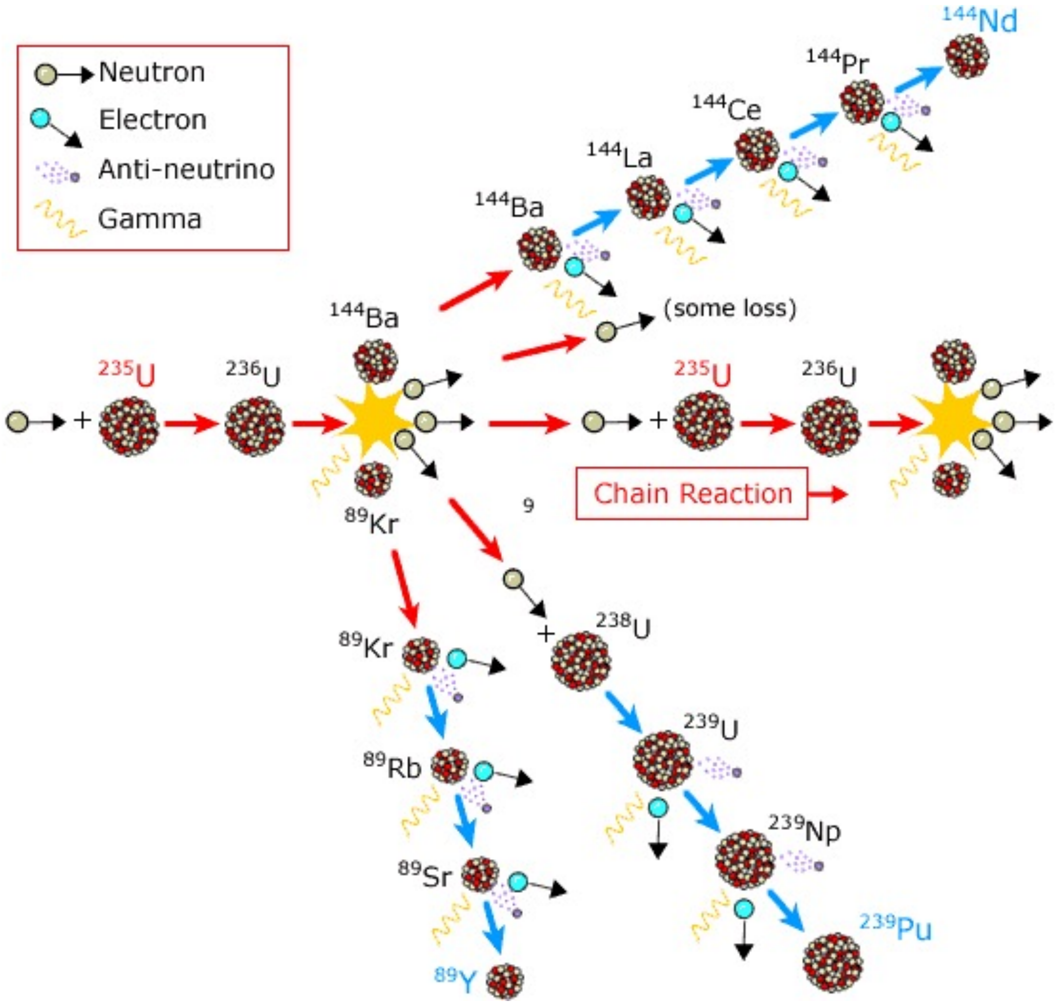
- On average, for each fission:
  - 200 MeV
  - <u>6 electron antineutrinos emitted</u>

Nuclear Fission: Chain Reaction

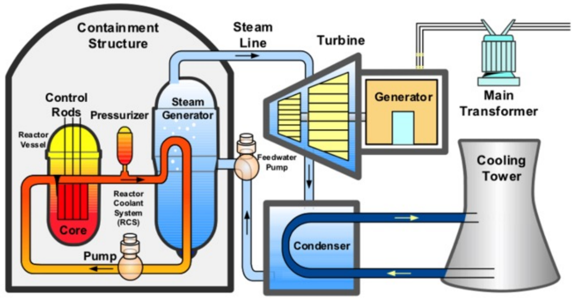


- Neutrons released in fission produce an additional fission in at least one further nucleus
- This next fission in turn produces neutrons, and the process repeats… it is a chain reaction.
- Process conceived by L. Slizard in 1933

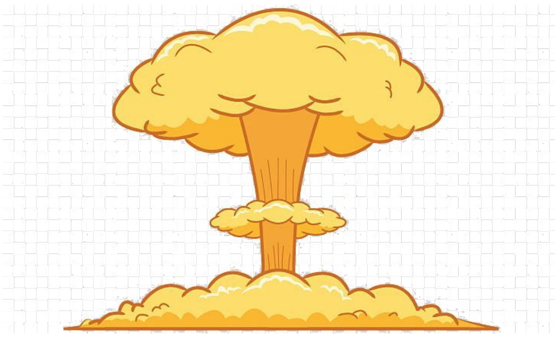
Nuclear Fission: Chain Reaction



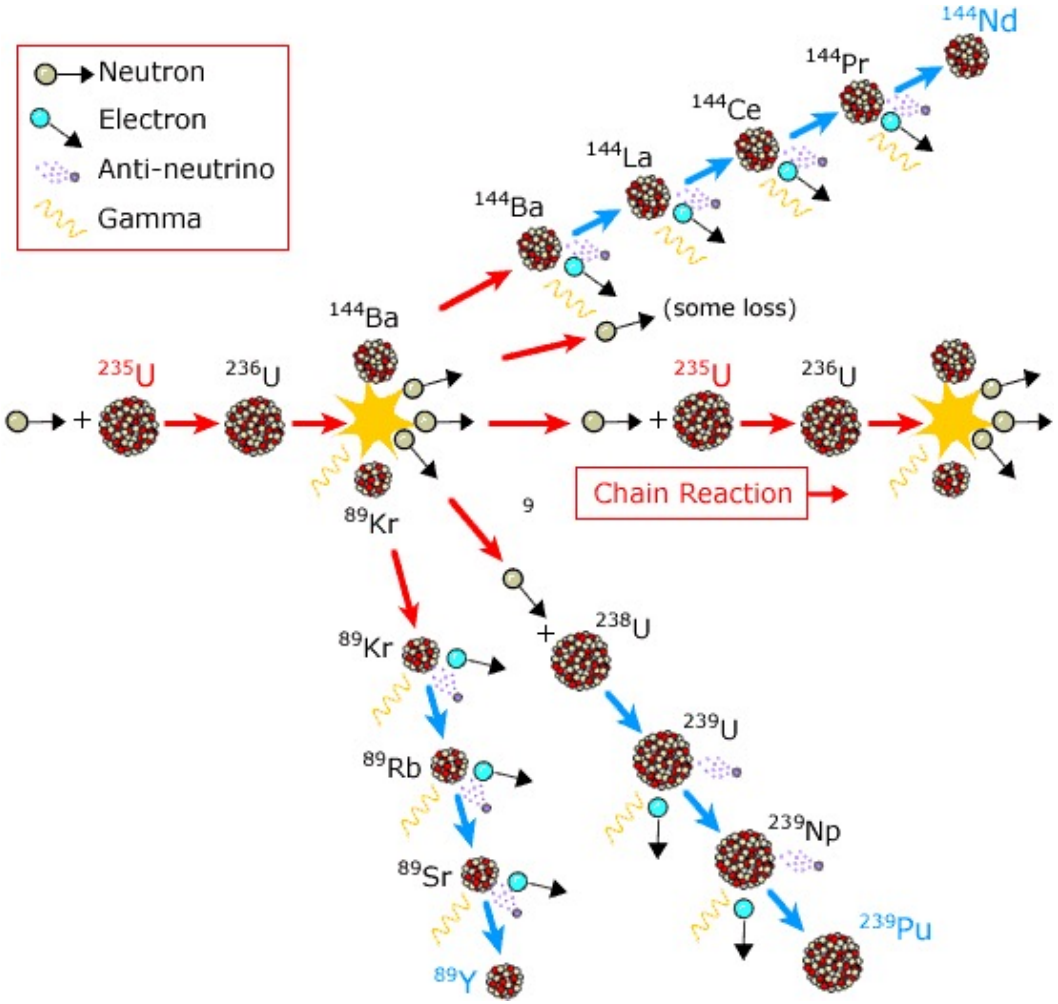
controlled



uncontrolled



First Attempt to detect neutrinos

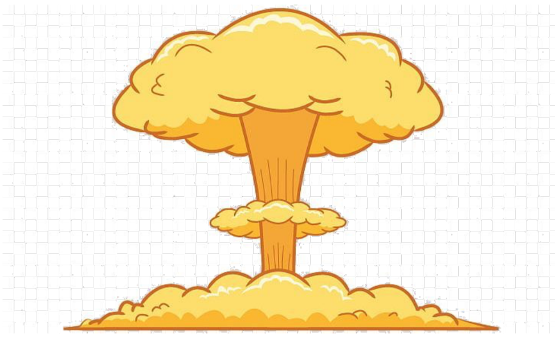


Nuclear explosion lasts for <10 sec

High neutrino flux : 10^{24} ν's within a few seconds

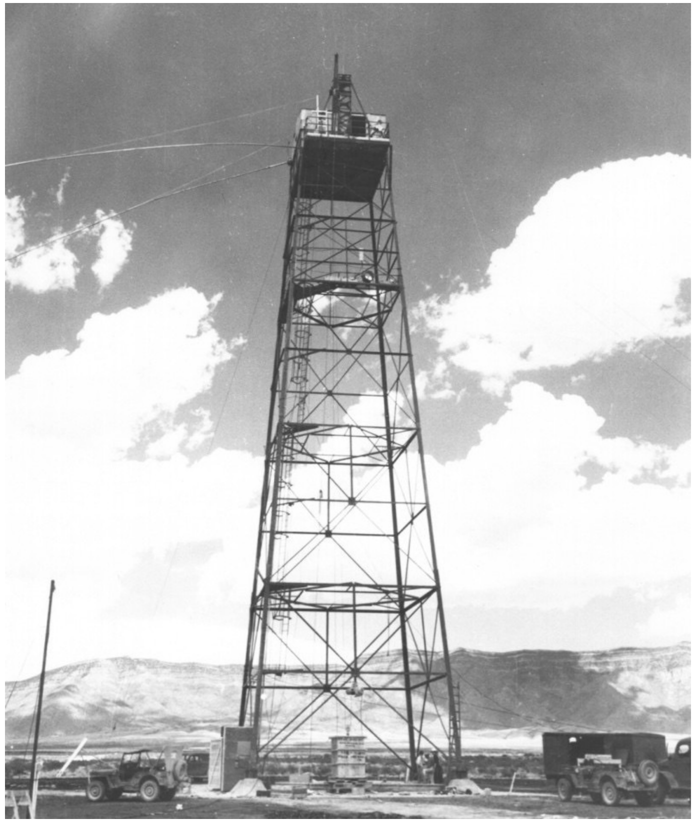
Any significant enhancement of the signal in this time window could be related to neutrinos

uncontrolled



The Manhattan Project*: Trinity Test, July 16, 1945

L. Groves
R. Oppenheimer

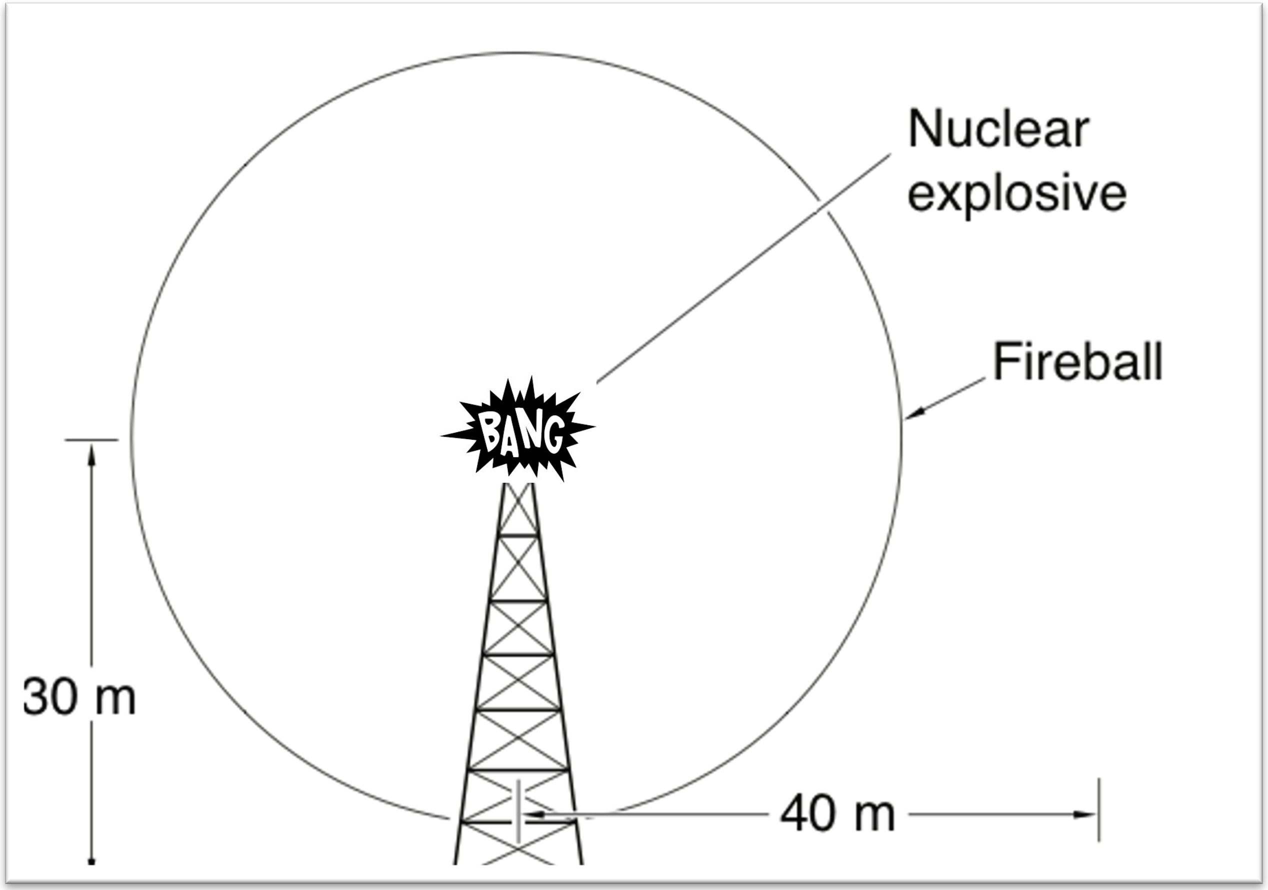


The 30-metre shot tower
constructed for the test

Original picture of the explosion

* *book: The Making of the Atomic Bomb, Richard Rhodes, 1987*

First proposal: neutrinos from a 20 kt nuclear test



- Use intense nuclear burst in an experi-ment designed to detect the neutrino.
- Advantages:
    - an intense neutrino source:
    - very short lived measurement: background events mimicking neutrino-induced events are minimized.
- F. Reines's proposal approved in 1951

First proposal: how many neutrinos are expected

- Energy release during the explosion: 20 kT TNT
  - 1 ton TNT = 4.18 10^{9} Joules

- Energy is generated via nuclear fission of ^{239}Pu: each fission releases 200 MeV
  - 200 MeV / fission = 200 x 10^{6} x 1.6 10^{-19} Joules / fission
  - Total number of fissions = 20 000 x 4.18 10^{9} / (200 x 10^{6} x 1.6 10^{-19}) = 2.6 10^{24} fissions

- On average, for each fission, 6 neutrinos are emitted

- Eventually, 6 x 2.6 10^{24} = 1.5 10^{25} antineutrinos are emitted during the explosion

- 30% are emitted within a 10 sec window
  - 5 10^{24} antineutrinos / 10 sec

First proposal: detection process envisaged

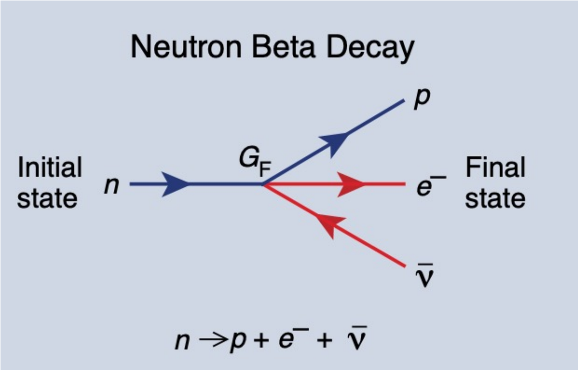
- Fermi's theory of the weak force predicts that the neutrino can induce an inversion of beta decay

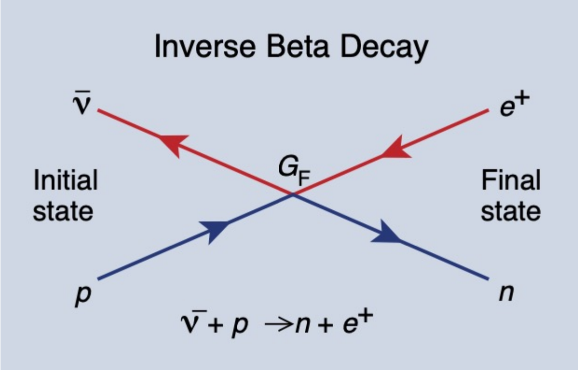
- Electron antineutrinos (the antiparticle of the neutrino) will occasionally interact with a nucleus through the weak force and will induce the transformation of a proton into a neutron.

