QSFP 2021 – Experimental Neutrino Physics

Lecture 2

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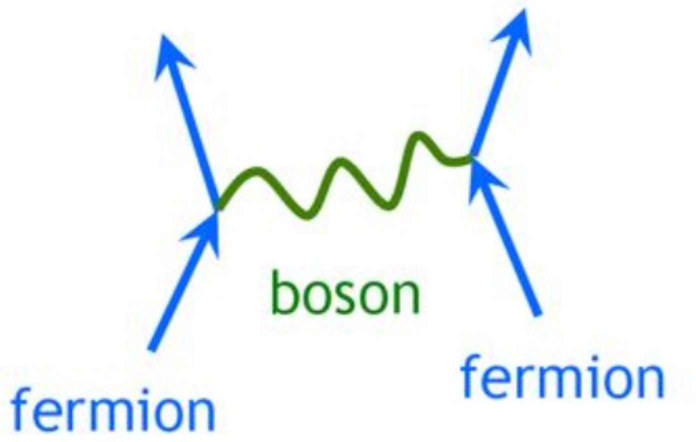
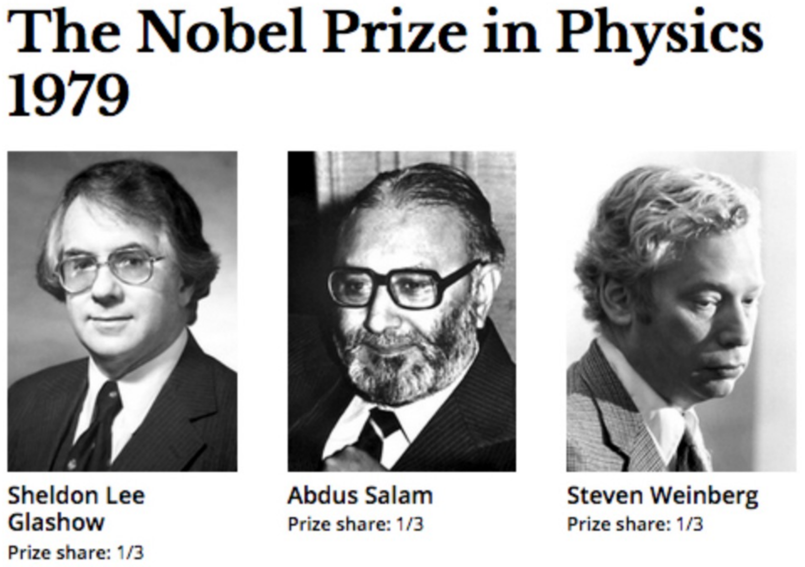
Selected facts about neutrinos in the Standard Model…

The Standard Model

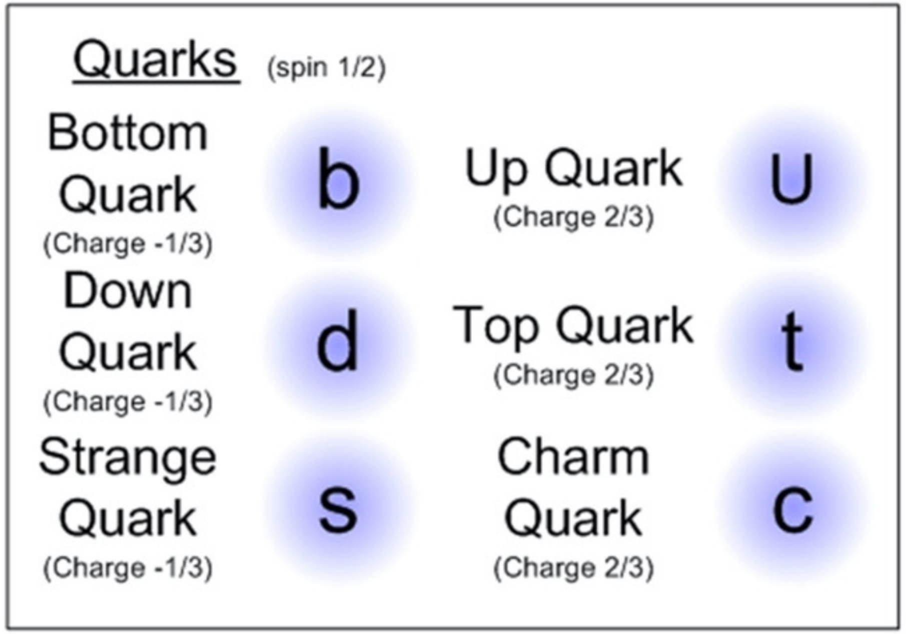
- The Standard Model combines the electromagnetic, weak, and strong interactions
- Bosons with spin 1 communicate the forces between Fermion of spin ½
- Mass of Fermions (but neutrinos?) is generated through the Higgs boson (spin 1)

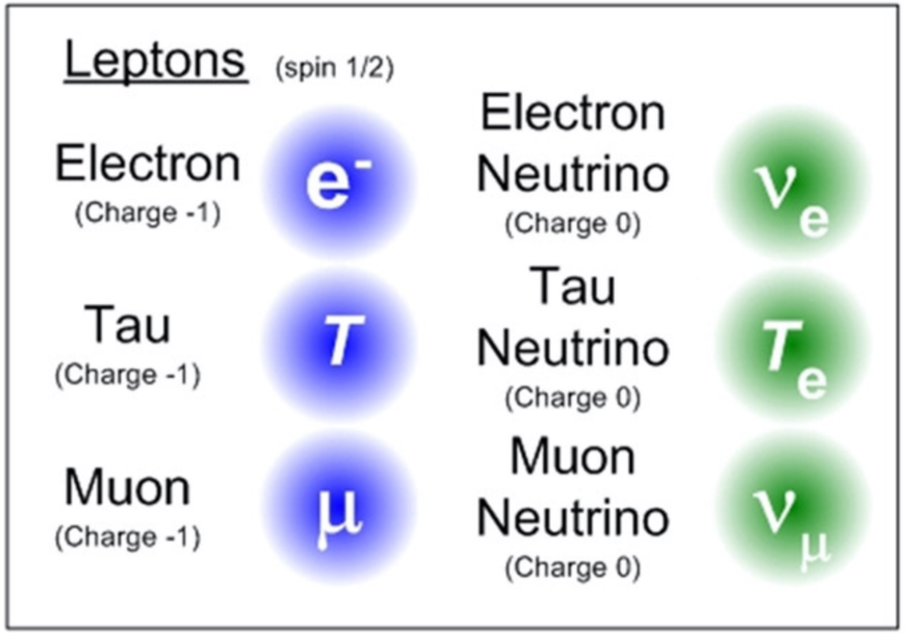




The Standard Model

- The Standard Model includes all known elementary fermions





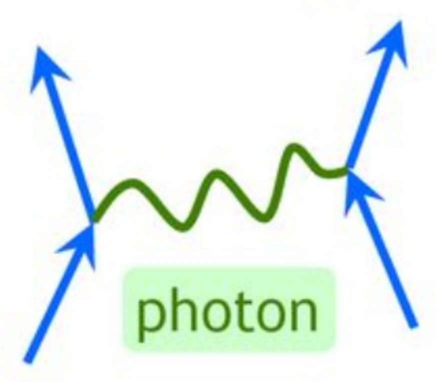
- Matter particles are grouped into three families

- Each fermion has a corresponding antiparticle

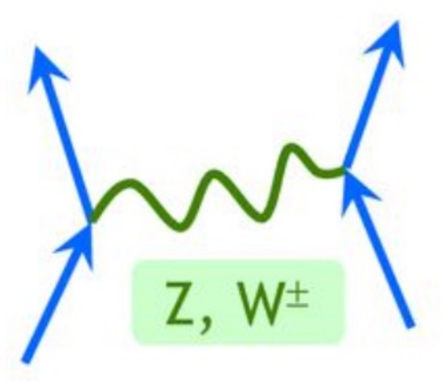
The Standard Model: Weak Interaction

- Three sets of bosons mediate three interactions

electromagnetism



weak interaction

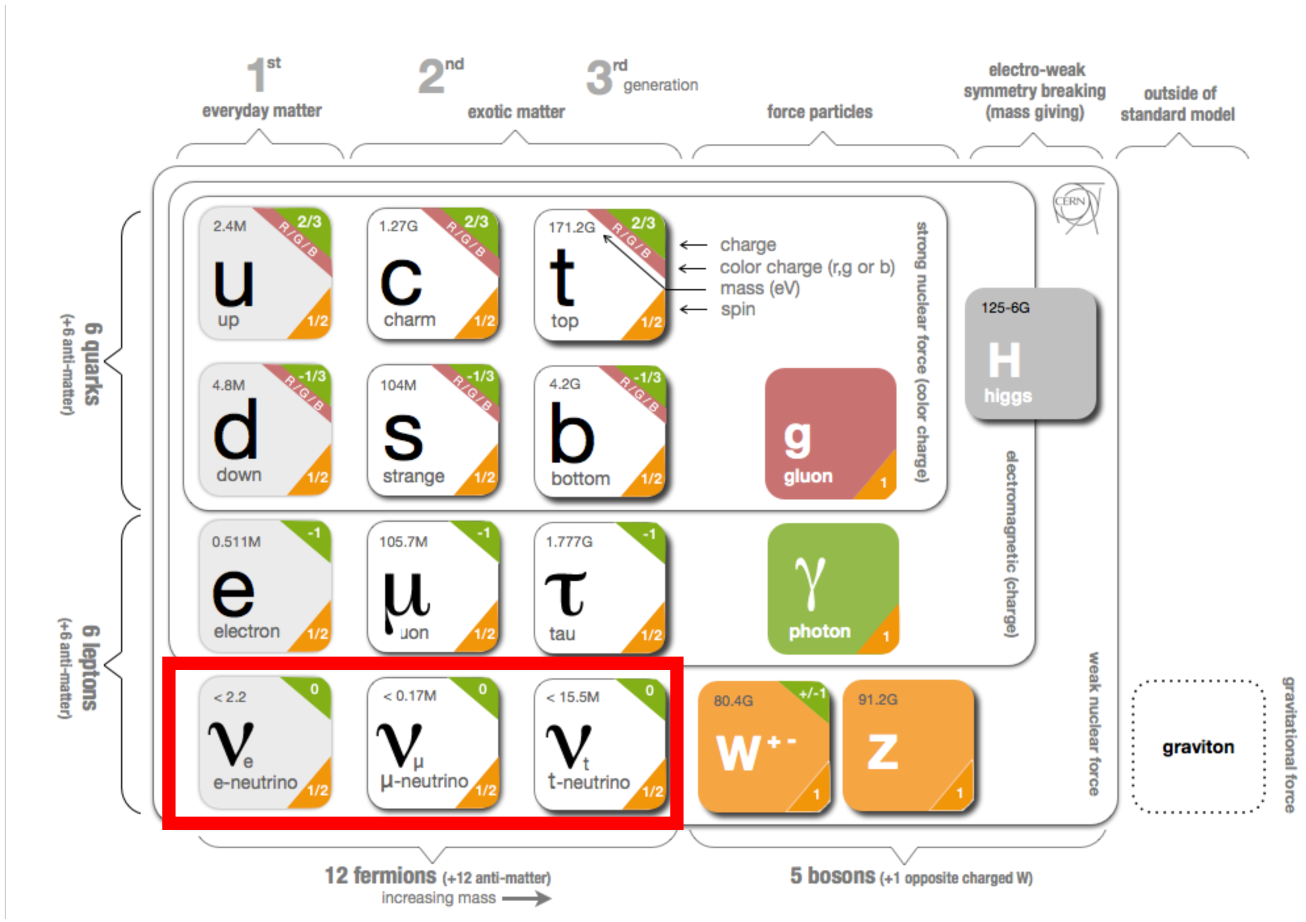


strong interaction

- Each interaction has its characteristic set of boson

- Neutrinos are only involved in weak interactions

Standard Model: 3 types of neutrinos



- Three neutrino flavors
- Neutrinos only interact via weak interaction (and gravity)

Interaction Rules

- Electric charge conservation
- Lepton number conservation
- Energy / Momentum conservation

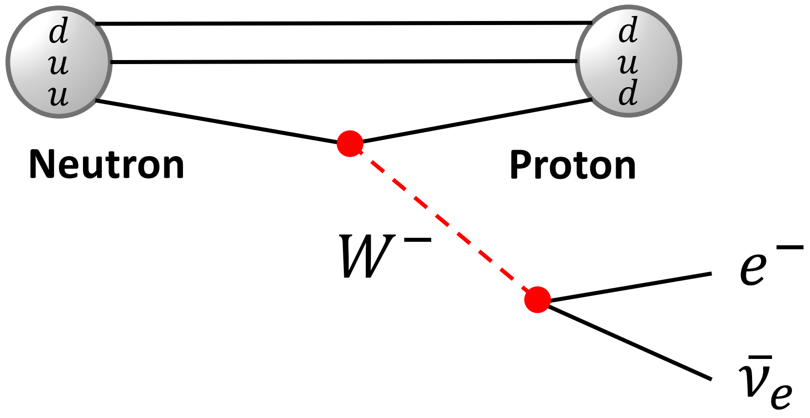
Neutrino Production

m$_p$ = 938.3 MeV
m$_n$ = 939.6 MeV

Semi-leptonic decay: β-decay's

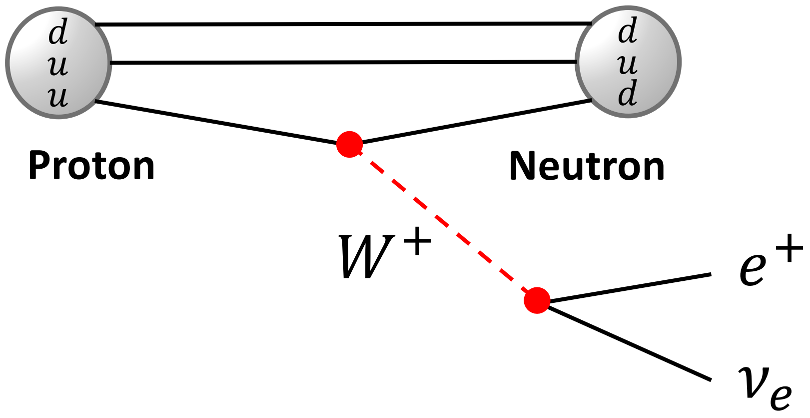
β$^-$decay

- Lifetime neutron: 15 minutes (887 s)
- Occurs in reactors, fission explosions



β$^+$-decay

- Free proton decay has never been observed



Energy balance has to be fulfilled

$$X \to Y + e + \nu$$
$$E_0 = M(X) - M(Y) - m_e - m_\nu > 0$$

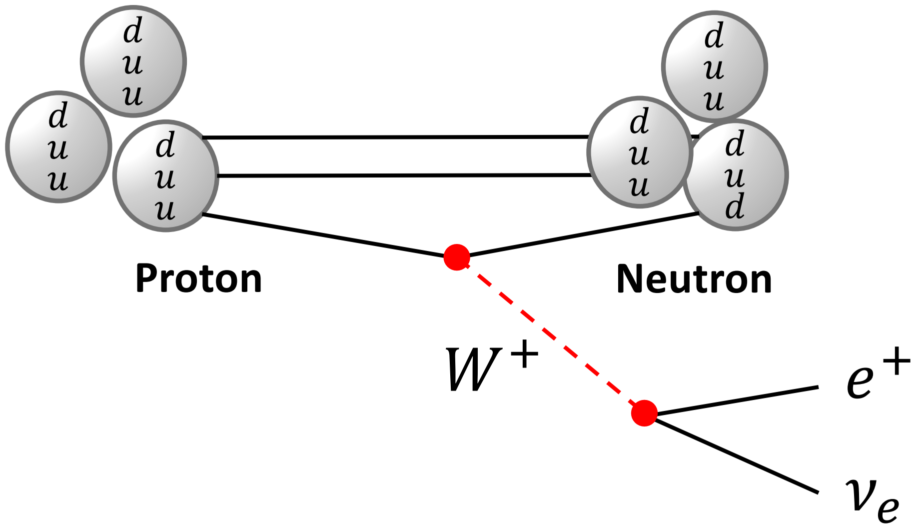
Semi-leptonic decay: β$^+$ and Electron capture

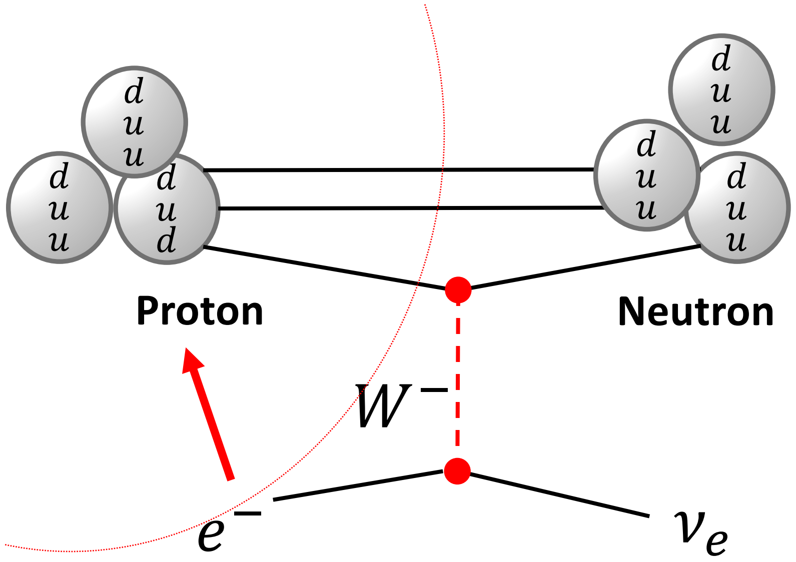
β$^+$-decay

- Free proton decay has never been observed
- β$^+$ decay only occurs in proton-rich nuclei

Electron capture:

- Electron captured from atomic shell
- Occurs when released energy is not enough to create a positron

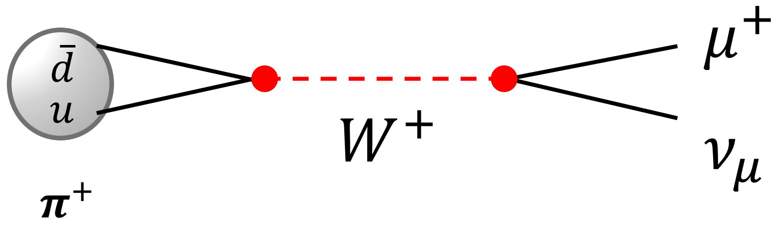


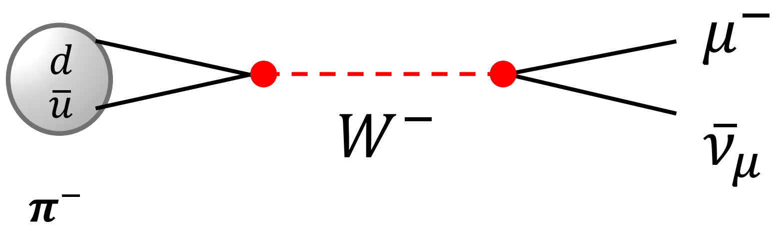


Semi-leptonic decay: e.g. Pion decay

Pion (quark and an antiquark) to muons

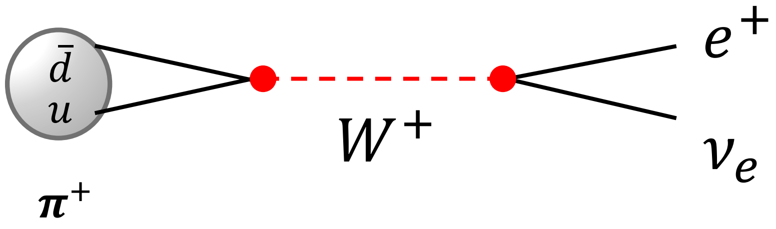
- Pion lifetime: 2.6×10^{-8} s
- Decays with 99.99% probability to muons
- Atmospheric / Accelerator neutrinos

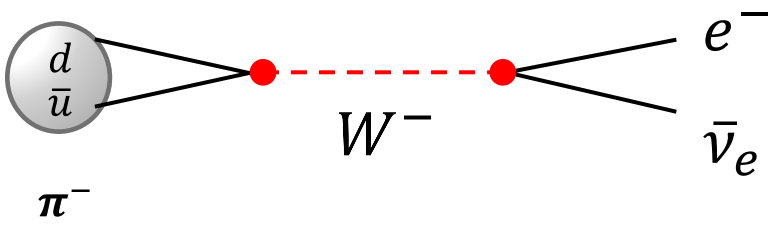




Pion to electrons

- Suppressed due to smaller mass of electron (compared to muon) → helicity suppression





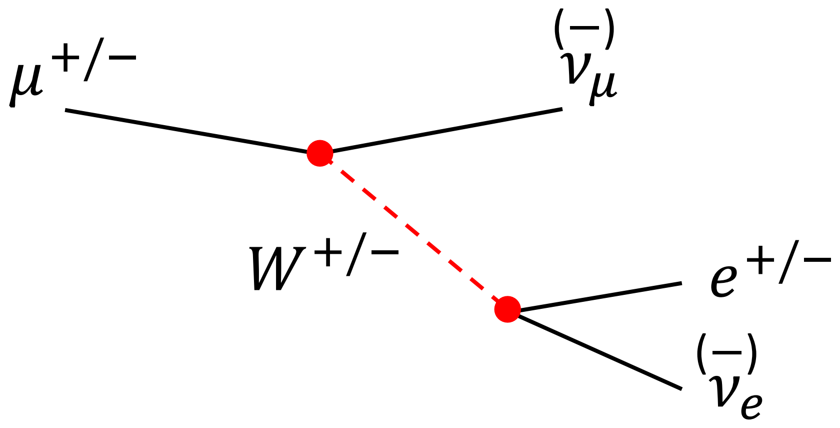
Leptonic Decay: muon and tau decay

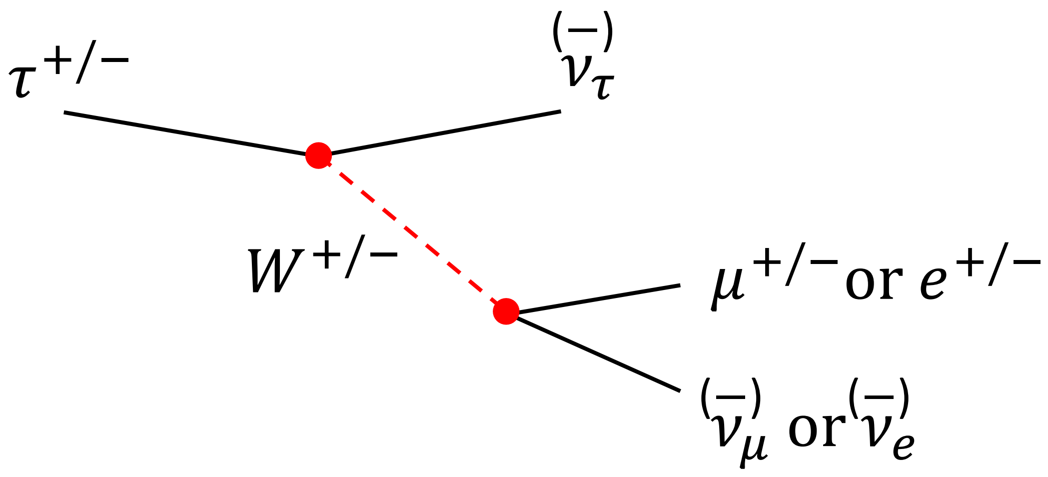
Muon decay

- Muon lifetime: 2.2 ms
- Decays to muon-neutrino, electron, and electron-neutrino of known spectrum
- Atmospheric / Accelerator neutrinos

Tau decay

- Tau lifetime: 2.3 x 10^{-13} s
- Decays to neutrinos + muon (17%) or electron (17%)
- Accelerator neutrinos