- If the nucleus happens to be that of hydrogen (a single proton), then the interaction produces a neutron and a positron:

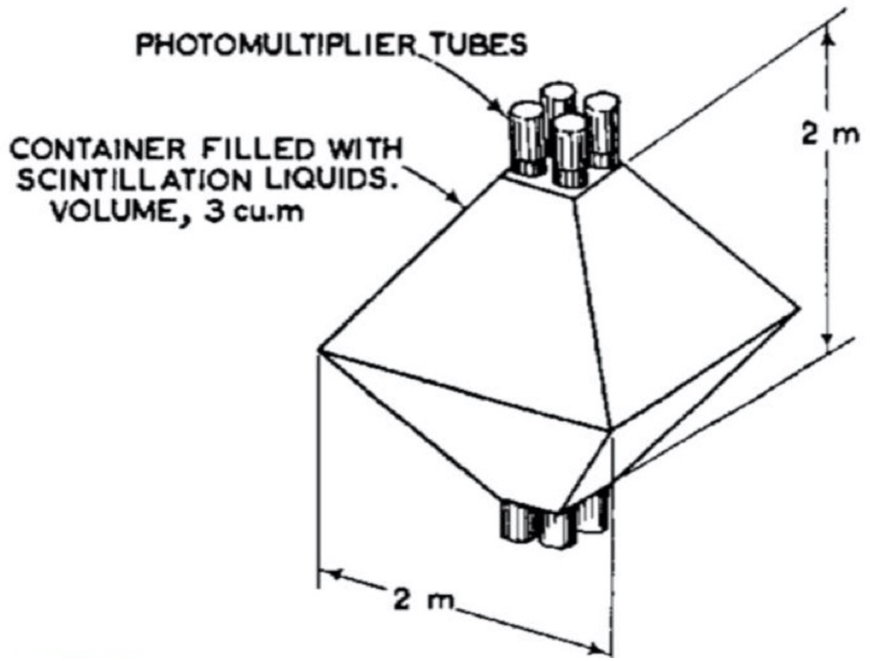
- Challenge: design a very large detector containing a sufficient number of target protons that would stop a few neutrinos.

- <u>Original plan: detect the positron emitted in inverse beta decay</u>



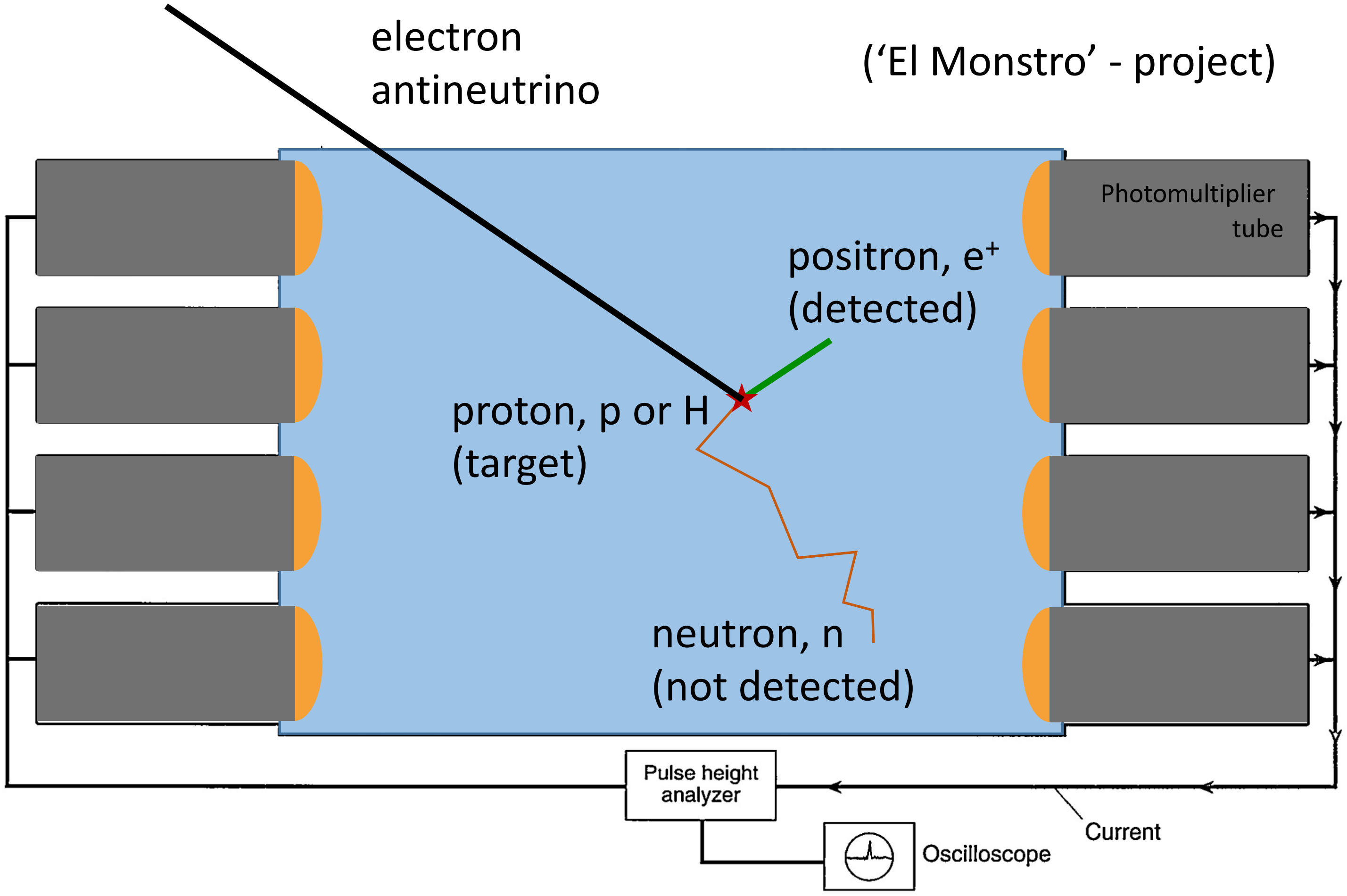


First proposal: the detector



('El Monstro' - 1952)

('El Monstro' - project)

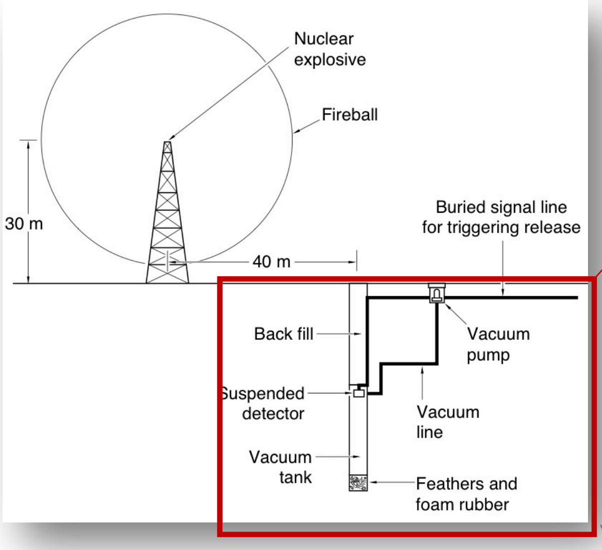


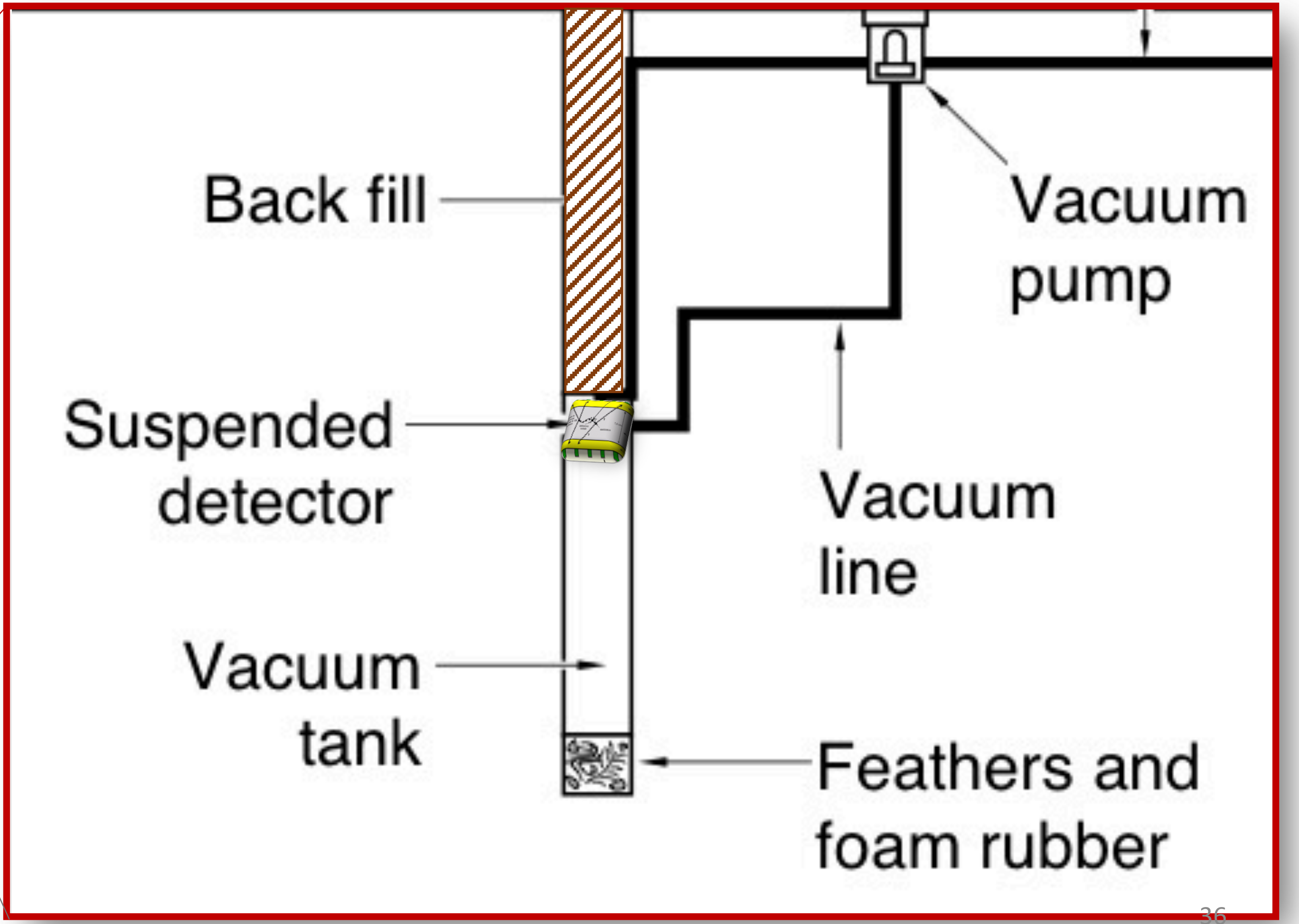
- Detect only the positron scintillation signal
- Drawback: very sensitive to background

First proposal: how large the detector shall be?

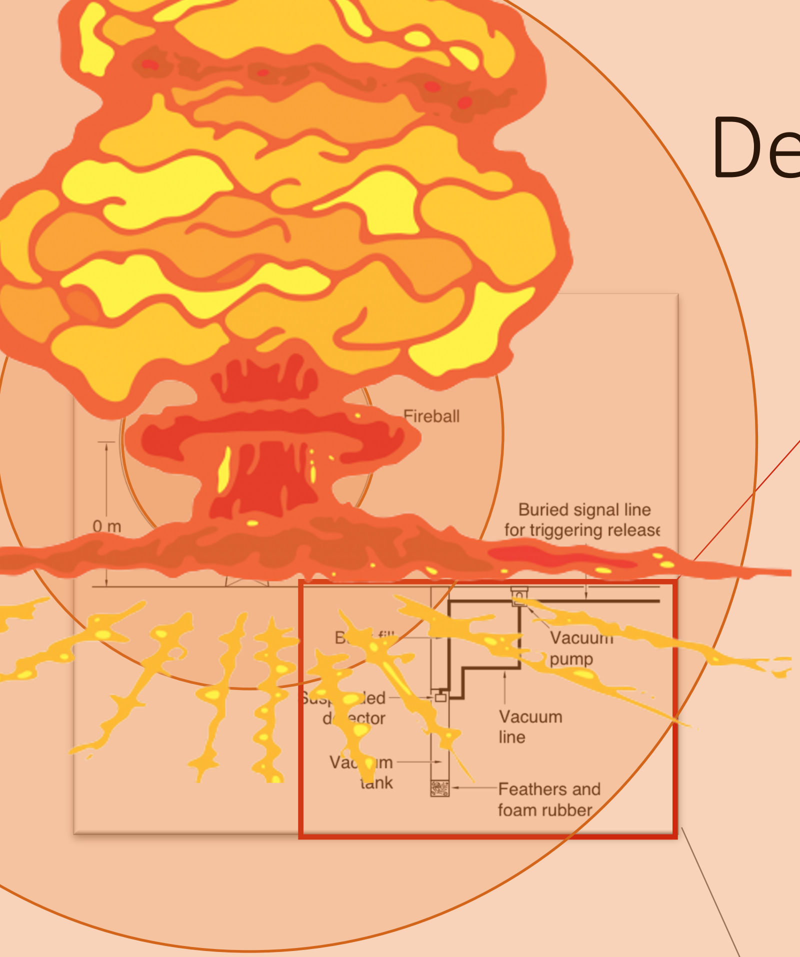
- Reaction considered:
- Technology: liquid scintillator to detect fluorescence flashes from the induced e+
- Probability of interaction (cross section – Fermi theory)
  - Theoretical prediction: $\sigma = 10^{-44}$ cm^2
  - Number of event per target-H: 10^{15} / cm^2 x 10^{-44} cm^2 /H = 10^{-29} interaction/H
  - 1 000 kg of oil : 6 10^{28} H / m^3 → <u>about 1 interaction per m^3</u>
- Several tons of active liquid scintillator (LS) volume would be requested
  - In 1950, the largest detector contained about 1 liter of LS, however…
  - Seemed to be the R&D challenge for F. Reines team!

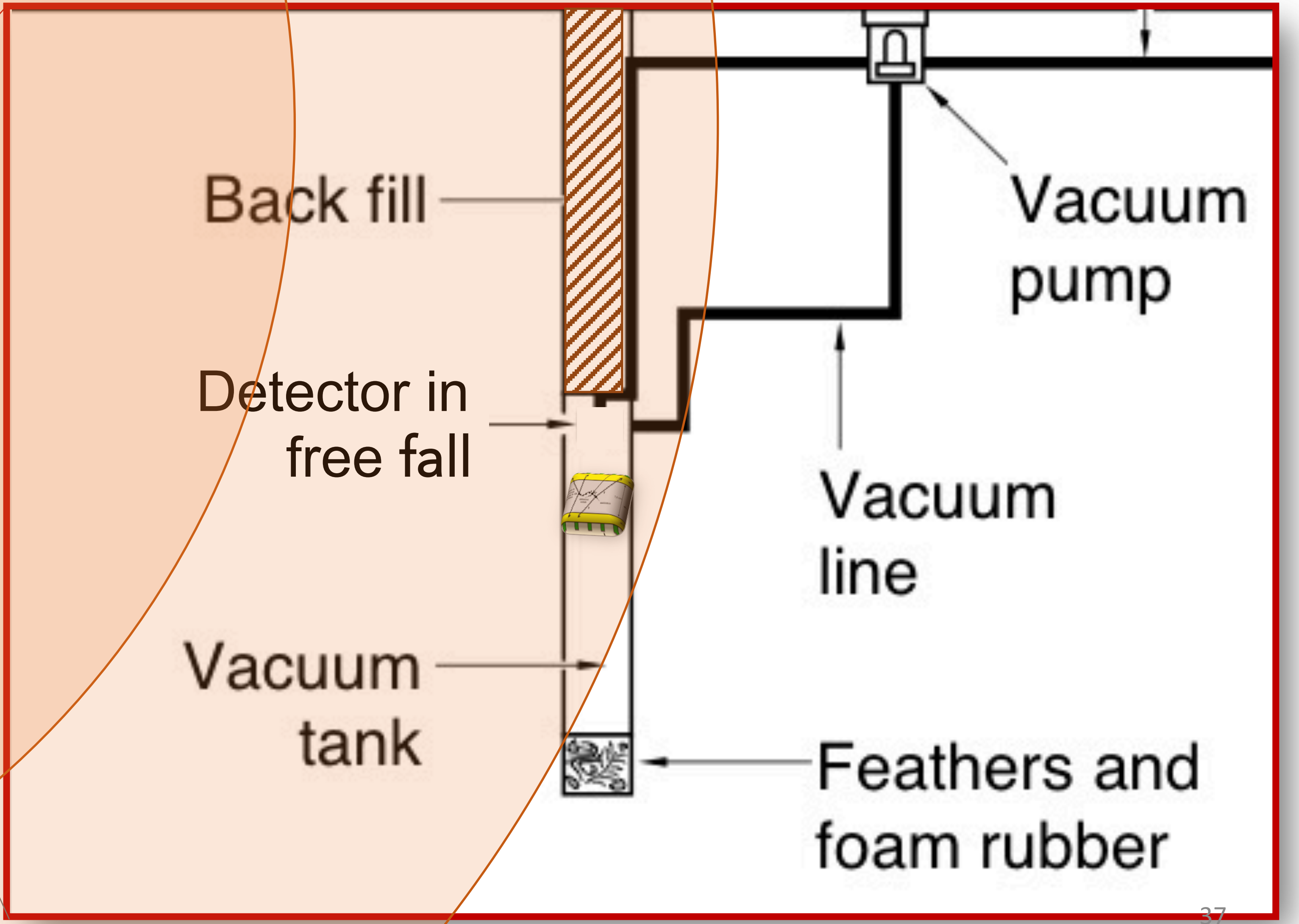
before blast



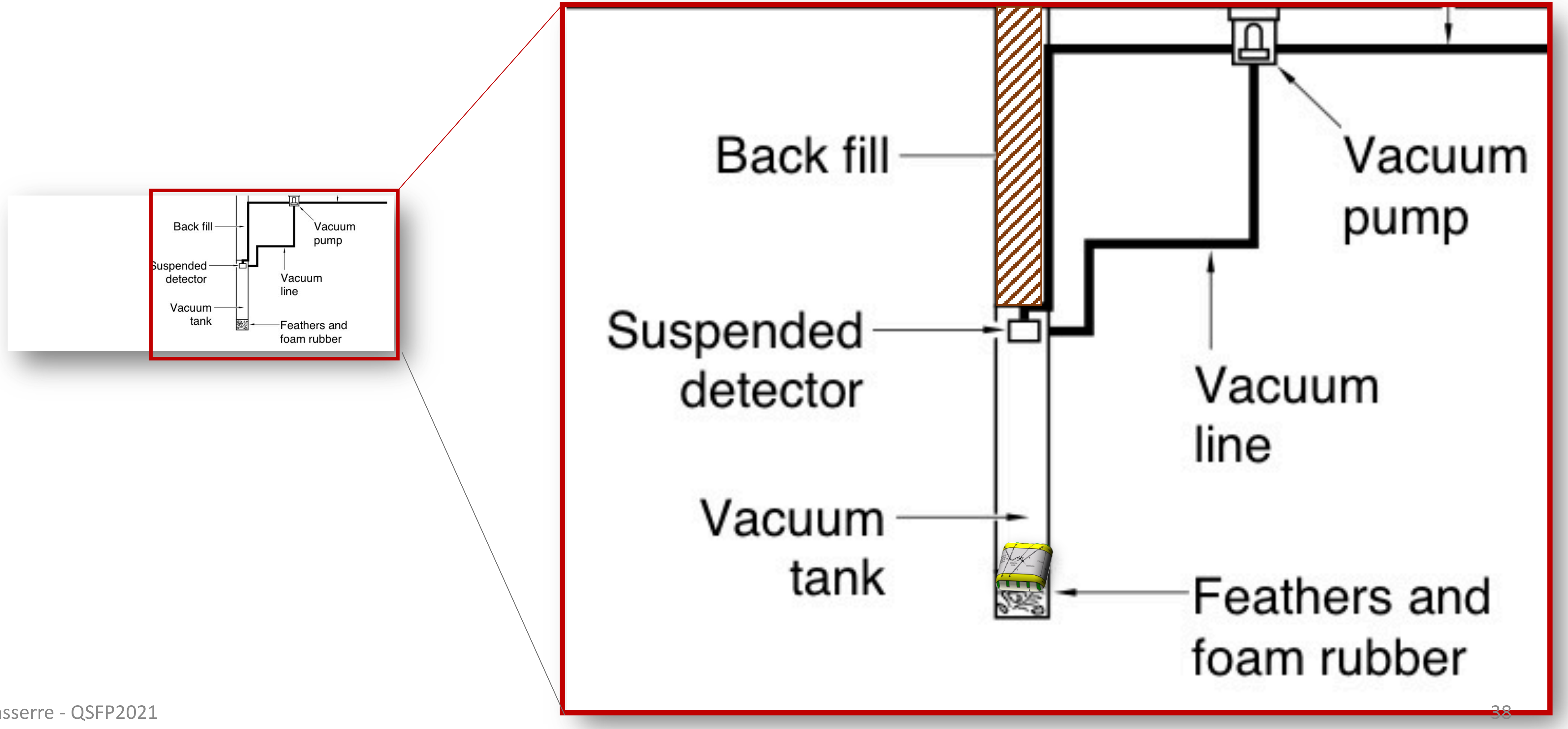


Detector in free fall during the blast (<3 sec)

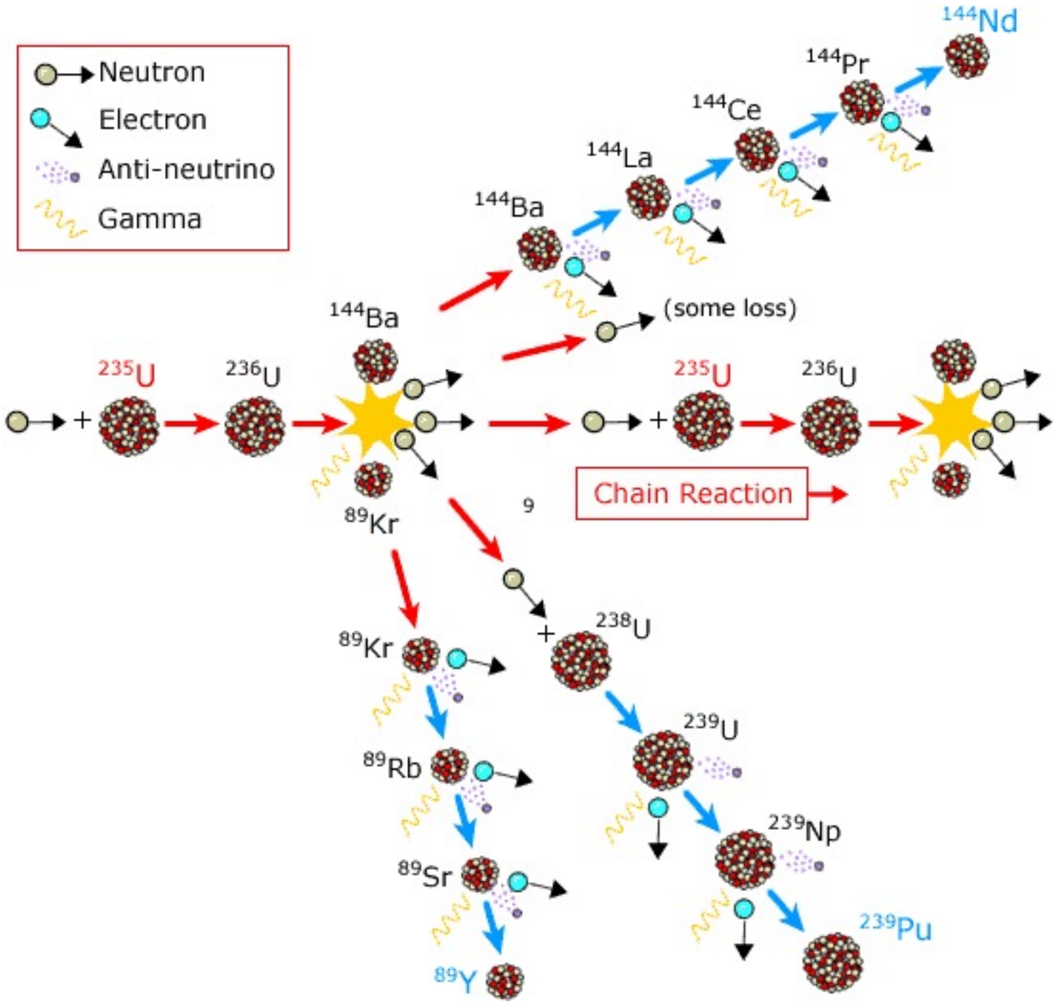




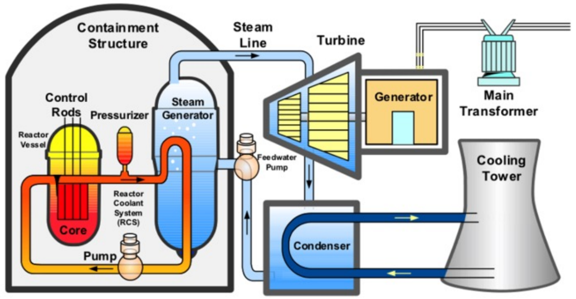
Recover the detector a few days after blast



Second attempt to detect neutrinos



controlled

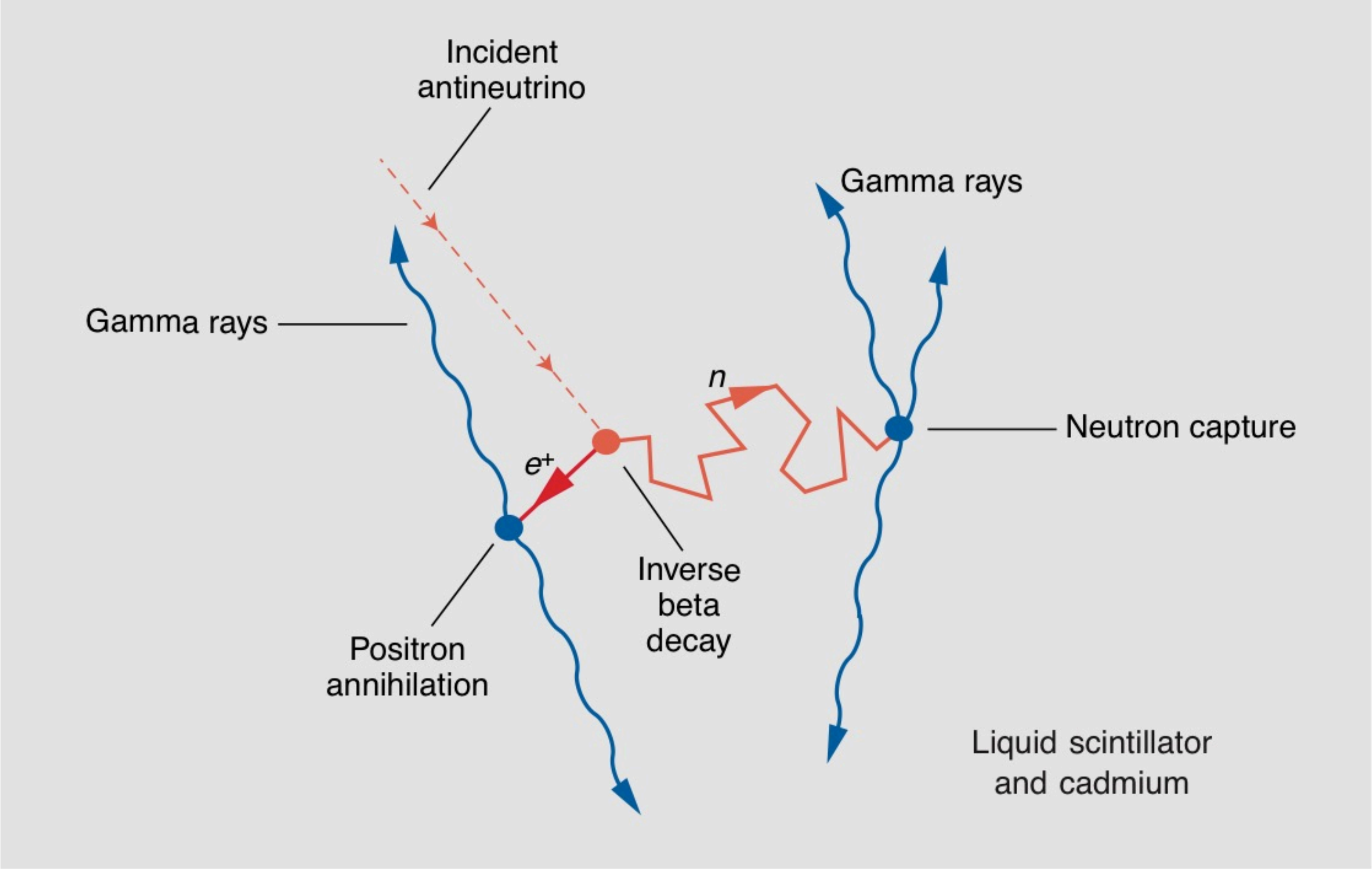


Continuous neutrino emission
(reactor ON / OFF periods)

Neutrino flux : 10^{13} $\nu/cm^2/s$
(100 smaller that the nuclear explosion)

Challenge: reduce background !