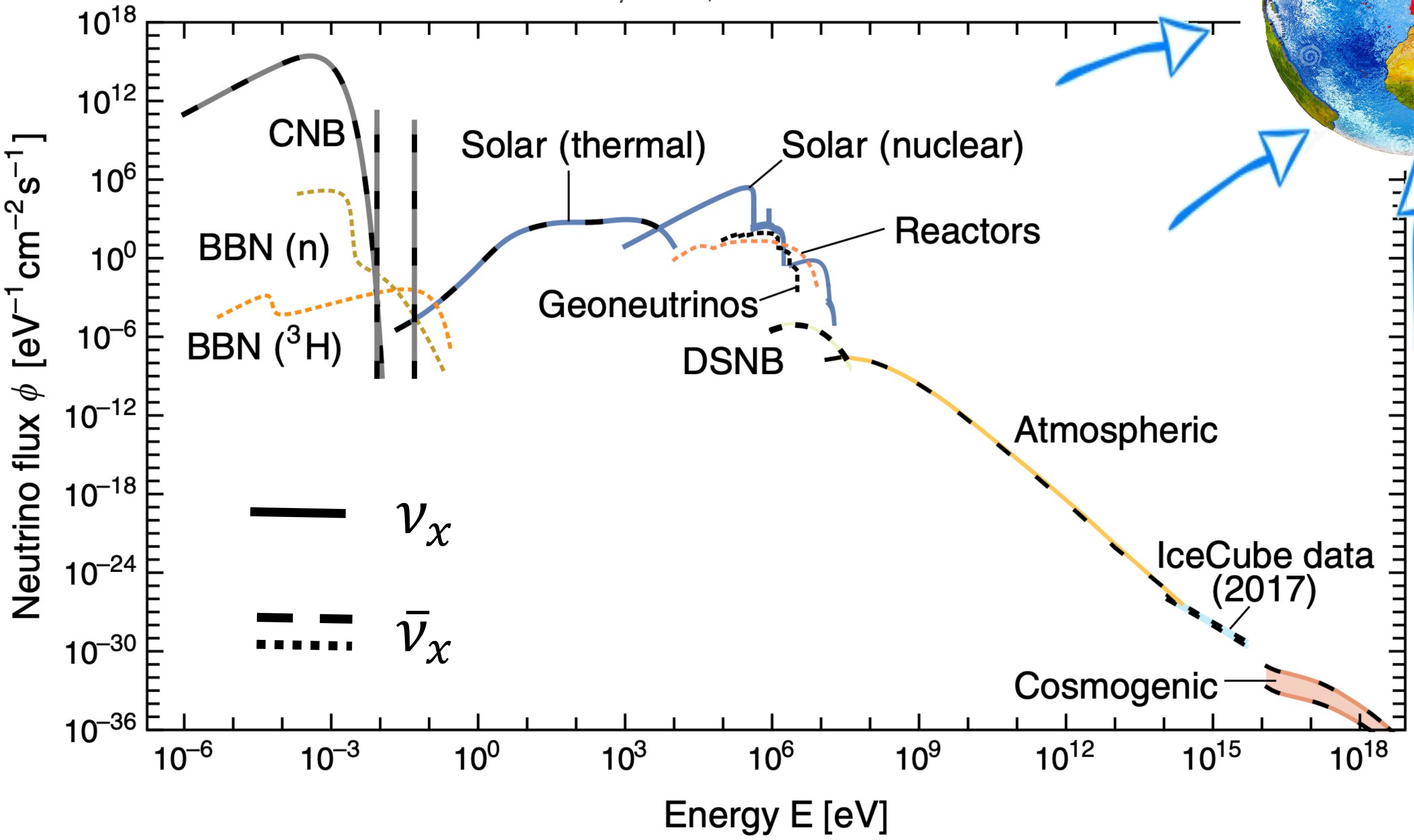


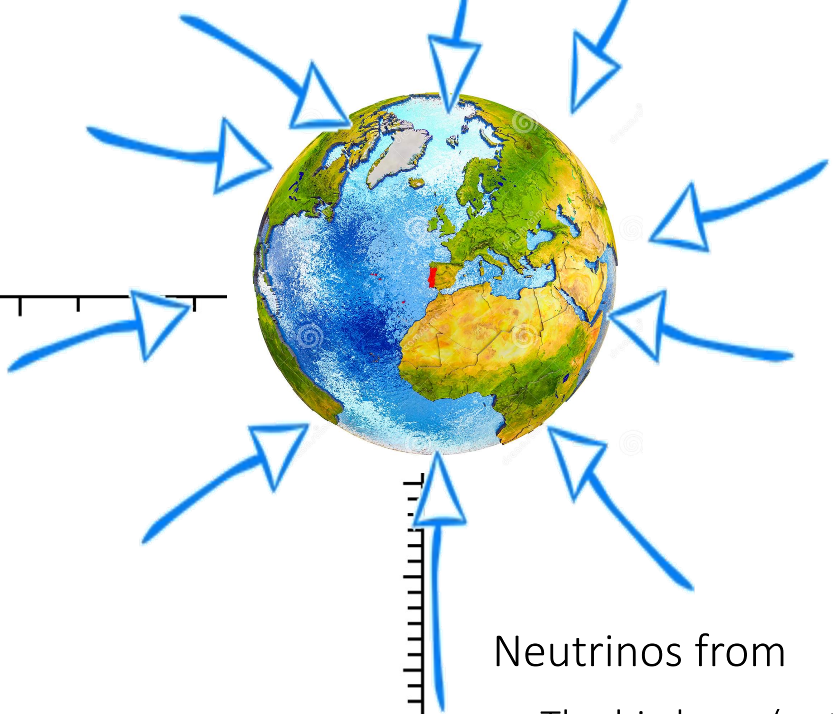


Neutrino Sources

Grand unified neutrino spectrum

Rev. Mod. Phys. **92**, 045006

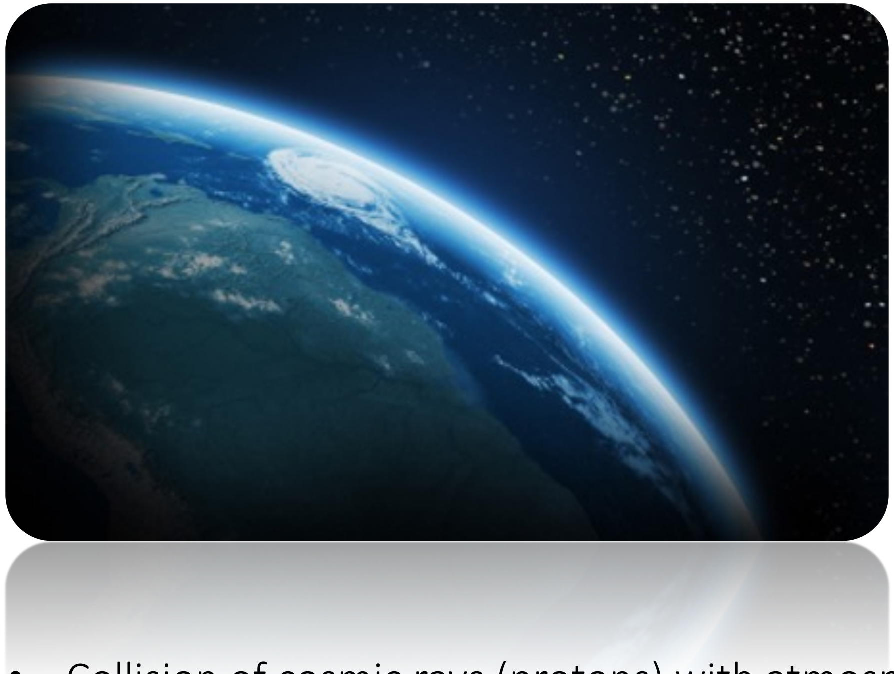




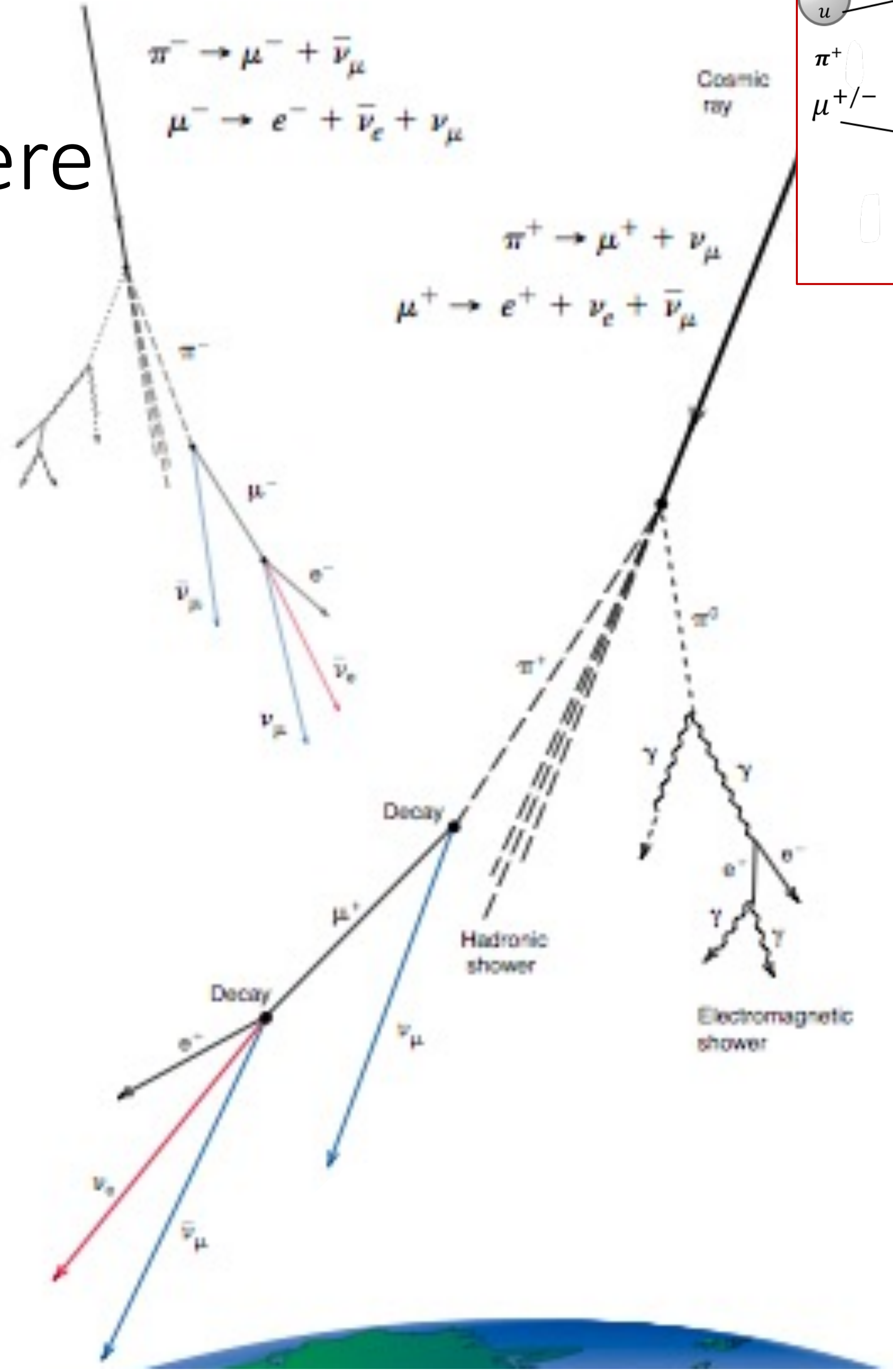
Neutrinos from

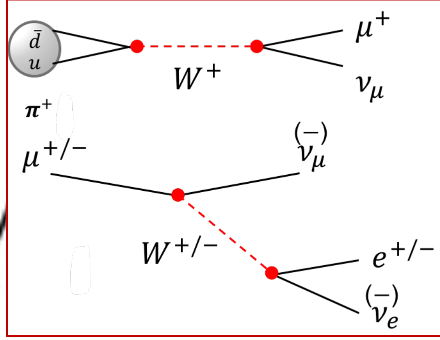
- The big bang (not yet detected directly)
- The sun (detected)
- **The earth (detected)**
- **Nuclear reactors (detected**
- **Accelerators (detected)**
- Super Nova (detected)
- Super Nova remnants (not yet detected)
- Galactic or extragalactic sources (detected)

Neutrinos from the atmosphere

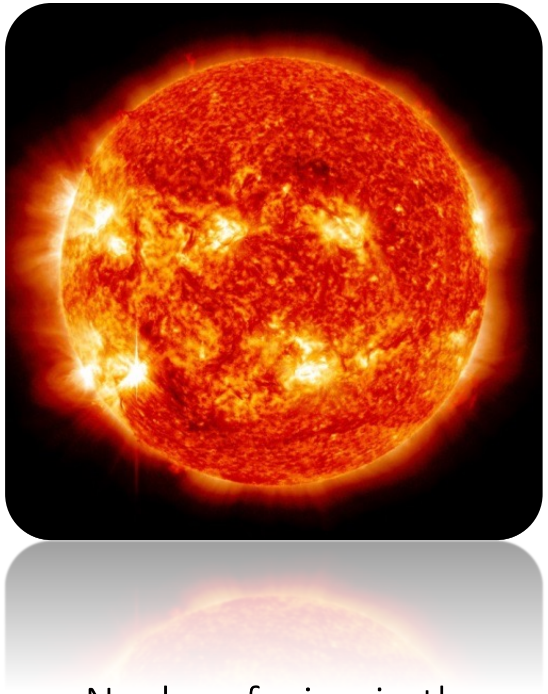


- Collision of cosmic rays (protons) with atmosphere
- Generation of showers of pions = ud quark
- Muon- and electron-neutrinos are produced in 2:1 ratio
- Used to detect neutrino oscillations (1998)