Breakthrough: detecting (e^+,n) in time coincidence



- After the IBD reaction (e+,n) are produced simultaneously
- Step 1)
  e^+ detection
- Step 2)
  neutron detection
- Step 3)
  check that time-difference is less than a few µs

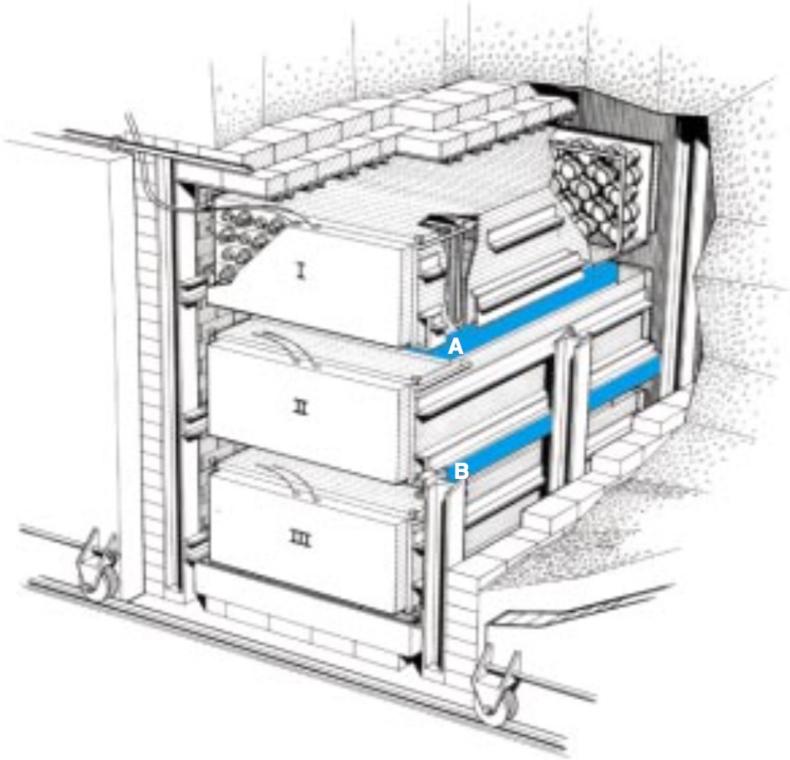
Electron Neutrino Discovery (Project Poltergeist)

Herr Auge (Mr Eye) at Hanford site

- ➢ e^+ detection only

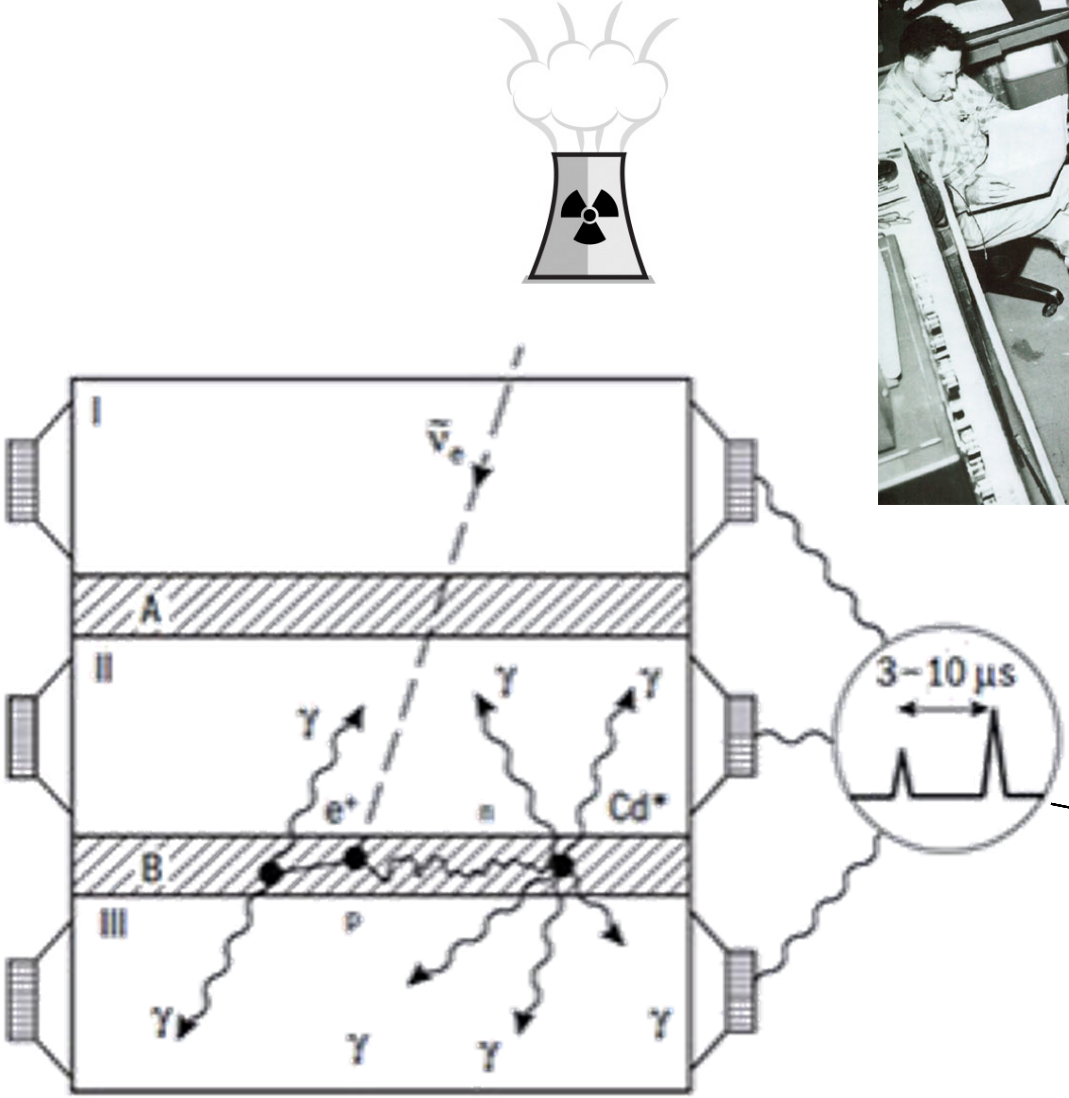
New design at Savannah river site

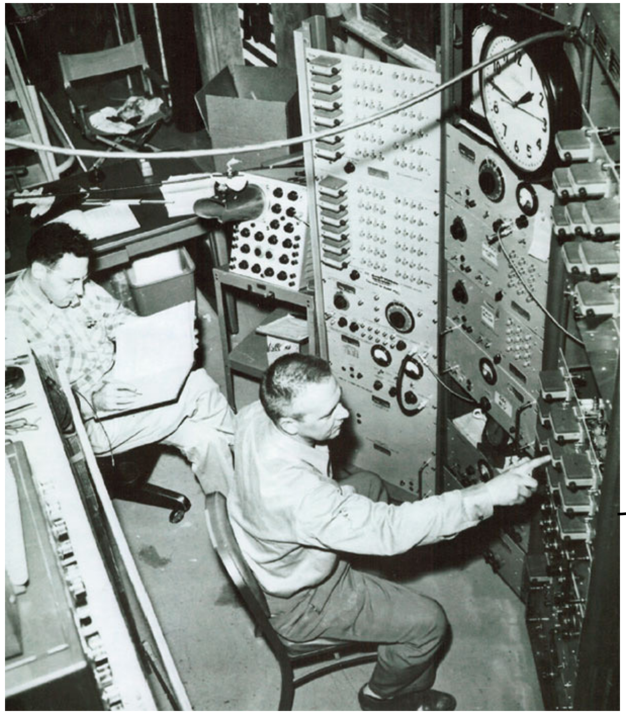
- ➢ (e^+,n) detection in coincidence



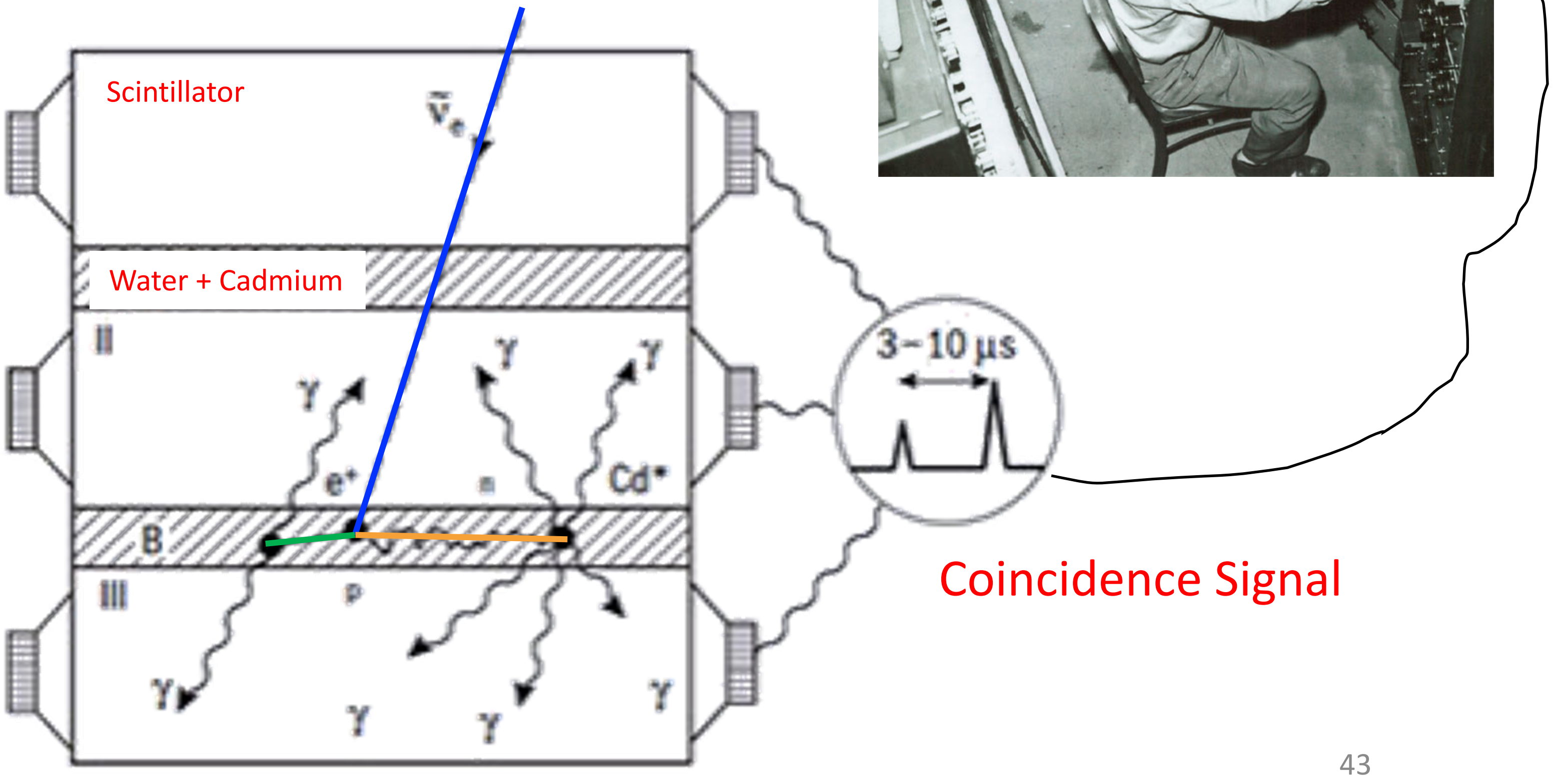
Electron Neutrino Discovery

- Use the Savannah River (USA) reactor Manhattan Project
- 5 x 10^{13} electron anti-neutrinos /cm^2/s from reactor
- Electron-anti neutrino interacts with proton in water, producing a positron and neutron
- Detector placed 11 m from reactor and 12 m underground
- 200 liters of water with about 40 kg of dissolved $CdCl_2$

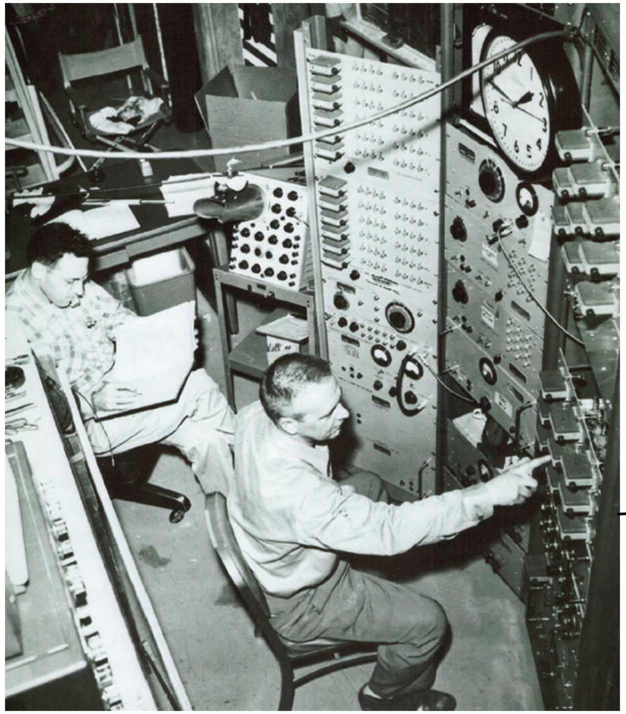




Electron Neutrino Discovery



Coincidence Signal

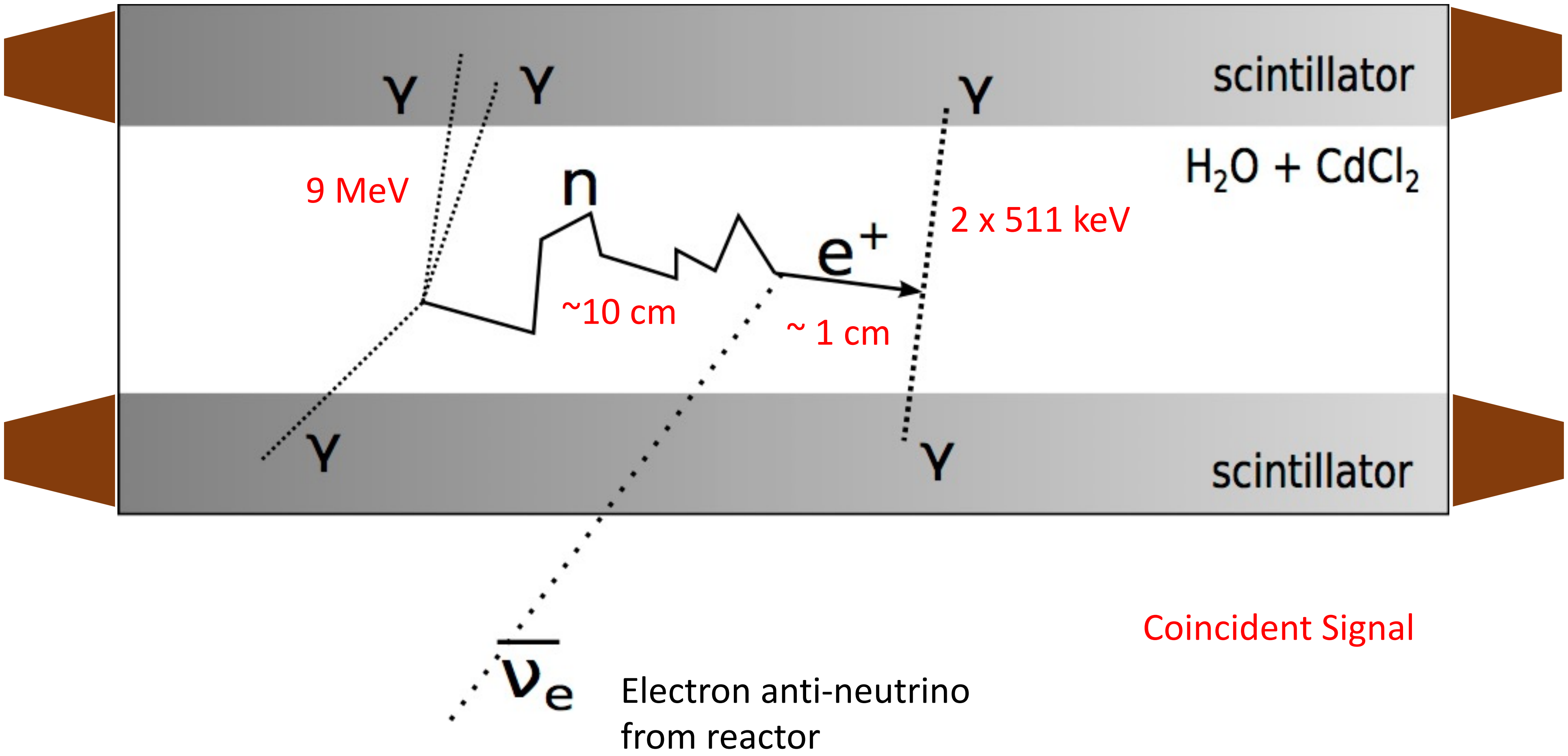


- Positron annihilates with electron
  → gamma ray's
- Neutron thermalizes and is captured on Cadmium
  → gamma ray's
- Gamma's are detected with scintillator in time-coincidence