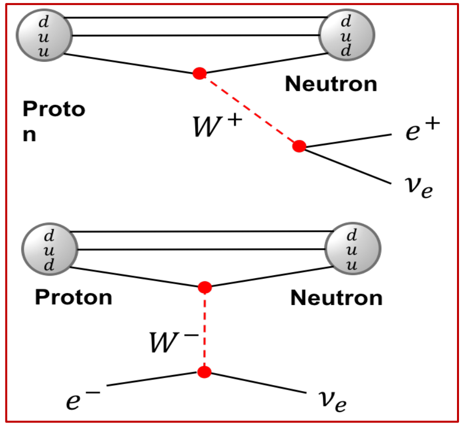


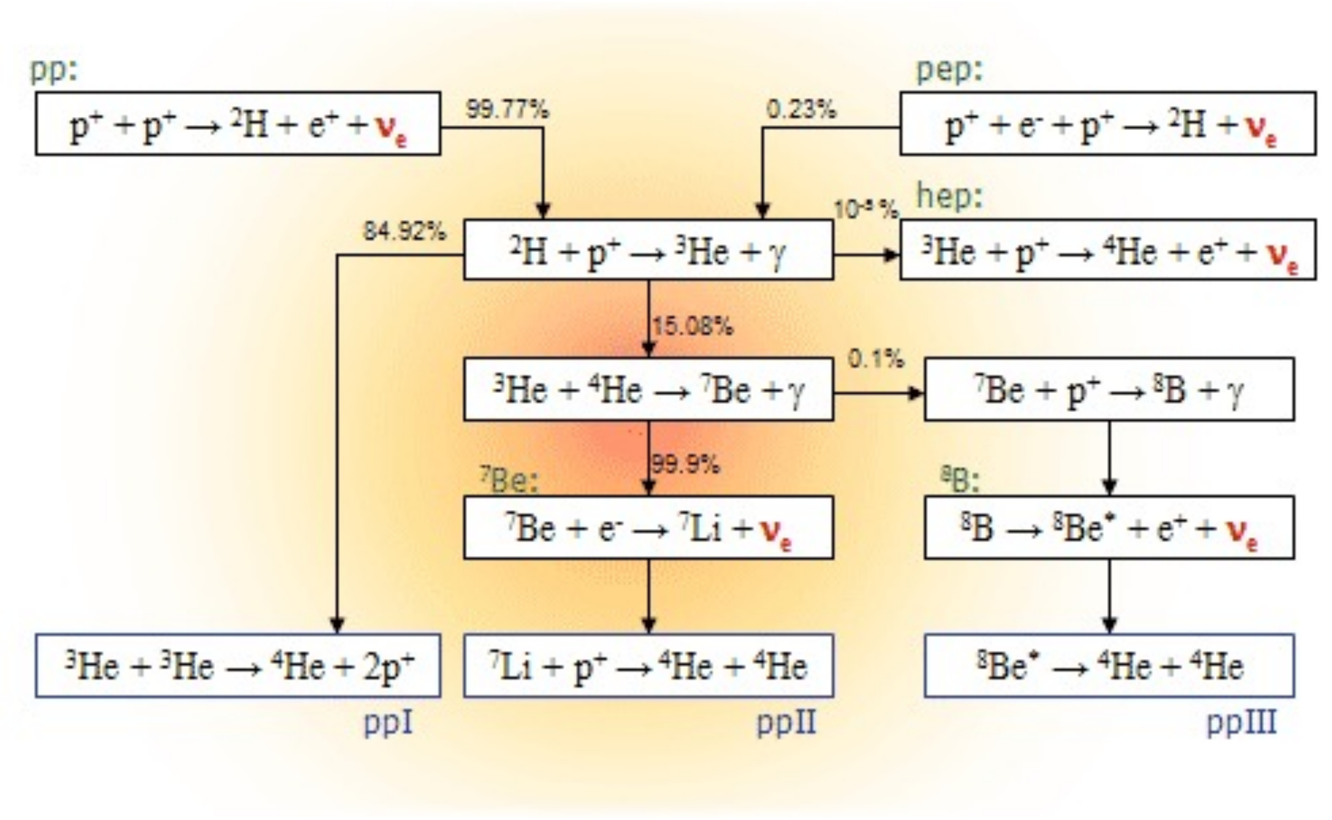


Neutrinos from the sun

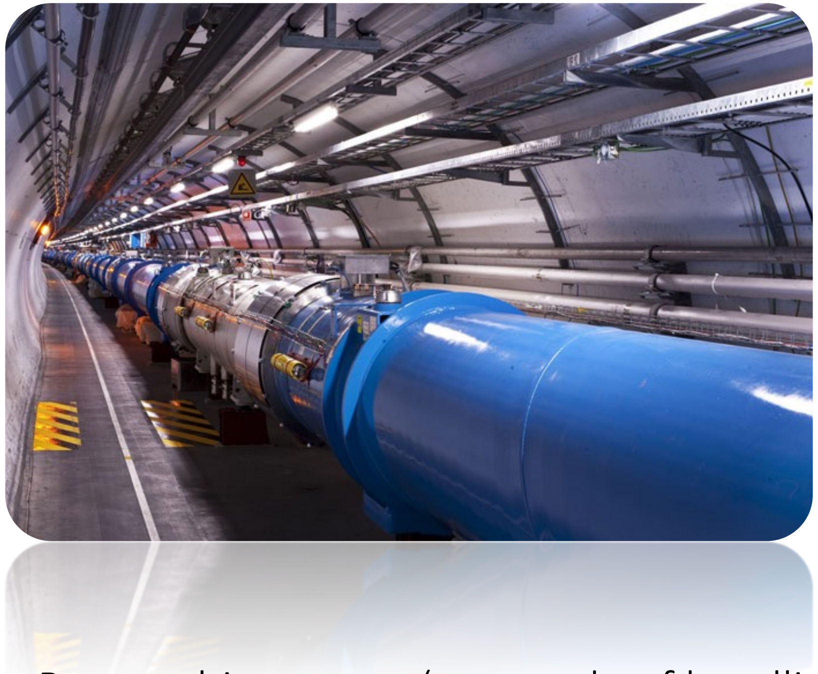


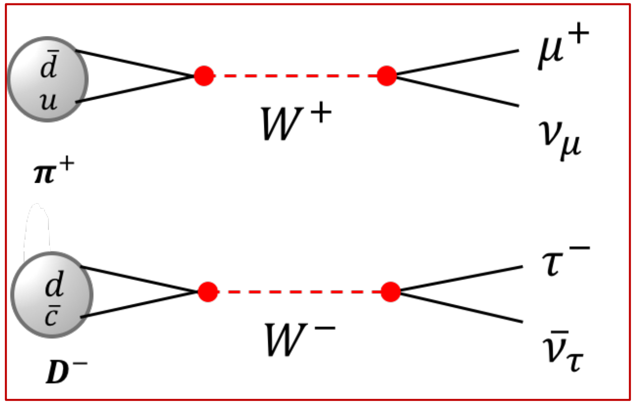
- Nuclear fusion in the sun
- Only electron neutrinos are created
- @Earth: 66 Billion neutrinos /cm^2/s

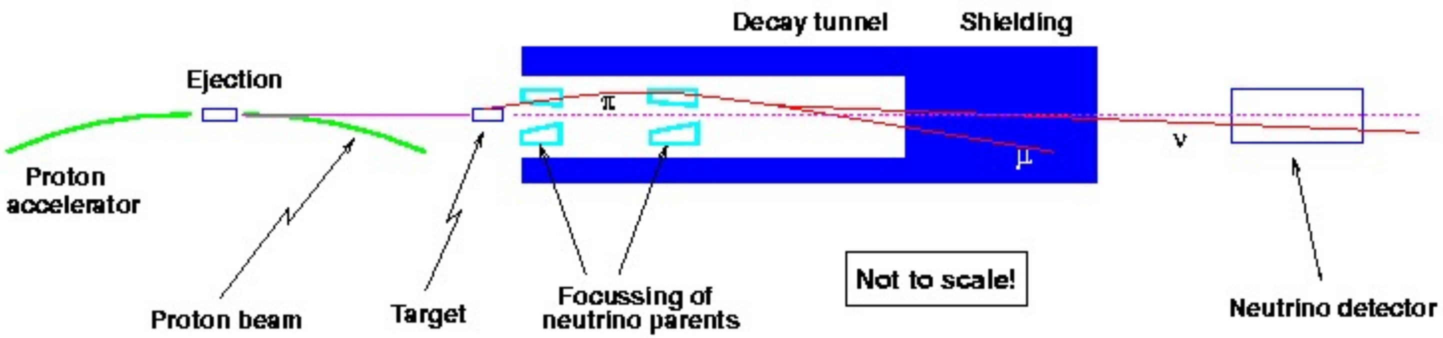




Neutrinos from accelerators







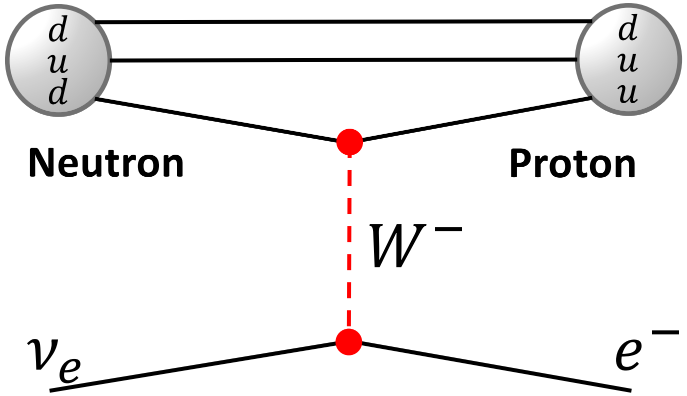
- Protons hit a target (e.g. made of beryllium)
- Generation of pions, kaons, and charmed mesons
- Mesons decay and produce neutrinos

Neutrino Interactions

Inverse beta decay

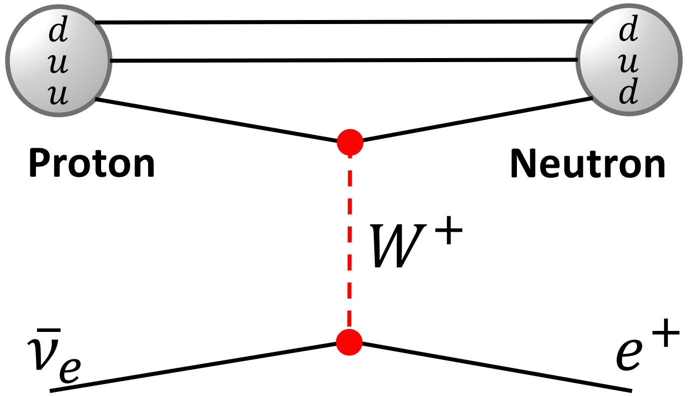
Inverse β^{-}-decay

- Capture of electron neutrino
- High-enough energy muon/tau-neutrinos would be needed to create a muon/tau



Inverse β^{+}-decay

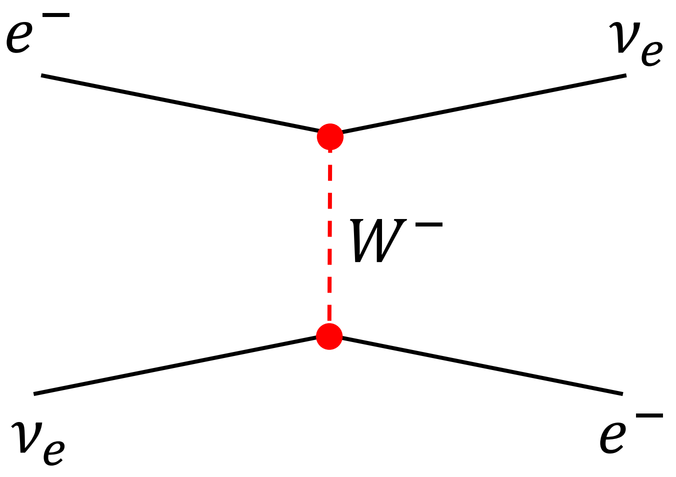
- Capture of electron anti-neutrino
- Important detection reaction !



Electron scattering

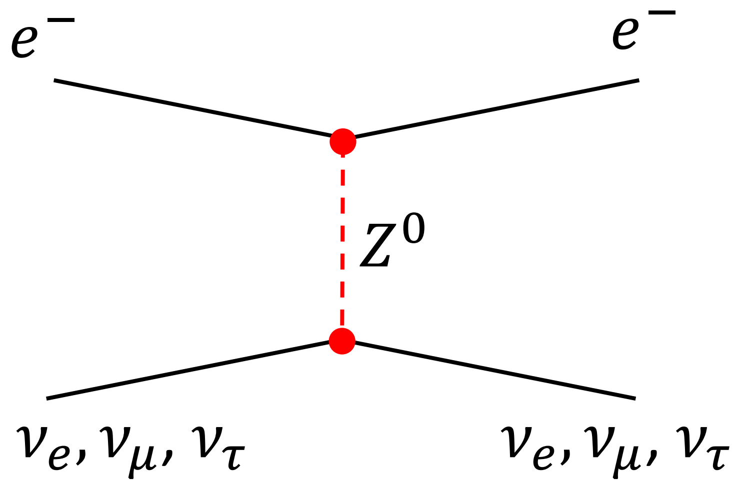
Charged-current

- Neutrino-electron scattering via the exchange of a charged current
- High-enough energy muon/tau-neutrinos would be needed to create a muon/tau



Neutral current:

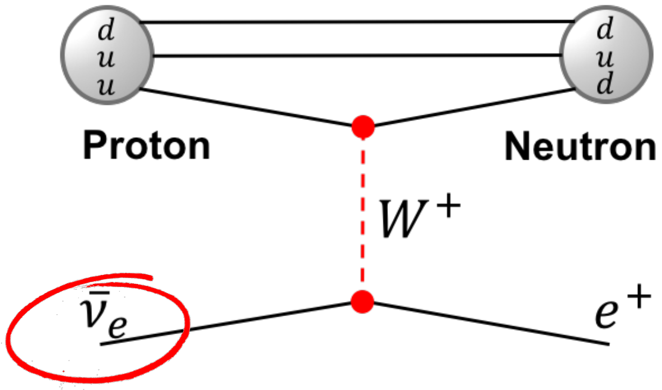
- Identical coupling of the neutral current to all flavors
- Very important for all-flavor neutrino detection



For all flavors, Charged Current interactions

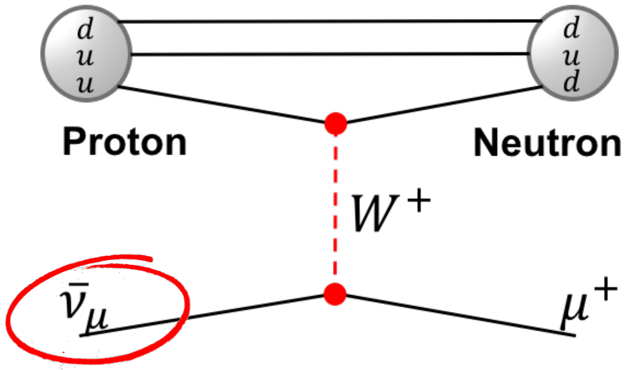
Electron ν:

… inverse beta decay (IBD)



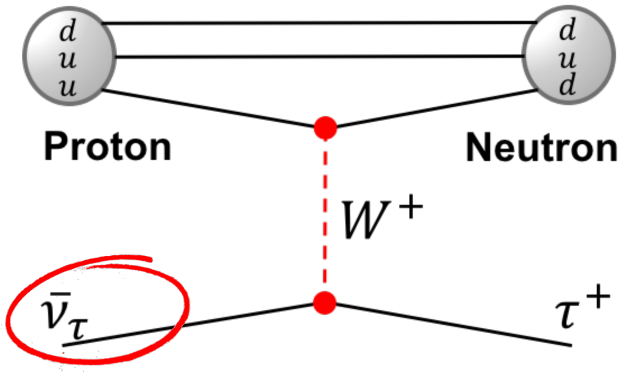
Muon ν:

… CC nuclear reaction (dominant)

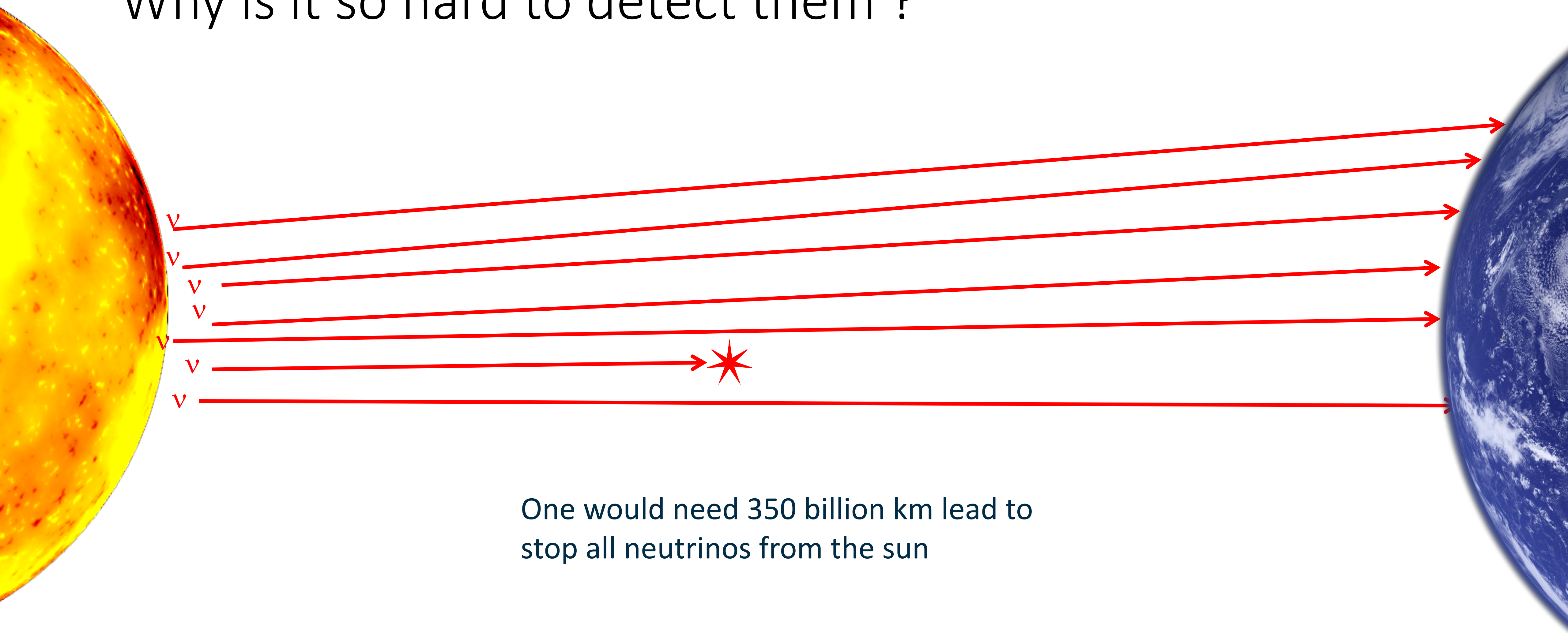


Tau ν:

… CC nuclear reaction (dominant)



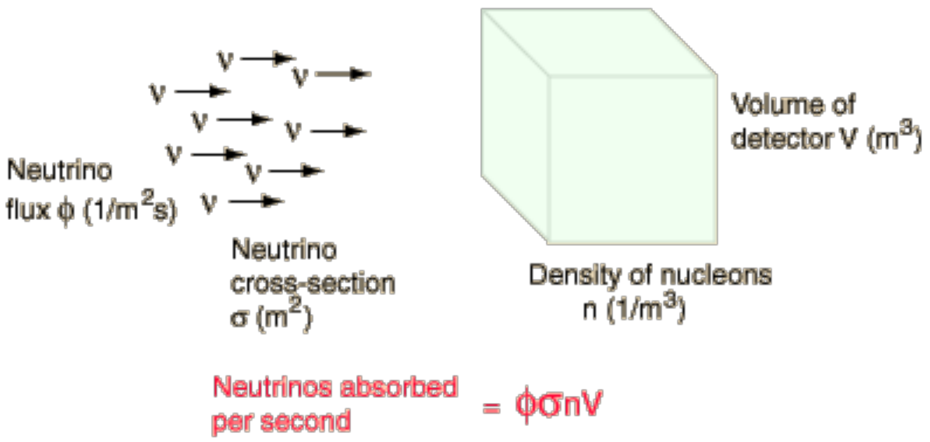
Why is it so hard to detect them ?

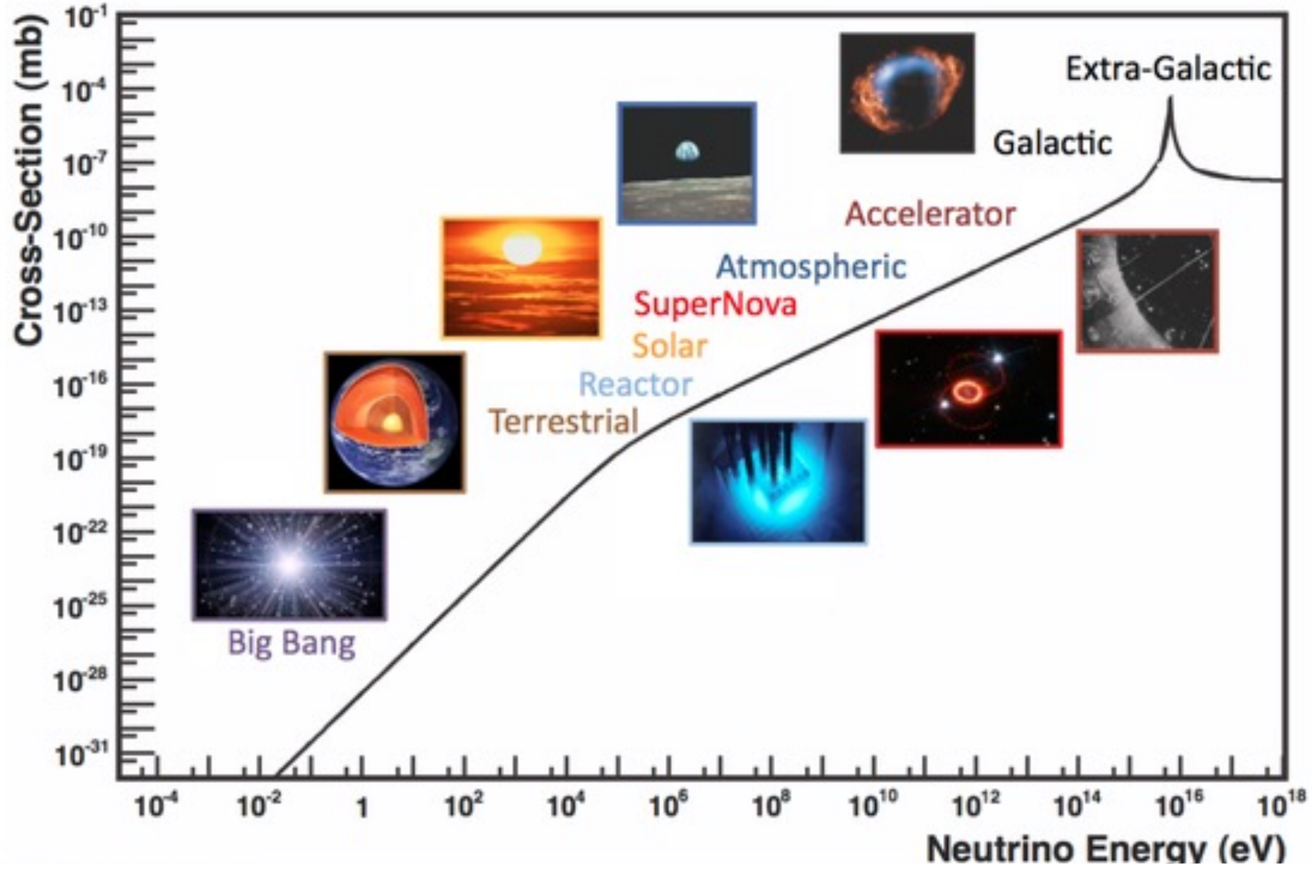


One would need 350 billion km lead to stop all neutrinos from the sun

Neutrino cross section (on nucleons)

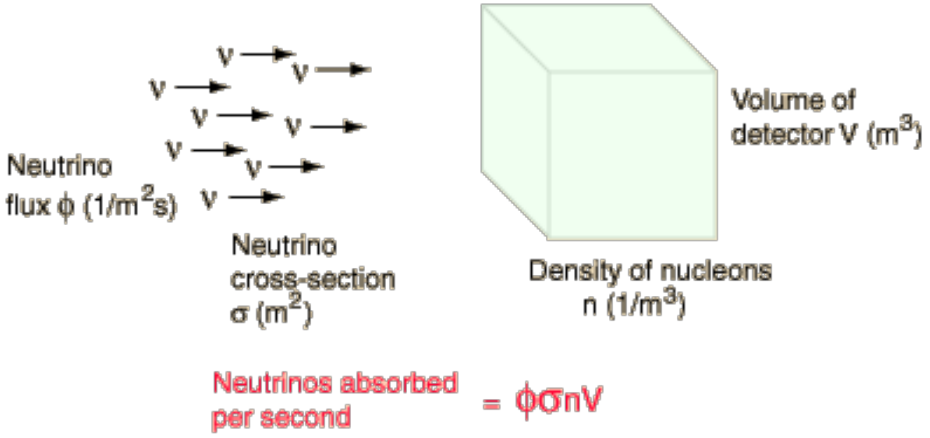
- 1 barn = 10^{-24} cm^2
- @1 MeV (solar, radioactive decay): $\sigma = 10^{-44}$ cm^2
- Comparison to electro-weak interaction: $e^+ + e^- \rightarrow \gamma\,\gamma$(1 MeV): $\sigma = 10^{-25}$ cm^2

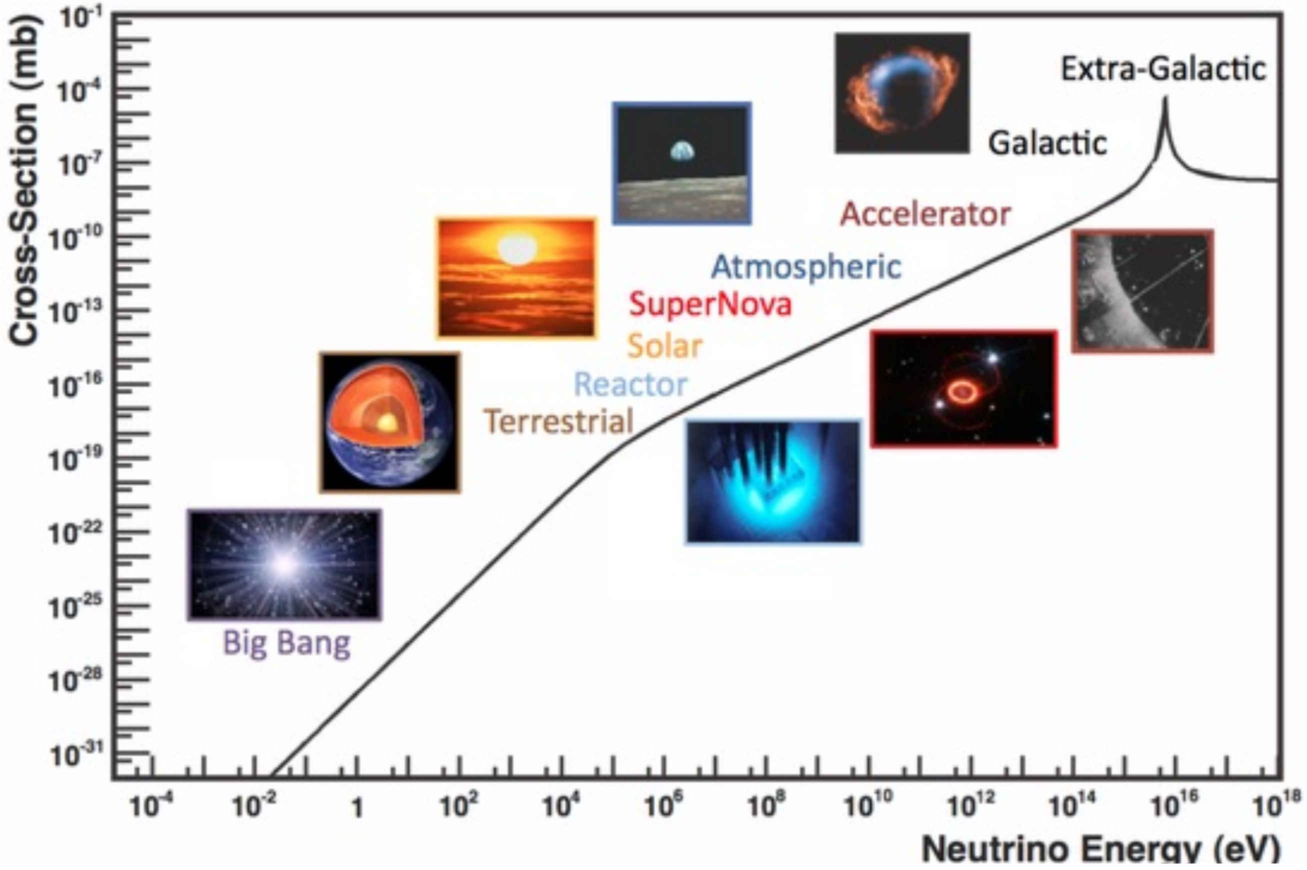




Neutrino cross section (on nucleons)