Electron Neutrino Discovery

Inverse β - decay

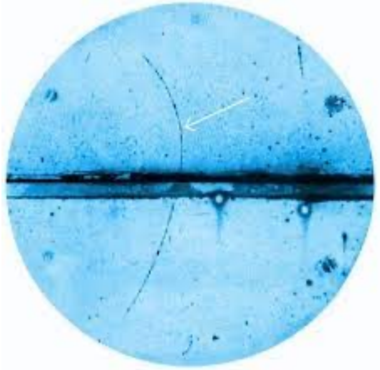
$$\boxed{\bar{\nu}_e + p \rightarrow n + e^+}$$



Coincident Signal

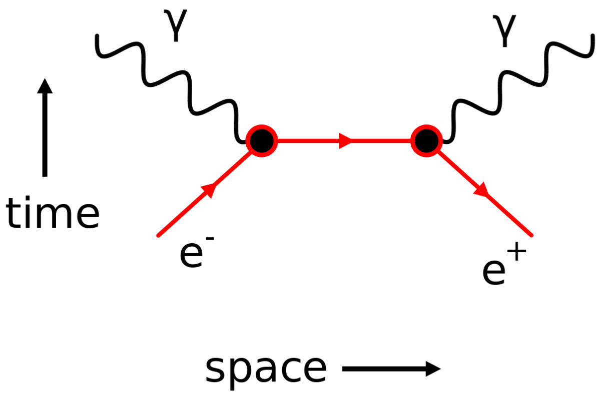
Positron interaction with matter

- **Positron:**
  - m_e = 0.511 MeV, electric charge = +1



- **1) Kinetic energy loss: $dE/dx = (dE/dx)_{scattering} + (dE/dx)_{rad}$**
  - $(dE/dx)_{scattering}$: Given by the Bethe-Bloch dE/dx theory
  - $(dE/dx)_{rad}$: Bremsstrahlung (few % for MeV e^+)
  - Mean free path is on the mm to cm scale

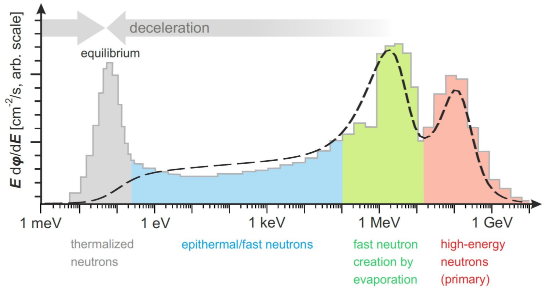
- **2) Annihilates:** $e^+ + e^- \rightarrow \gamma + \gamma$
  - Gamma energy : 2 x 511 keV → E_g=1.022 MeV
  - Back-to-back emission (momentum conservation)
  - 511 keV attenuation length in oil is about 10 cm



Neutron interaction with matter

- **Neutron:**
  - m_n = 938.27 MeV, no electric charge
  - Must path close to nucleus to interact (10^{-11} cm) → penetrating particle

- **Energy & terminology**
  - *Fast* n: E > 100 keV - ten's of MeV
  - *Slow* n: E = 0.025 eV - 1 eV
  - *Epithermal* n: E = 1 eV - 100 keV
  - *Thermal* n: E = 0.025 eV



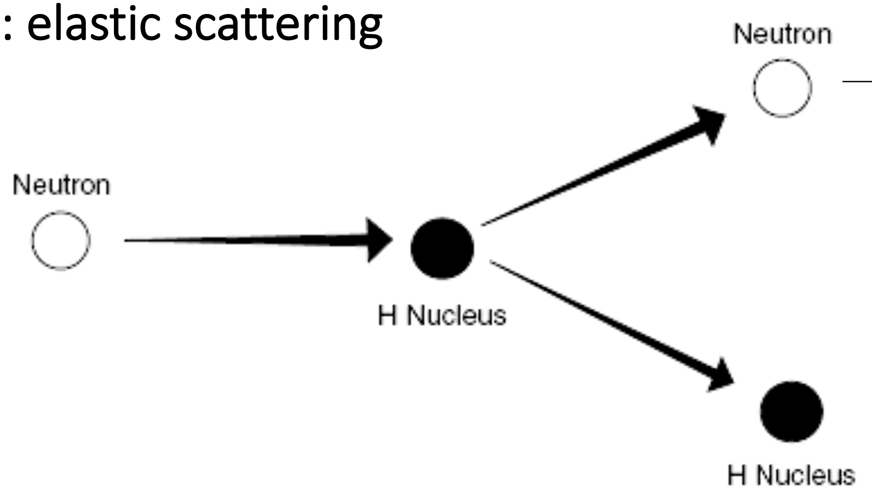
- **Interactions**
  - Elastic scattering (main) : A + n → A + n'
  - Inelastic scattering (main) : A + n → A* + n ; A + n → B + n' + n''
  - Radiative neutron capture : n + (Z,A) → (Z,A+1) + γ
  - Others : (n,p), (n,d), (n,α), …

- **Mean free path length**
  - $1/\lambda$ (cm^{-1}) = n (cm^{-3}) . σ (cm^2), with n the density of atoms in matter
  - collimated n beam : $N=N_0 \exp(-x/\lambda)$

Step 1) Neutron Moderation (elastic scattering)

- **Moderation:**
  - Fast neutrons scatter loosing their energy until thermal equilibrium
  - Then neutrons diffuse before being captured

- **Main process: elastic scattering**



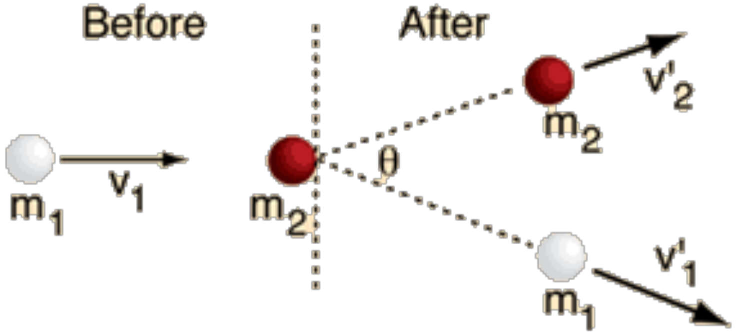
Kinetic Energy of the scattered neutron

$$\frac{(A-1)^2}{(A+1)^2} E_{n-1} < E_n < E_{n-1}$$

Number of scattering

- **Implication for neutron shielding**
  - The lighter the target nucleus, the more recoil energy is absorbed by the neutron
  - Low-Z material are being used to slow down neutrons
    - Water, paraffin (CH_2), oil

Step 1) Neutron Moderation (elastic scattering)



before the collision.

General relationships:

a. Conservation of momentum: $m_1\vec{v}_1 = m_1\vec{v}'_1 + m_2\vec{v}'_2$

b. Conservation of kinetic energy: $\frac{1}{2}m_1v_1^2 = \frac{1}{2}m_1v'^2_1 + \frac{1}{2}m_2v'^2_2$
(elastic collision assumption)

c. For head-on collisions: $v'_1 = \frac{(m_1 - m_2)}{(m_1 + m_2)}v_1$; $v'_2 = \frac{2m_1}{(m_1 + m_2)}v_1$

$m_1 = m_2$

$v_1' = 0$ → slow

$v_2' = v_1$

$m_1 \ll m_2$

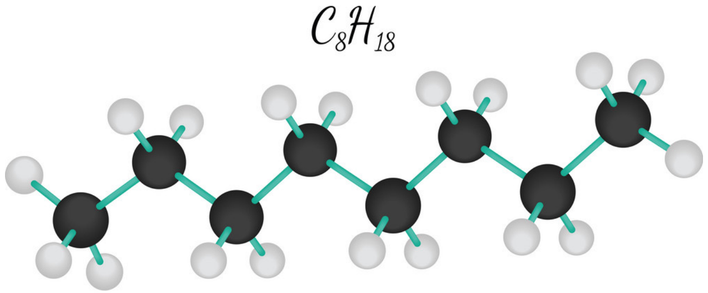
$v_1' = v_1$ → fast

$v_2' = 2\,\frac{m_1}{m_2}\,v_1'$

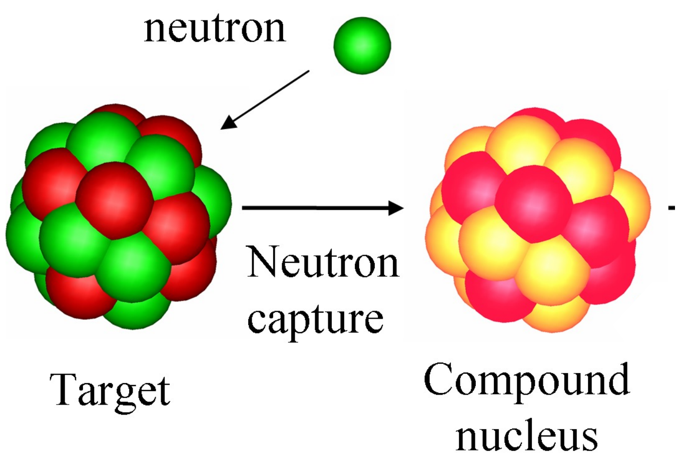
Step 2) Neutron Capture

- Inverse β-decay: neutrons with kinetic energy of about 10-50 keV are produced

- Oil or water acts as a moderator
  - neutron collides with hydrogen nuclei
  - ½ of its energy lost in each collision
  - It takes about 20 collisions to reach the thermalization

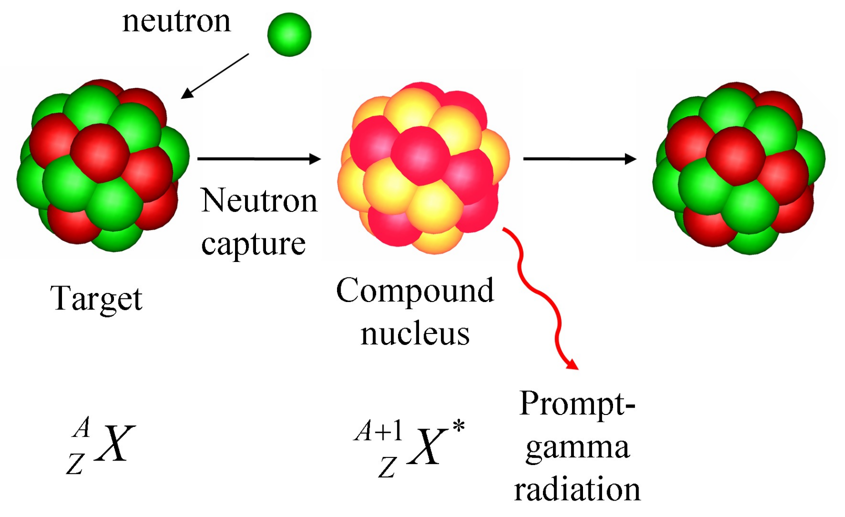


- Then neutron is captured by another nuclei



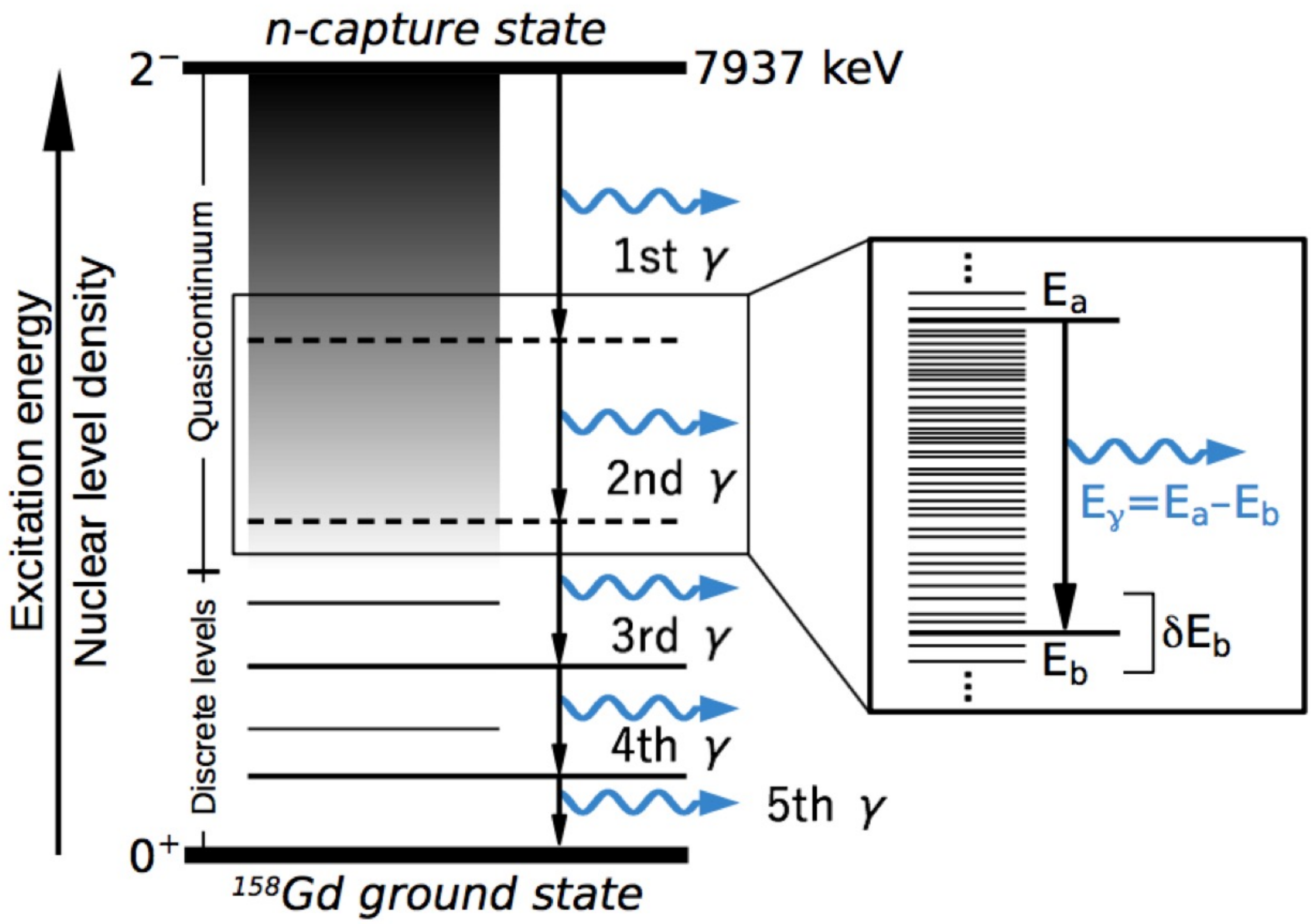
Step 2) Radiative Neutron Capture

- Compound nucleus is brought to an excited state and deexcite emitting gamma ray’s



- Example: Cadmium
  - 12.2% of ^{113}Cd
  - $^{113}Cd + n \rightarrow {}^{114}Cd^{*} \rightarrow {}^{114}Cd + \gamma$’s
  - ^{113}Cd, high neutron capture cross section (>10^4 barns for E<0.5 eV)
  - Emission 9.21 MeV gamma’s on average → clear signal!