- 1 barn = 10^{-24} cm^2
- @1 GeV (accelerator, atmospheric): $\sigma = 10^{-38}$ cm^2
- Comparison to p-p interaction (1 GeV): $\sigma = 10^{-26}$ cm^2





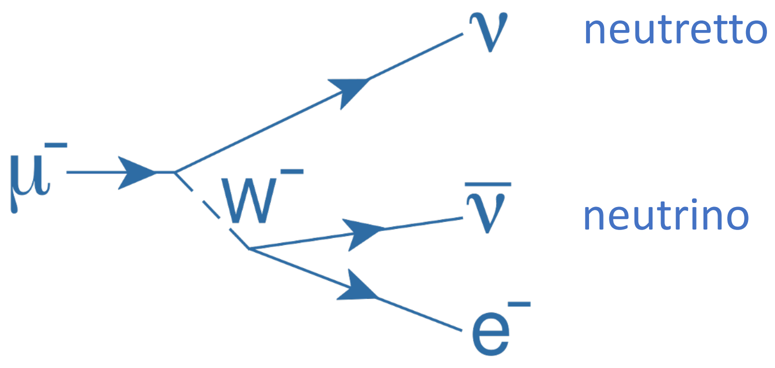
Muon neutrinos

A bit of history

- **1930**: Neutrino Predicted

- **1937**: Muon Discovered

- **1941**: Muon shown to decay into electron + neutrino(s)



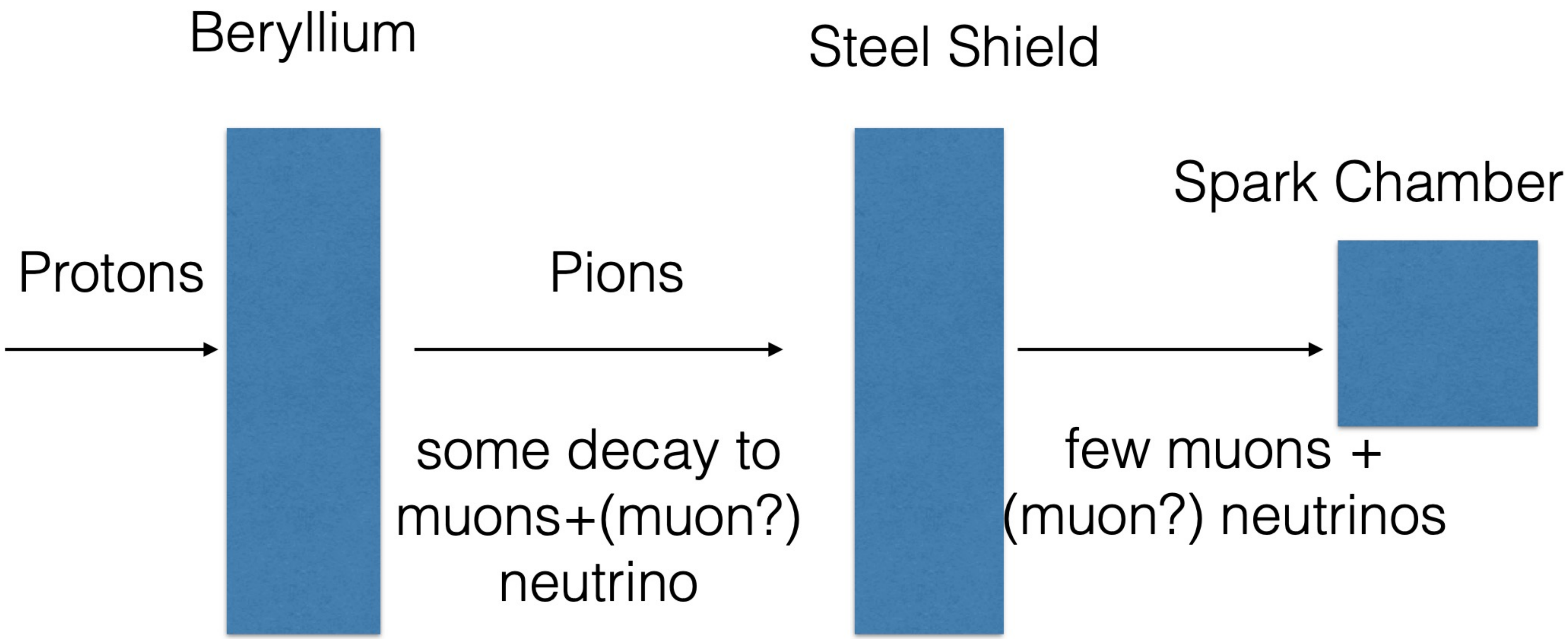
- **1948**: Energy spectrum of Muon decay shown to be continuous: there must be 2 neutrinos in the decay

  Most people felt that the neutrinos should be different, and they named them : neutrino and neutretto

- **1955**: (electron) antineutrino directly observed

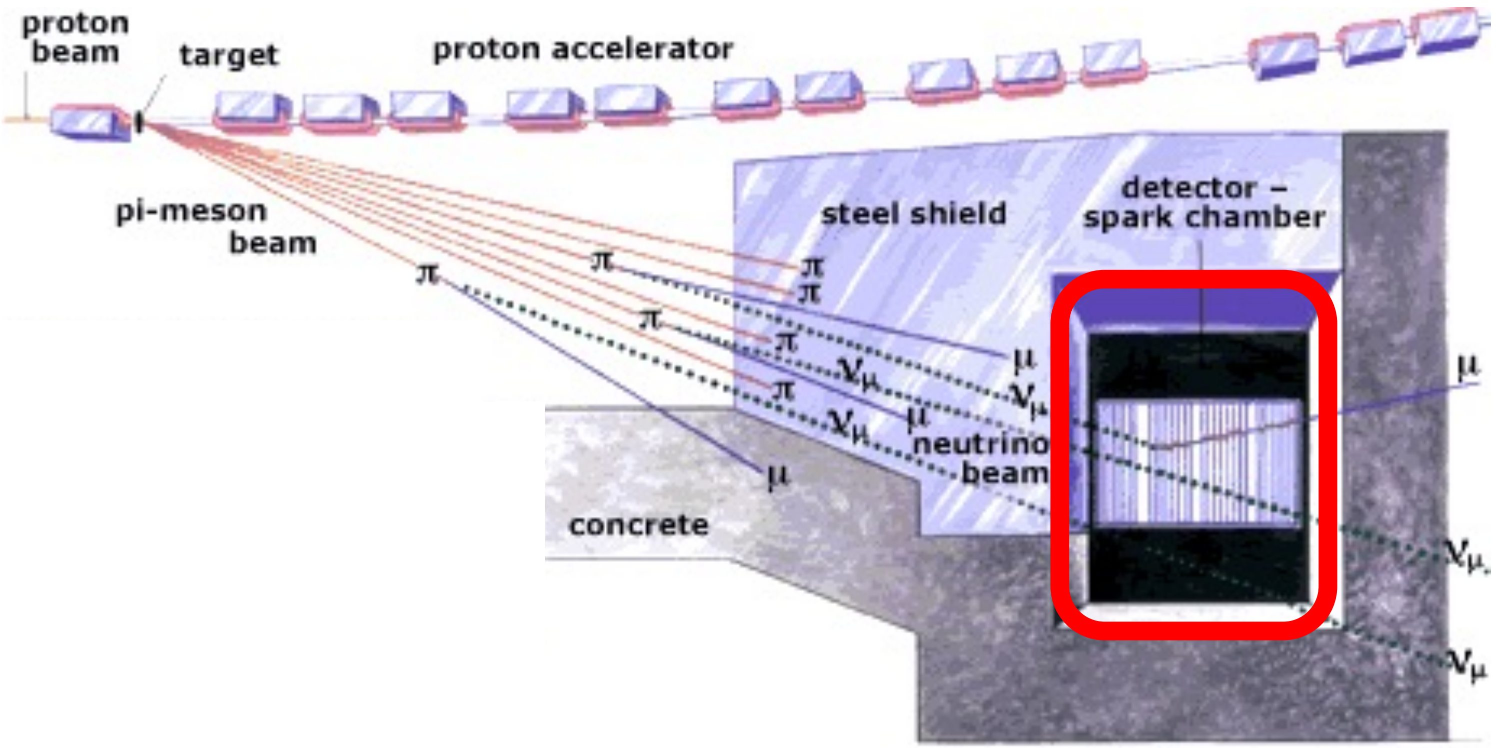
- **1962**: direct observation of muon neutrino

Muon neutrino discovery: experimental concept

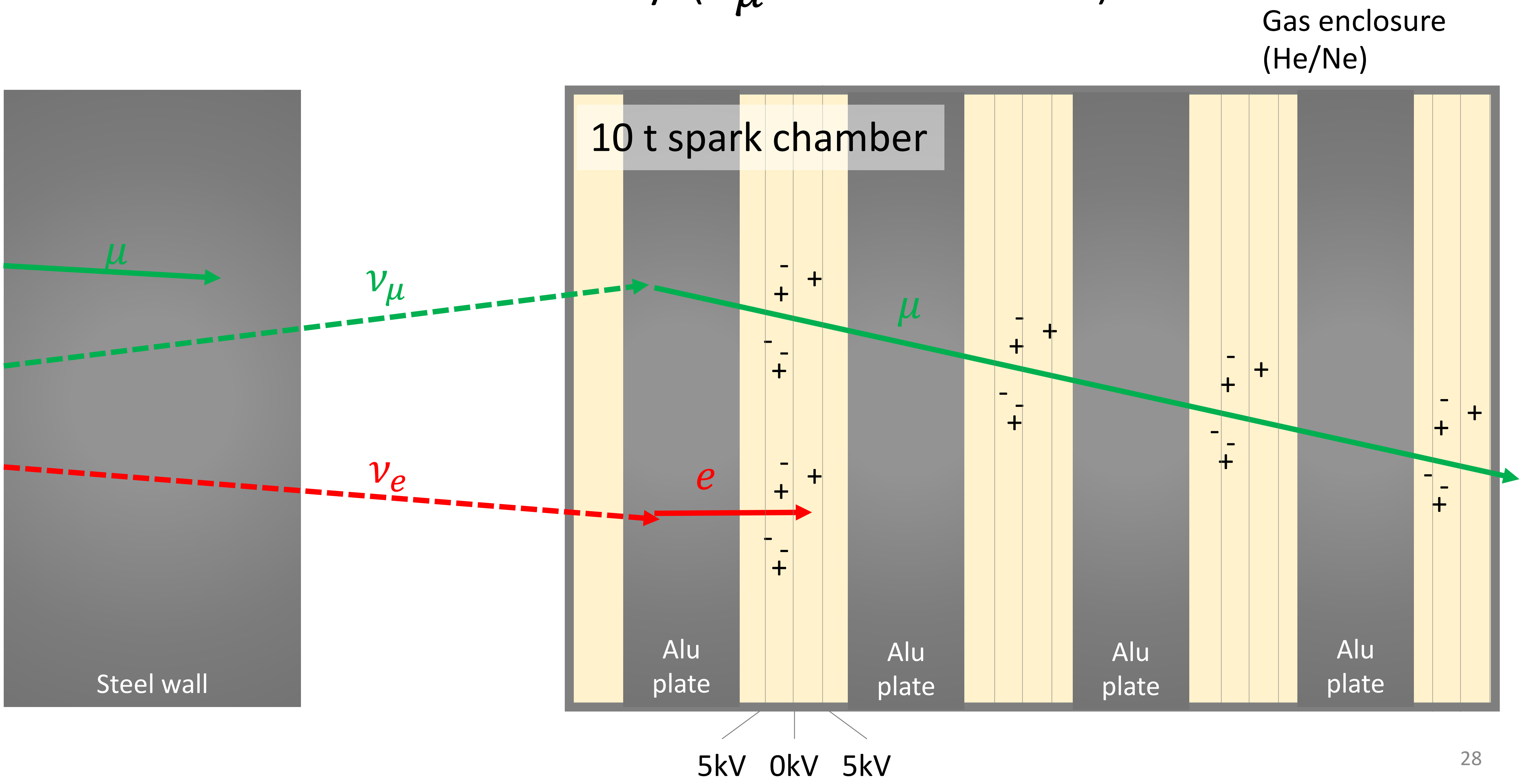


Muon neutrino discovery (ν_μ – detection)

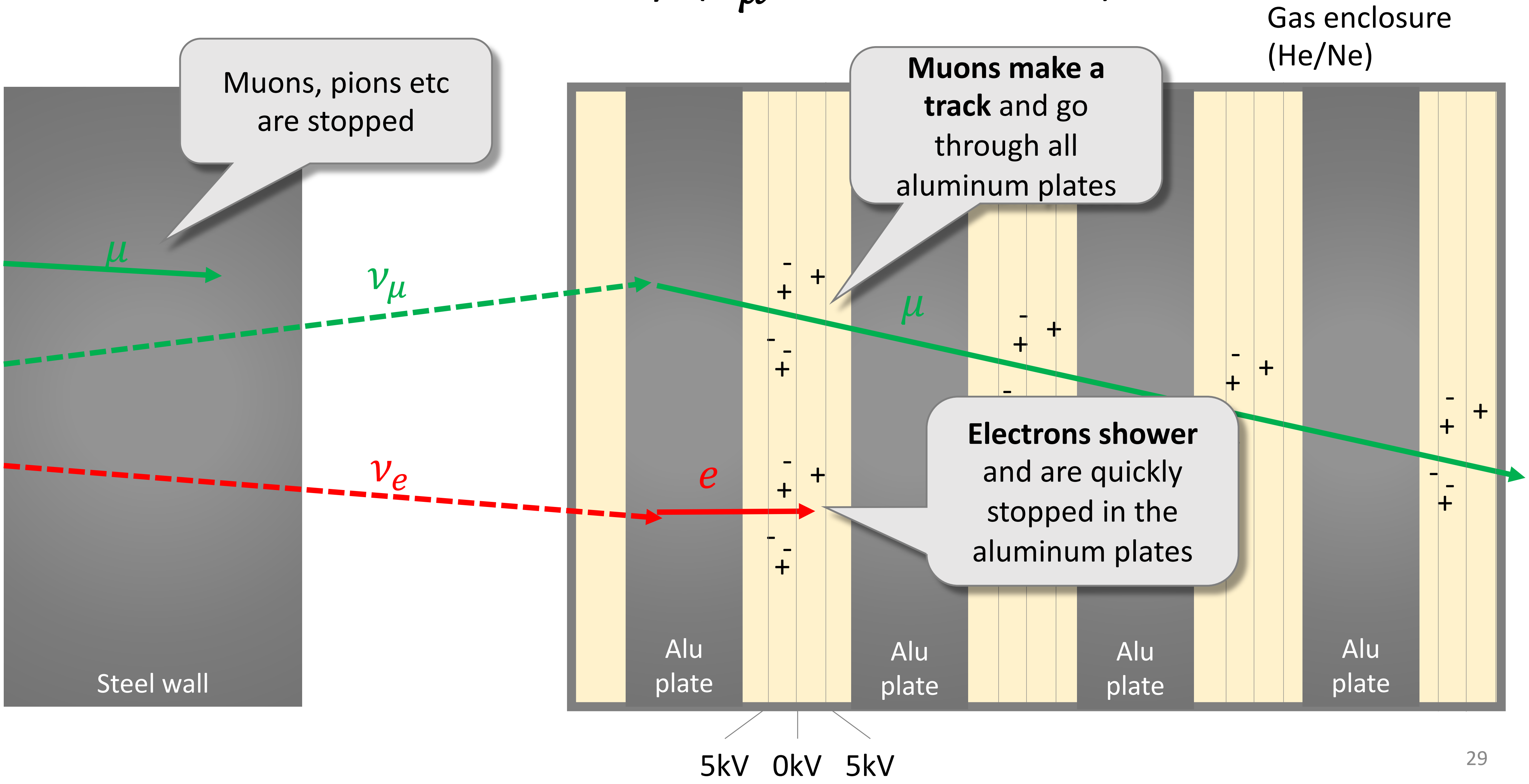
- Brookhaven National Laboratory Alternating Gradient Synchrotron (AGS) generates protons of 15 GeV
- Proton beam hits beryllium target, producing pions
- Pions decay into muons and muon-neutrinos
- Neutrinos, Pions, muons, etc. pass through a wall of 13.5 meters thick steel: only neutrinos pass
- Neutrinos detected in 10-ton spark chamber
- Muon and electron neutrino creates different signature



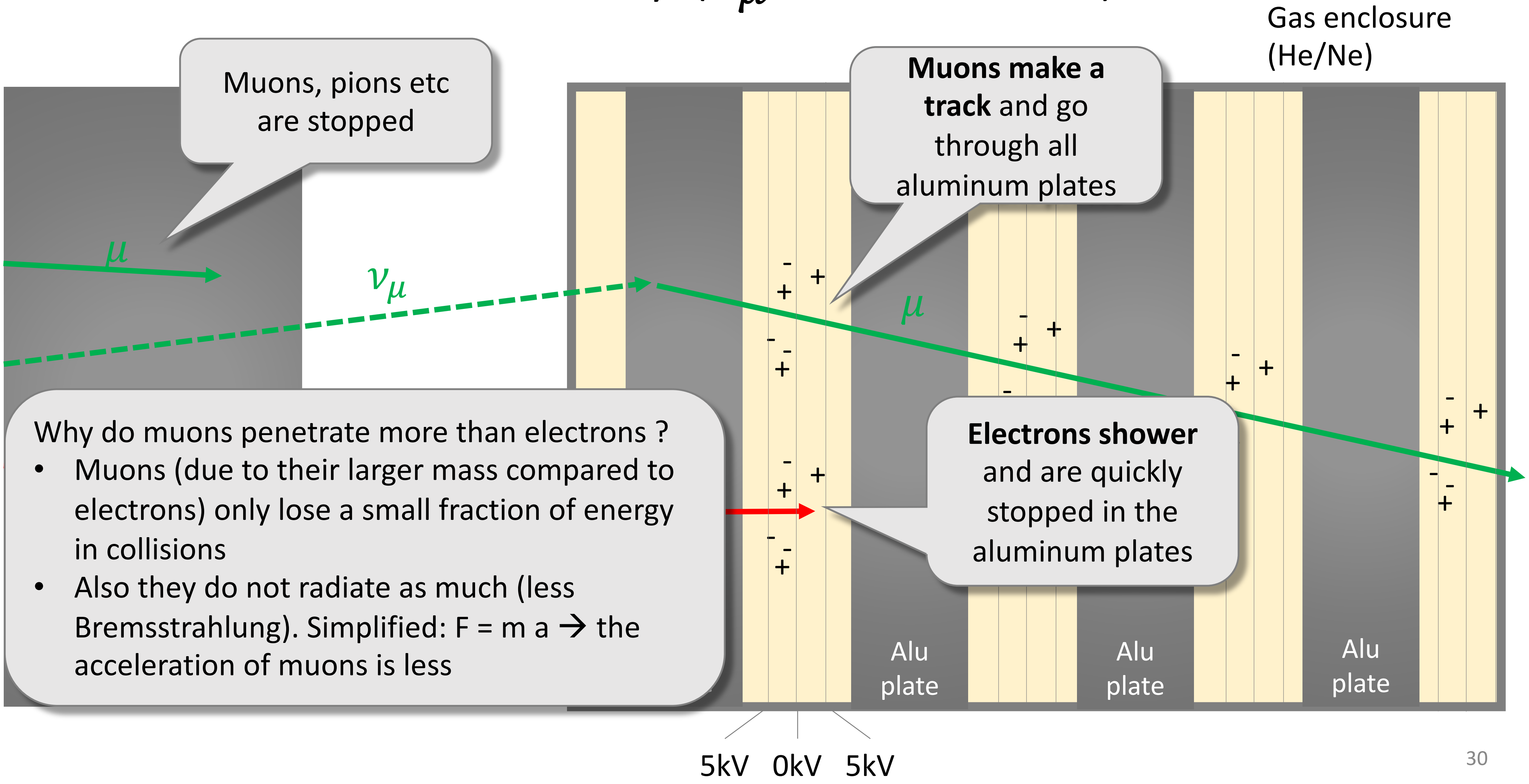
Muon neutrino discovery (ν_μ − detection)



Muon neutrino discovery (ν_μ – detection)



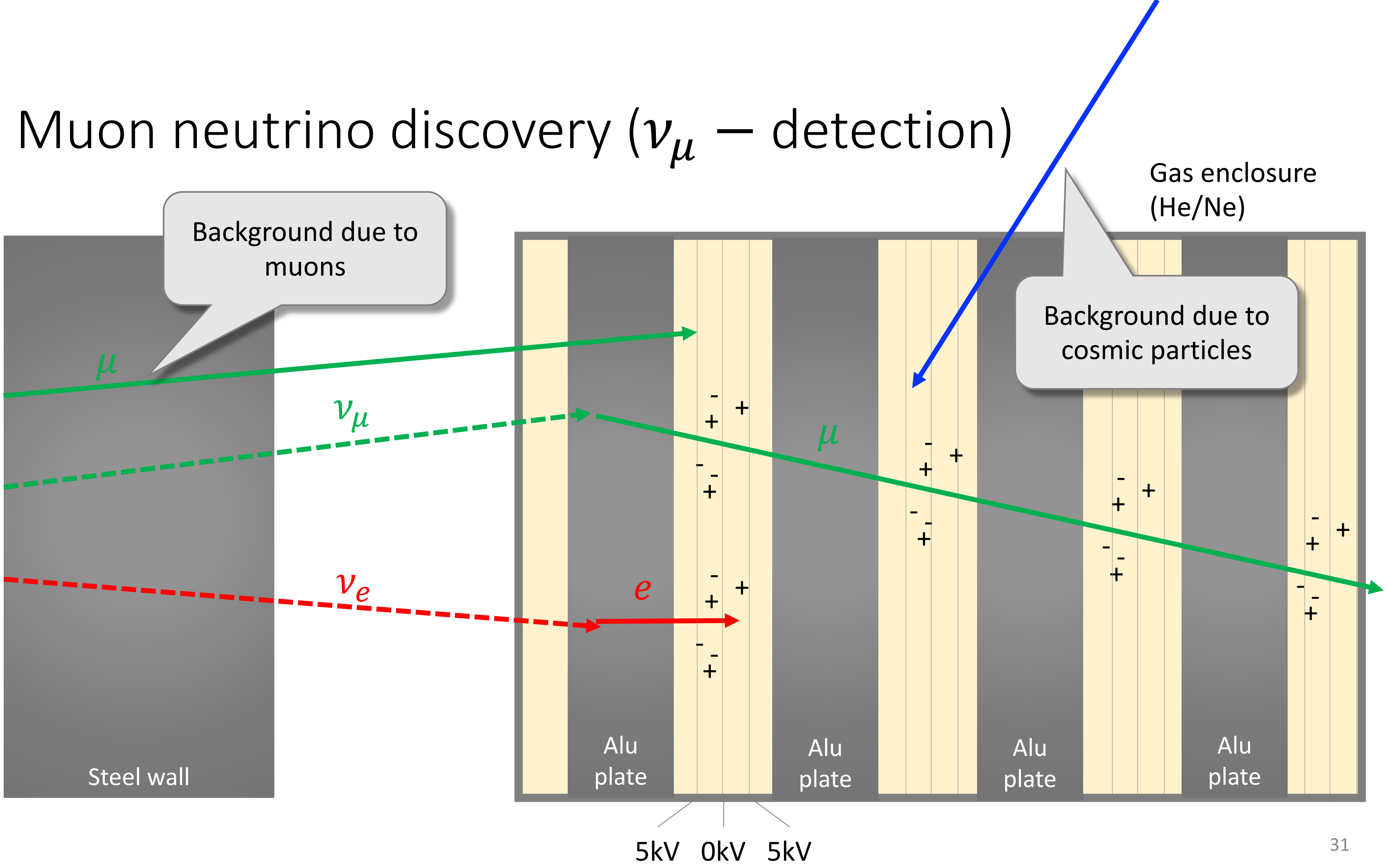
Muon neutrino discovery (ν_μ − detection)



Why do muons penetrate more than electrons ?