Radiative neutron capture: gamma cascade ($^{158}Gd^*$)

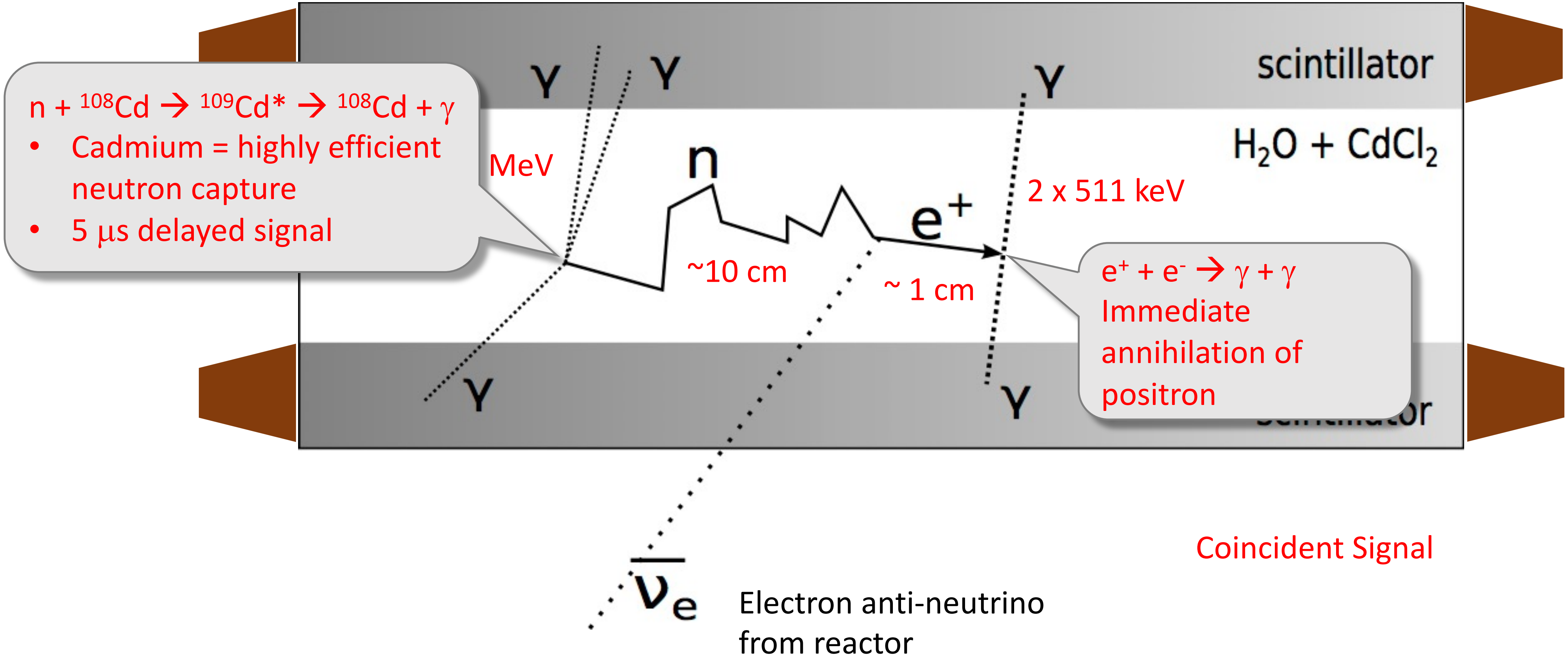


- multi-step γ-ray cascade from the neutron capture (neutron capture) state down towards the ground state via many intermediate levels in the deex- citation of $^{158}Gd*$ after the thermal $^{157}Gd(n,\gamma)$ reaction

Electron Neutrino Discovery

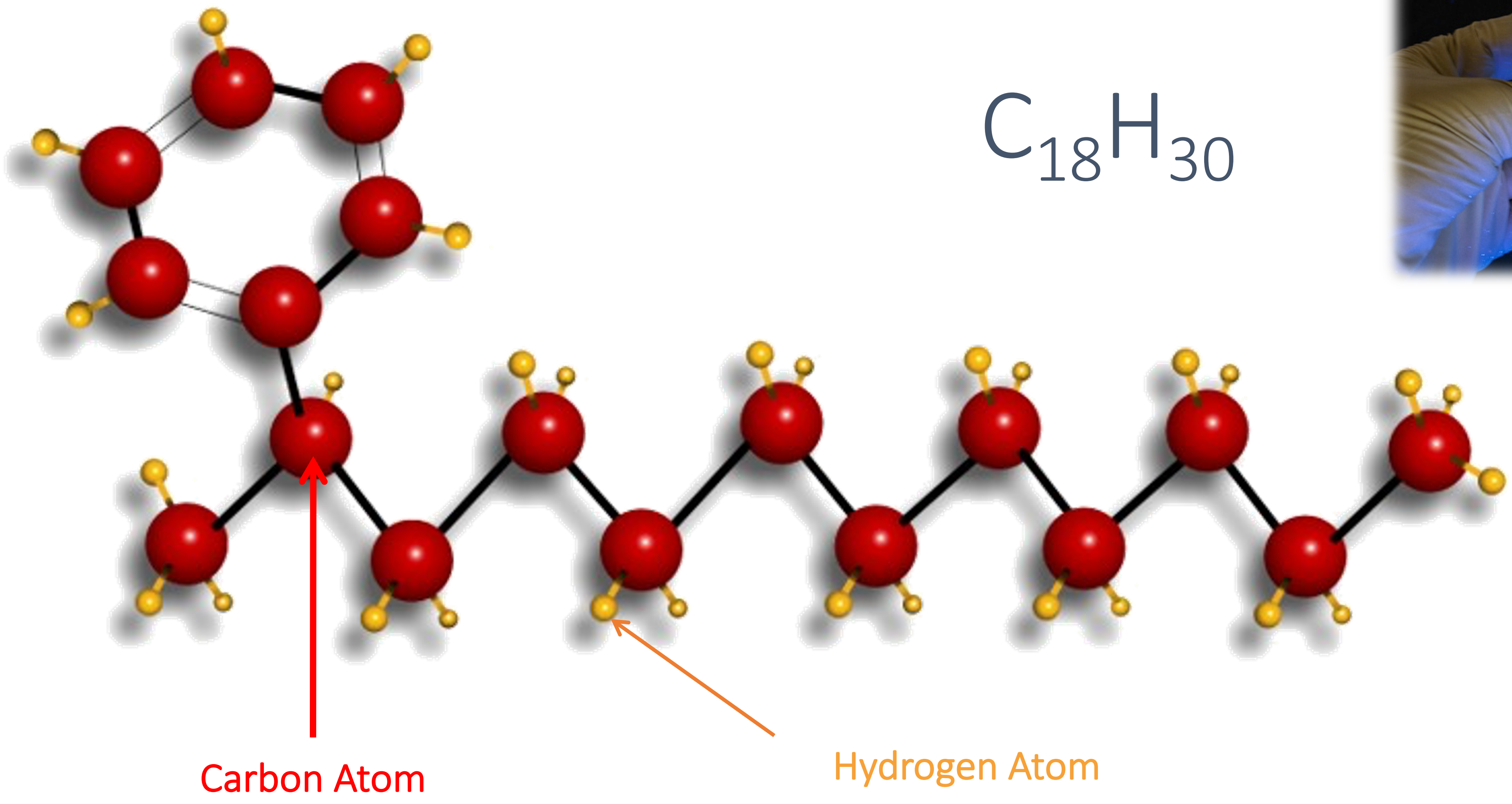
Inverse β - decay

$$\boxed{\bar{\nu}_e + p \rightarrow n + e^+}$$

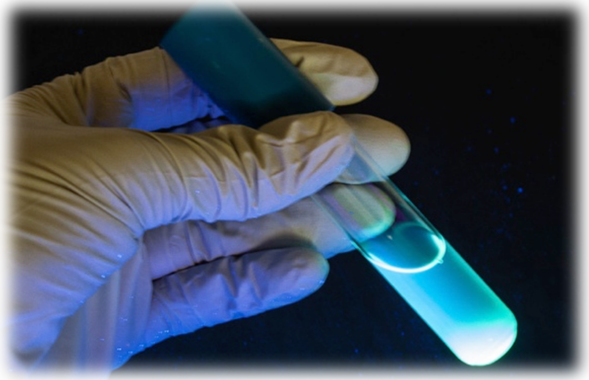


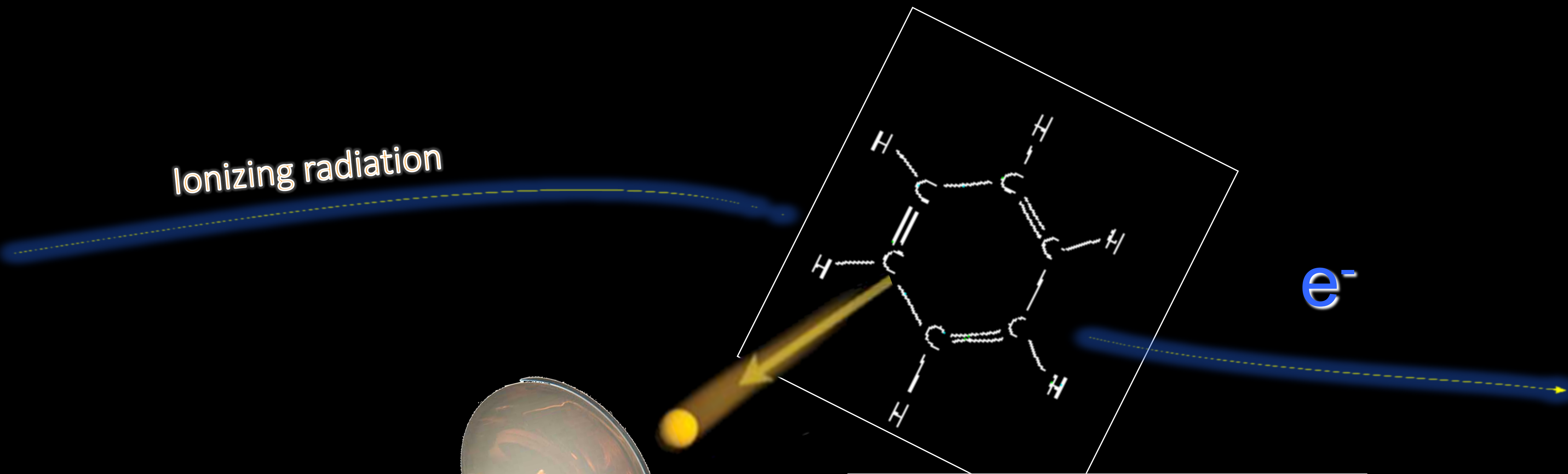
Coincident Signal

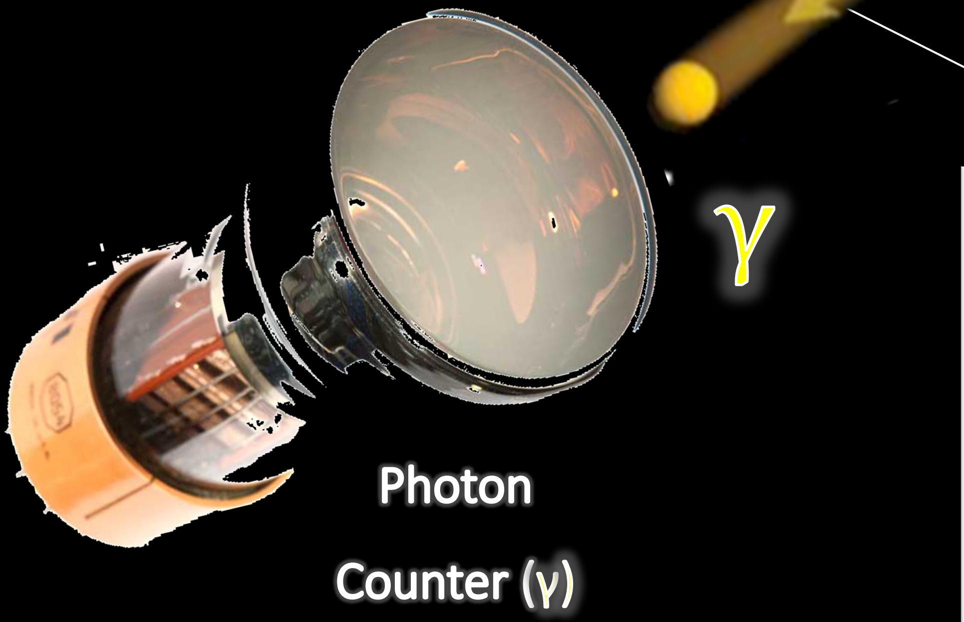
Liquid Scintillator & Fluorescence

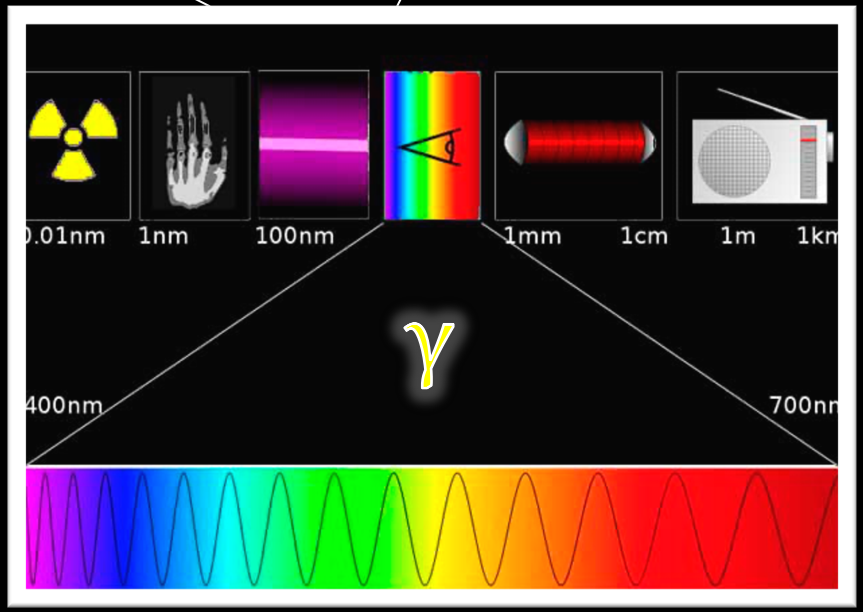


$C_{18}H_{30}$




Ionizing radiation
e-

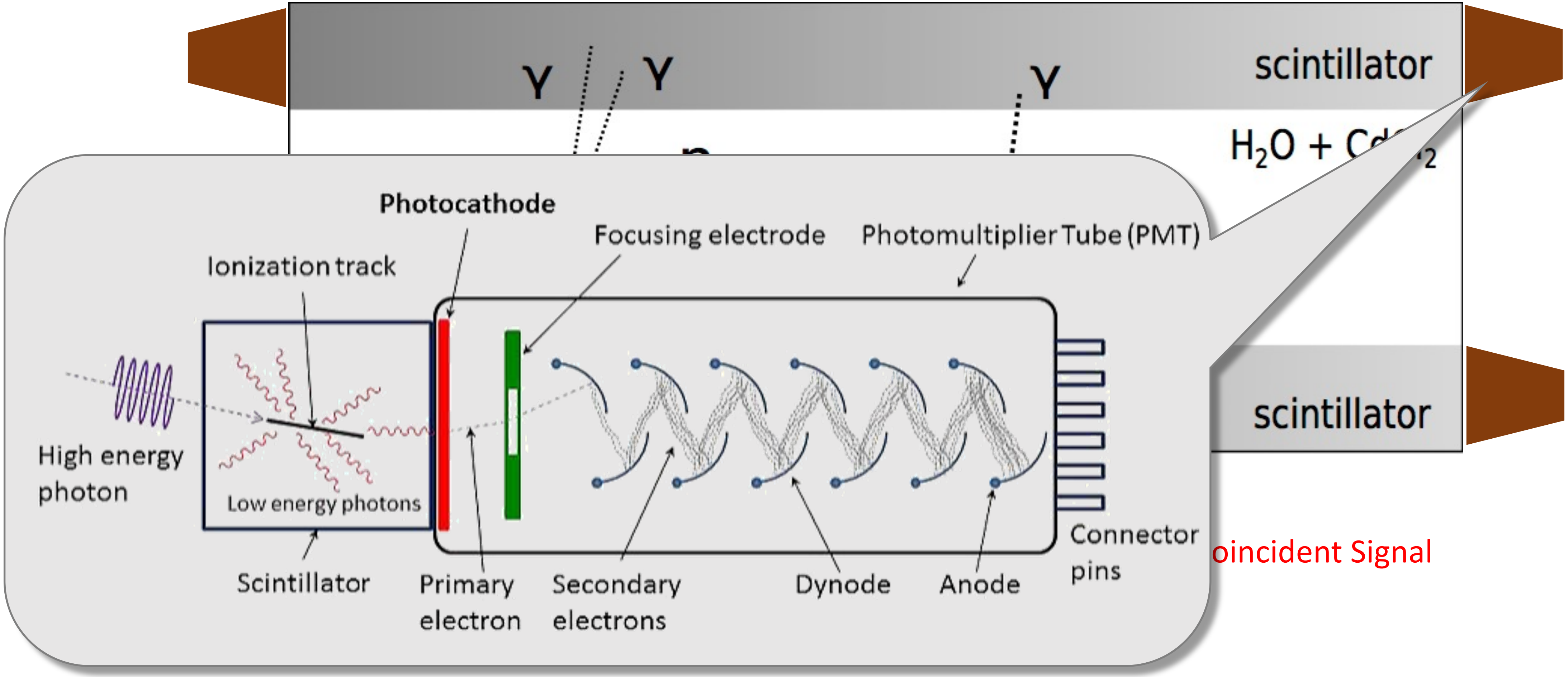

γ
Photon
Counter (γ)


.01nm
1nm
100nm
1mm
1cm
1m
1km
γ
400nm
700nm

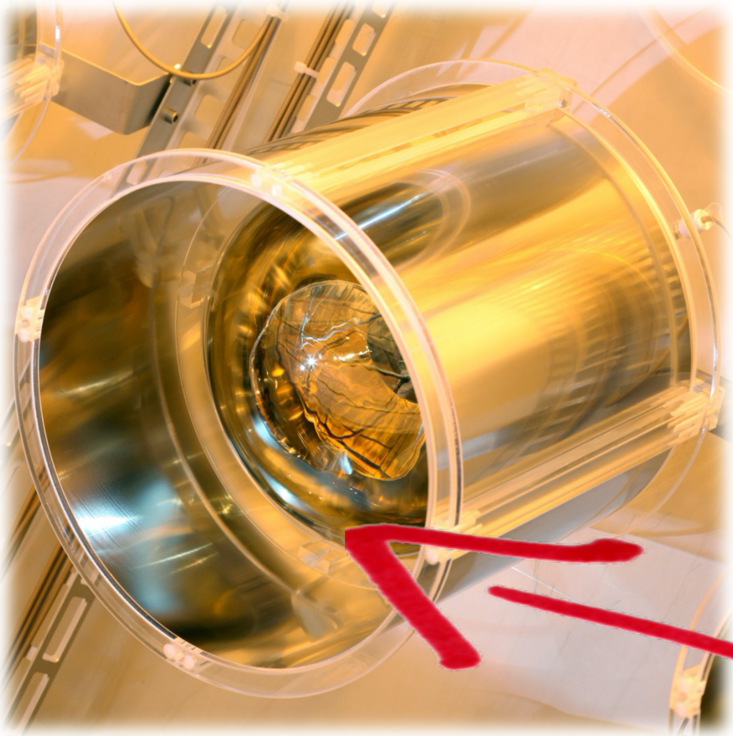
Electron Neutrino Discovery

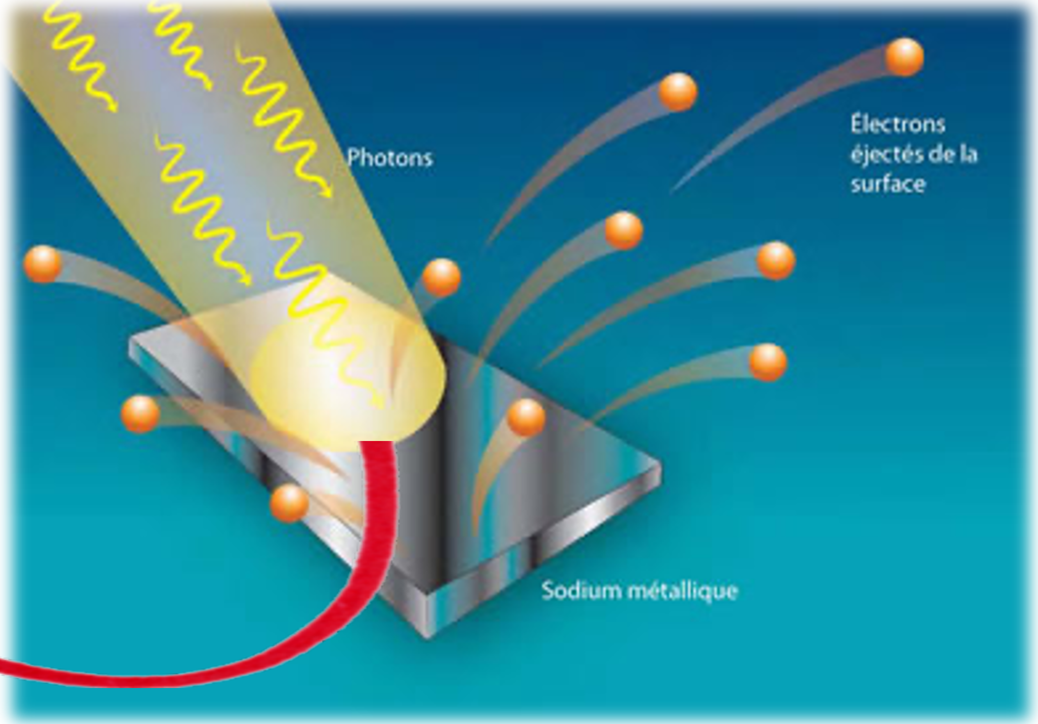
Inverse β - decay

$$\boxed{\bar{\nu}_e + p \rightarrow n + e^+}$$



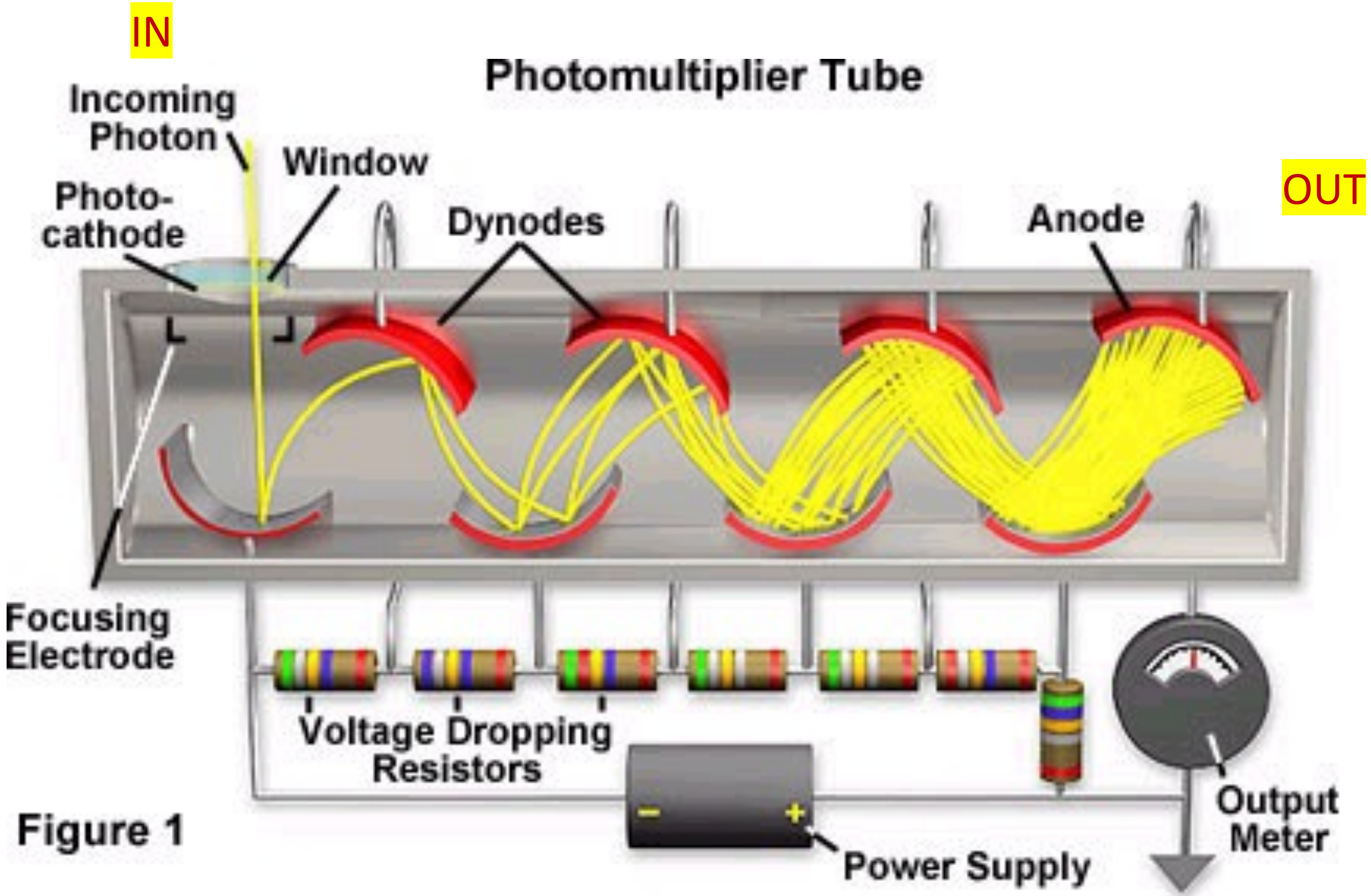
Step 1: photons to electrons conversion (photoelectric effect)



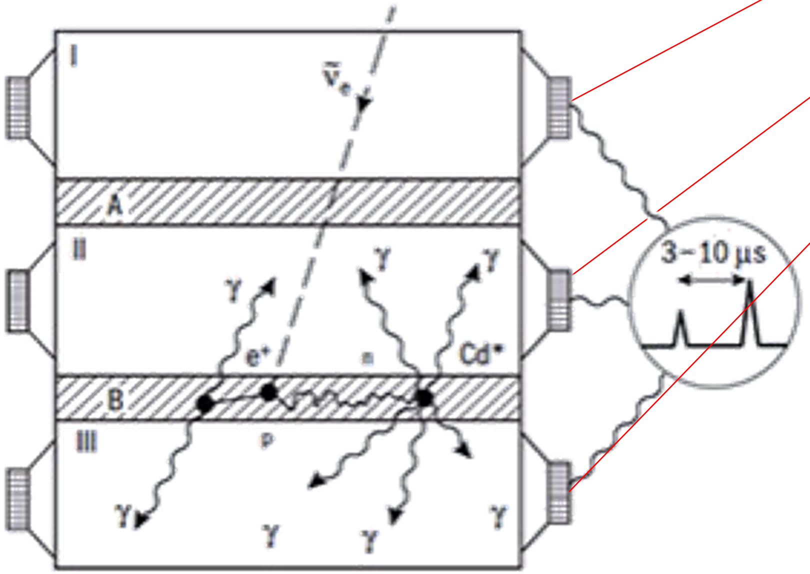


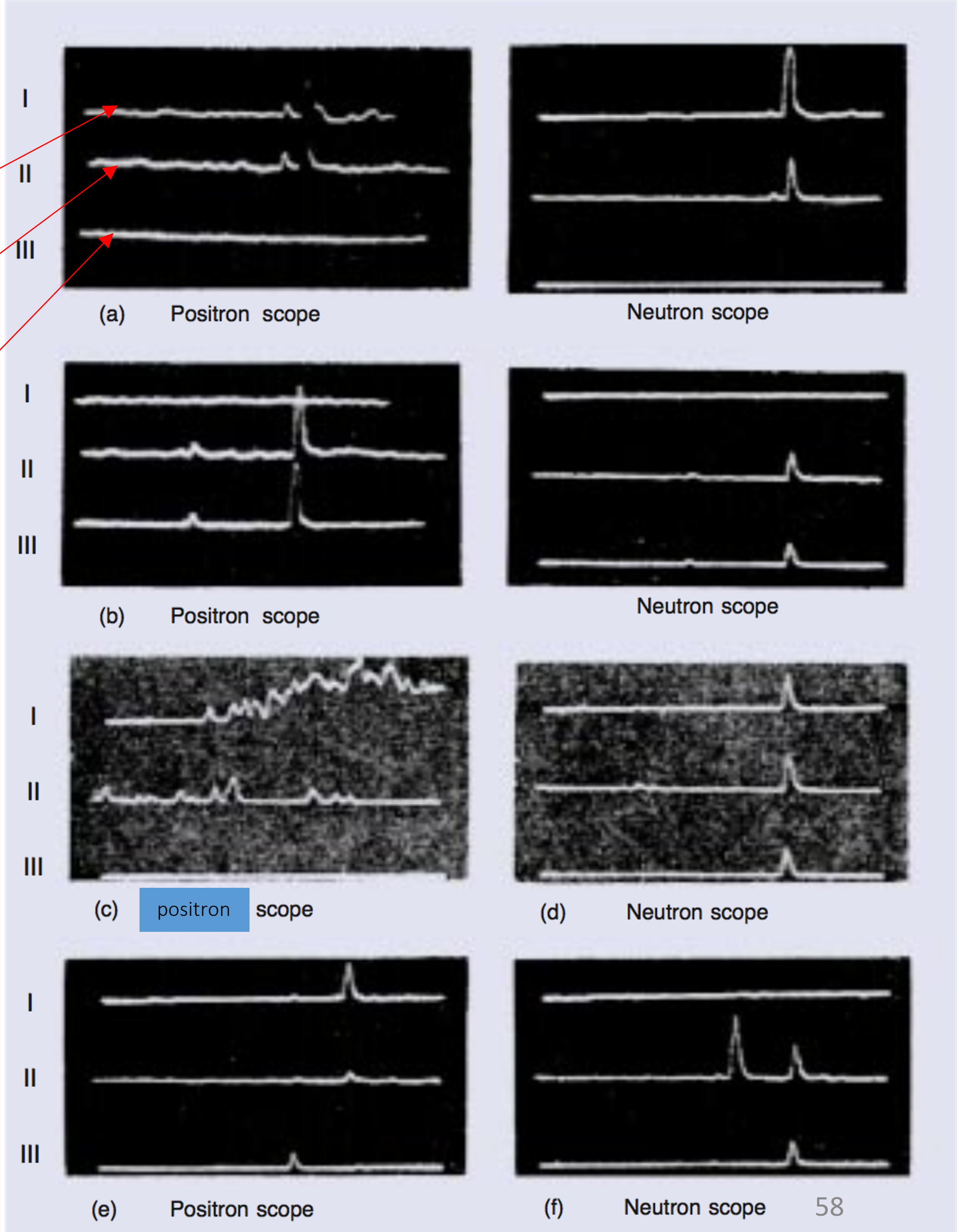
Transformation of a flux of photons (light) into a flux of electrons (electric current)

Step 2: multiplication of the electrons x 10^6



Electron Neutrino Discovery

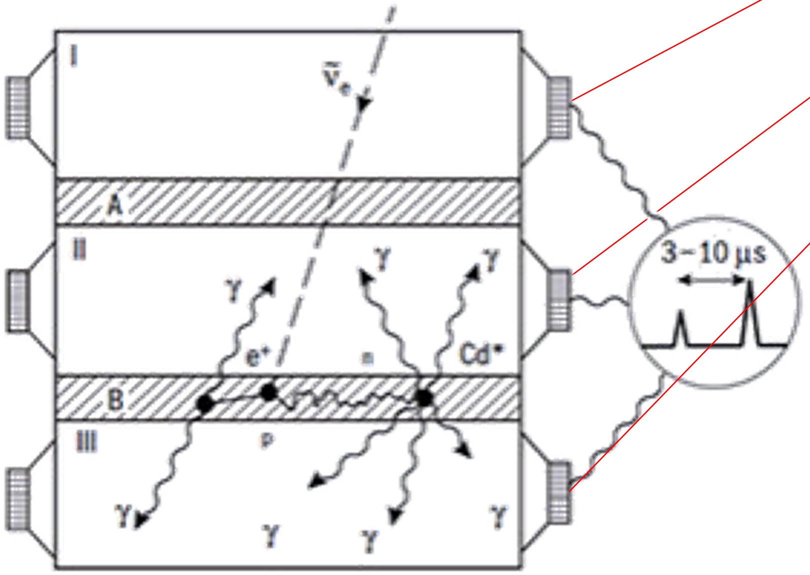


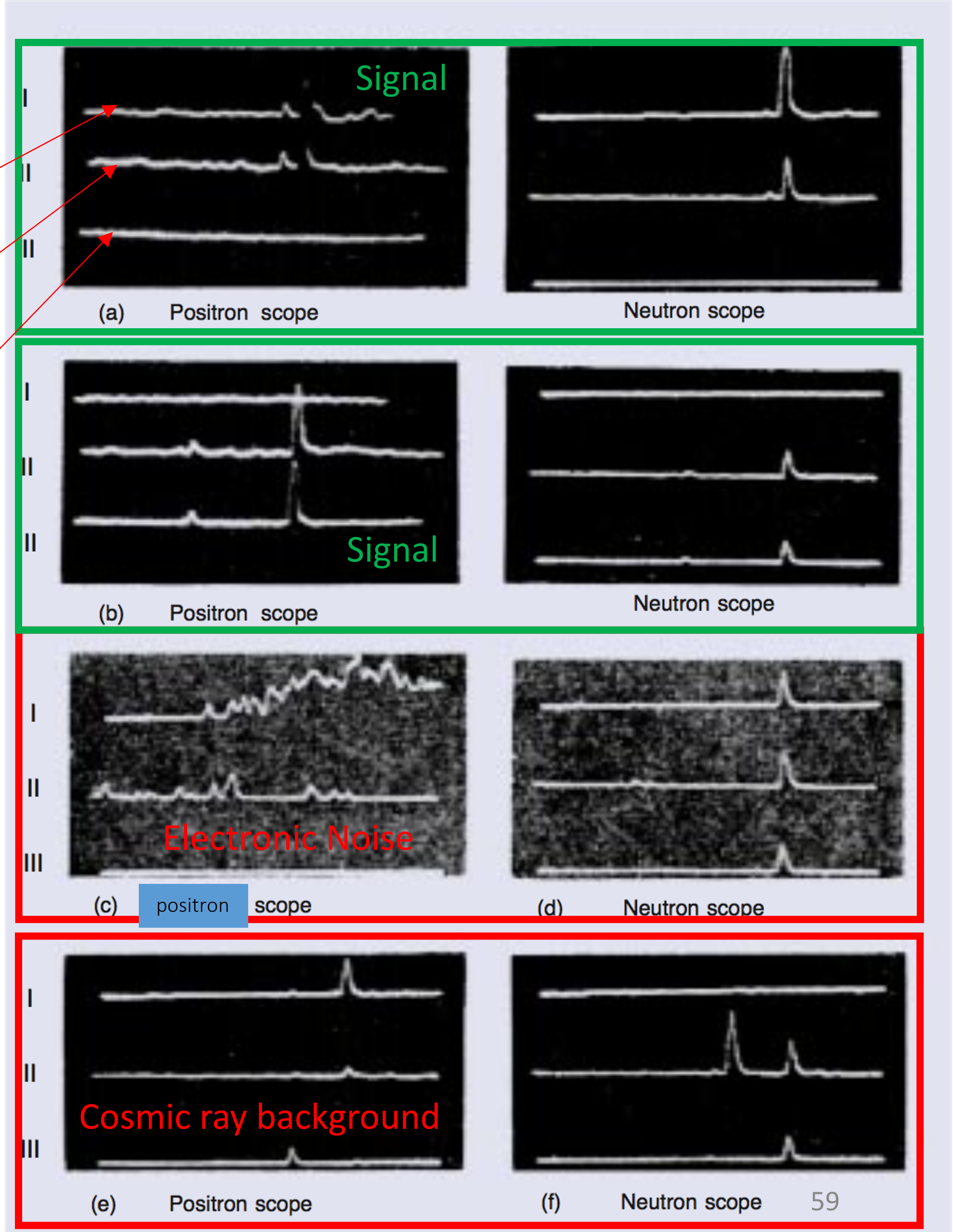


Observables:

- Energy
- Timing

Electron Neutrino Discovery



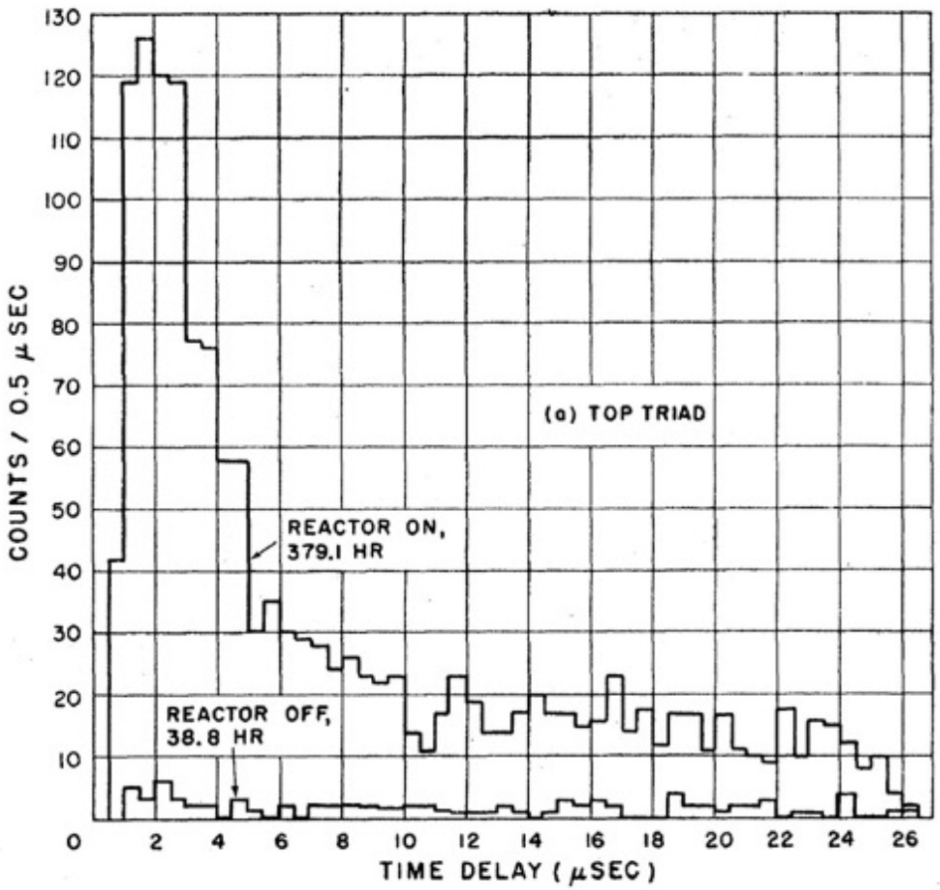


Observables:

- Energy
- Timing

Electron Neutrino Discovery

Coincidence counts versus time delay



- Reactor ON:
  - 379.1 hours
  - Three neutrinos per hour detected
- Reactor OFF:
  - Reactor was shut down to prove that these events come from the reactor, for 38.8 hours
  - Nowadays, the turnover of a reactor unit is 1 million euros
  - Reines was a convincing person!
- First measurement of the cross-section: $\approx 1\times 10^{-43}$ cm^2

http://permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-97-2534-02

1957: Discovery of the Neutrino (Reines & Cowan)

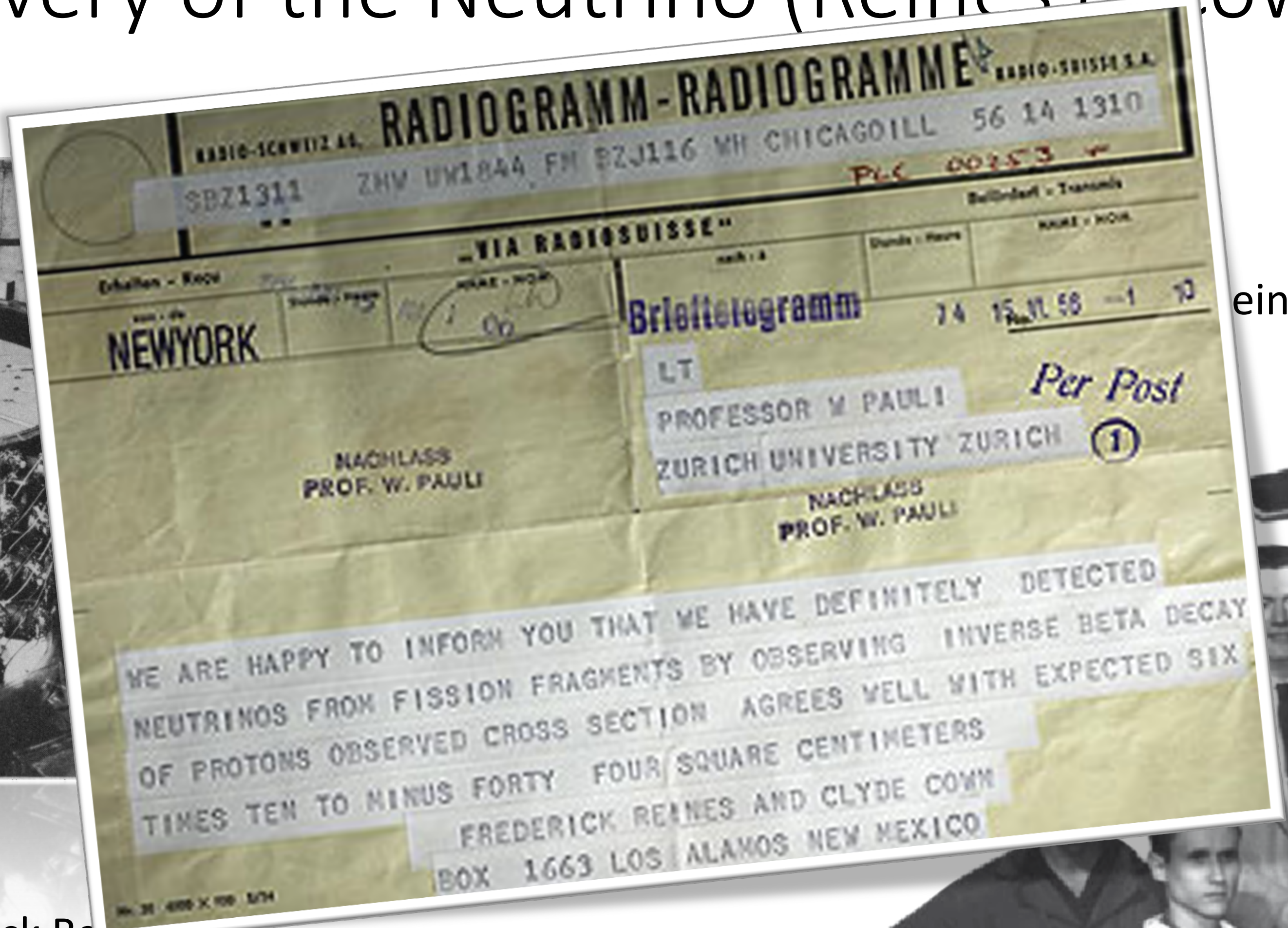
- ‘El Monstro’
  1951
  @ Los Alamos
- ‘Herr Auge‘
  1953
  @ Hanford reactor site
- ‘Poltergeist’
  1956
  @ Savannah river reactor

1995: Frederick Reines
"for the detection of the neutrino"

Clyde Cowan

Fred Reines

1957: Discovery of the Neutrino (Reines & Cowan)


RADIOGRAMM - RADIOGRAMME
RADIO-SCHWEIZ AG. RADIO-SUISSE S.A.
SBZ1311 ZHV UW1844 FN BZJ116 WH CHICAGOILL 56 14 1310
VIA RADIOSUISSE
NEWYORK
Briefteleogramm 74 15.VI.56
LT
PROFESSOR W PAULI
ZURICH UNIVERSITY ZURICH
Per Post
NACHLASS PROF. W. PAULI
NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS
FREDERICK REINES AND CLYDE COWAN
BOX 1663 LOS ALAMOS NEW MEXICO

eines

Clyde Cowan

1995: Frederick Re
"for the detection of the neutrino"