- Muons (due to their larger mass compared to electrons) only lose a small fraction of energy in collisions
- Also they do not radiate as much (less Bremsstrahlung). Simplified: F = m a → the acceleration of muons is less

Muon neutrino discovery (ν_μ − detection)



Muon neutrino discovery

- DAQ = 
- Detected 113 events
  (with 3.48×10^{17} protons on target)
- Of these, 34 were single muon events
- Only 6 electron neutrinos (showers) observed
- If there was no difference between muon neutrinos and electron neutrinos, we would expect a similar number of electron showers

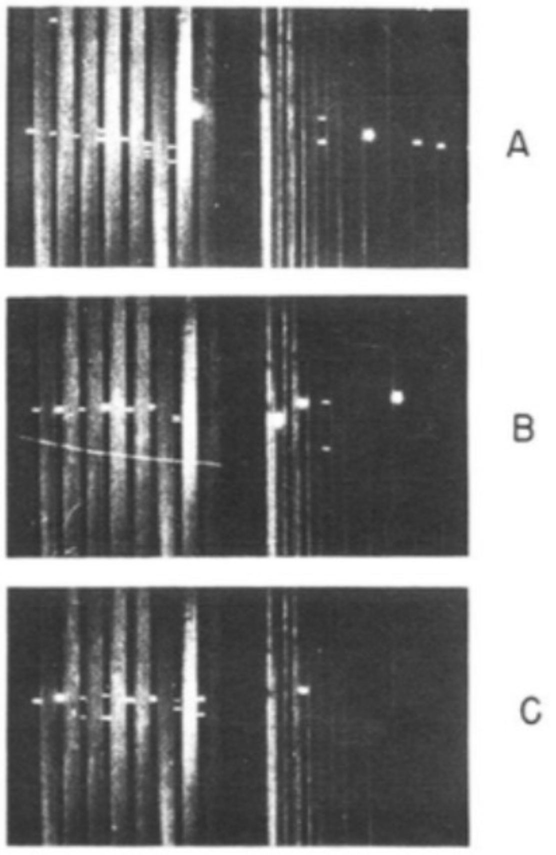


FIG. 8. 400-MeV electrons from the Cosmotron.

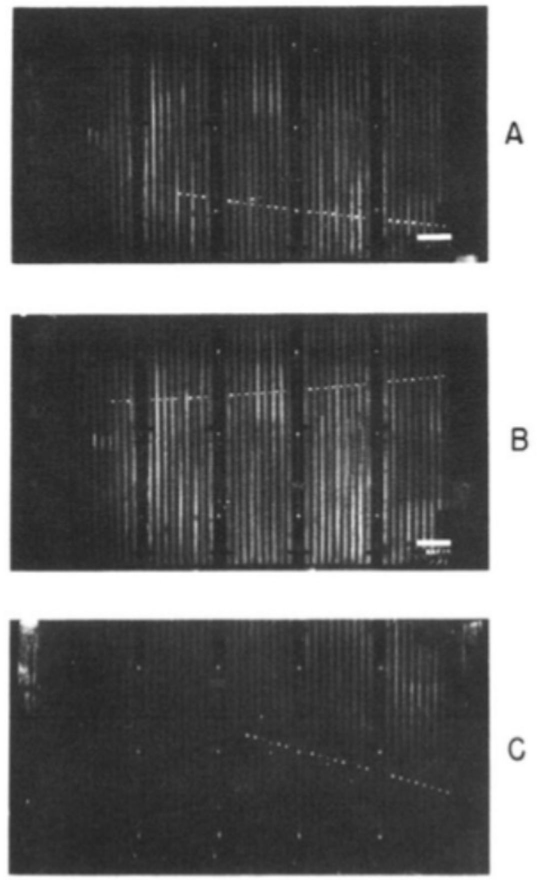


FIG. 5. Single muon events. (A) $p_\mu > 540$ MeV and δ ray indicating direction of motion (neutrino beam incident from left); (B) $p_\mu > 700$ MeV/c; (C) $p_\mu > 440$ with δ ray.

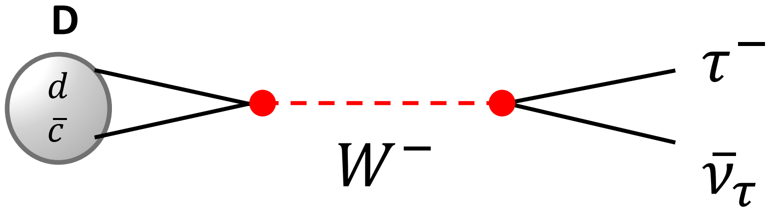
Muon neutrino discovery

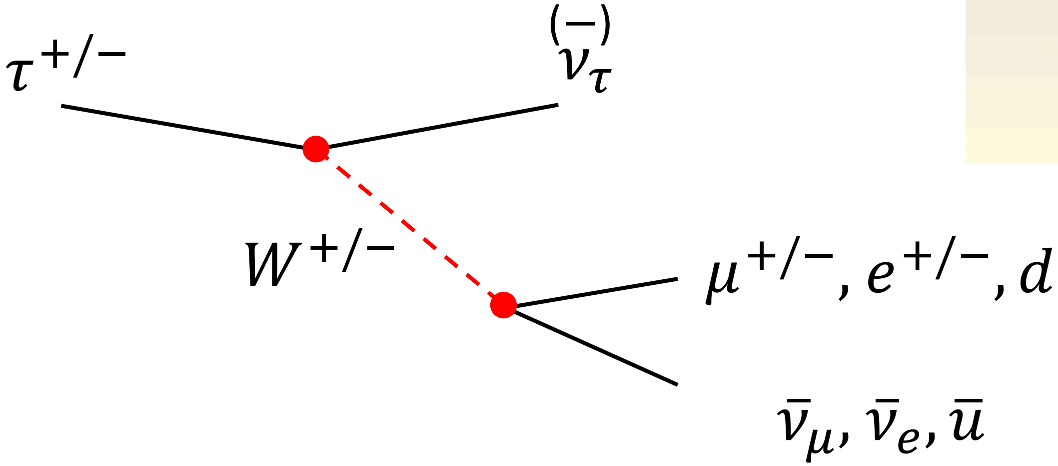
The Nobel Prize in Physics 1988: Leon M. Lederman, Melvin Schwartz and Jack Steinberger *"for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino"*.

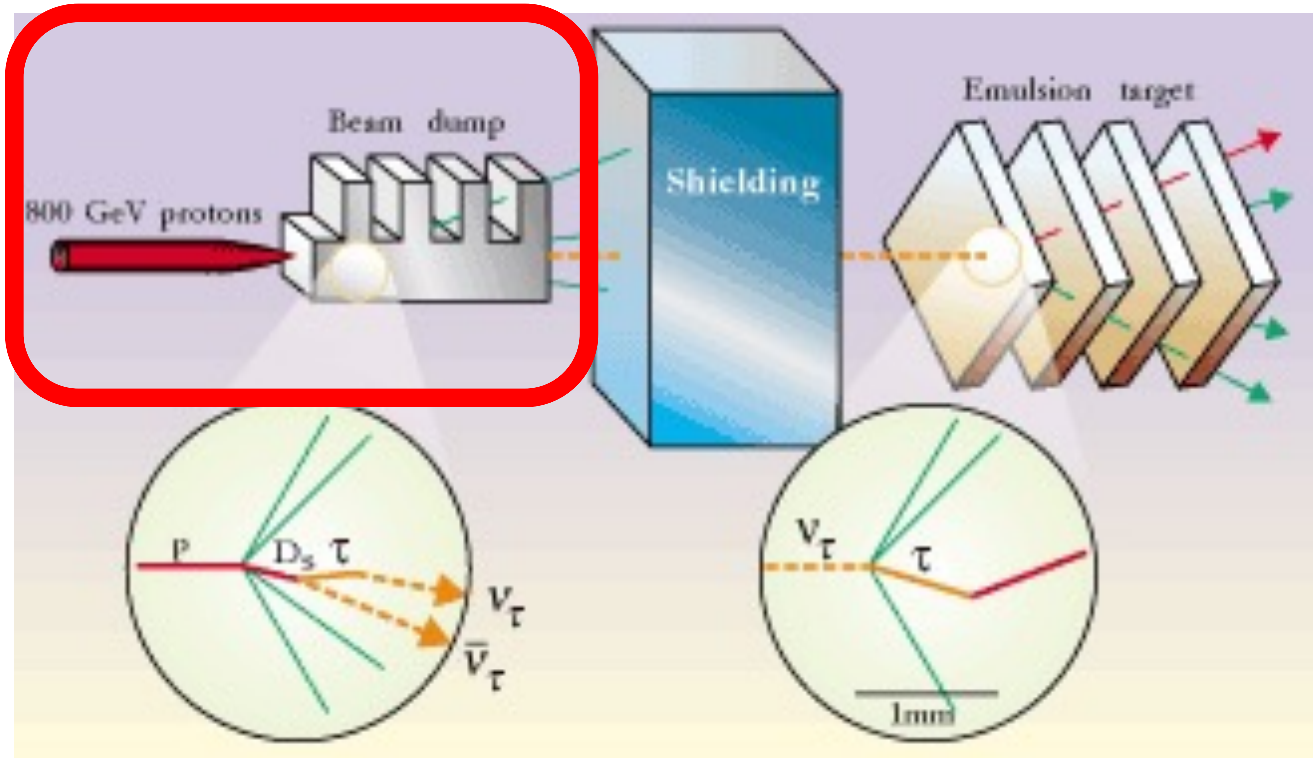
Tau neutrinos

Tau neutrino discovery

- Protons accelerated by the Tevatron (Fermilab) produce tau neutrinos via decay of charmed mesons



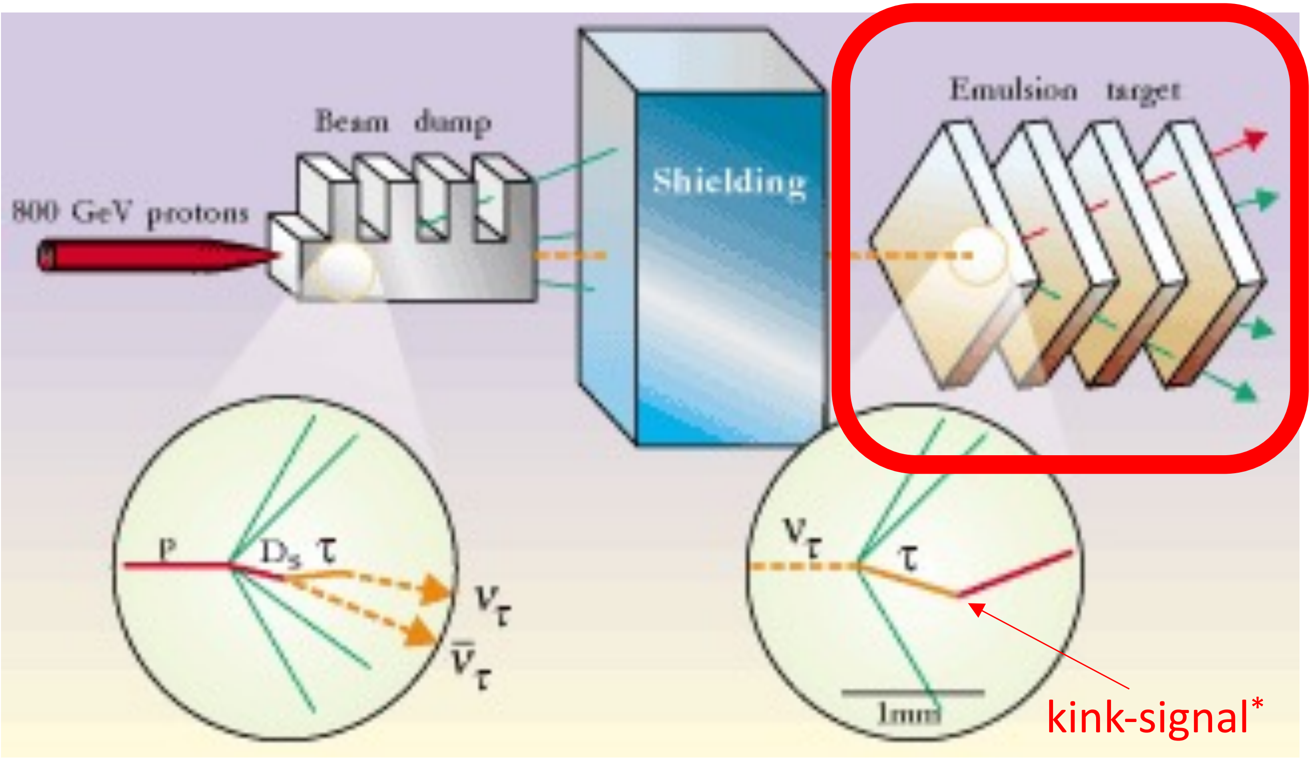


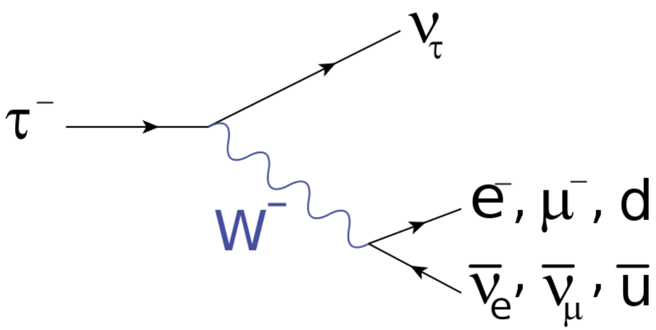


Tau neutrino discovery

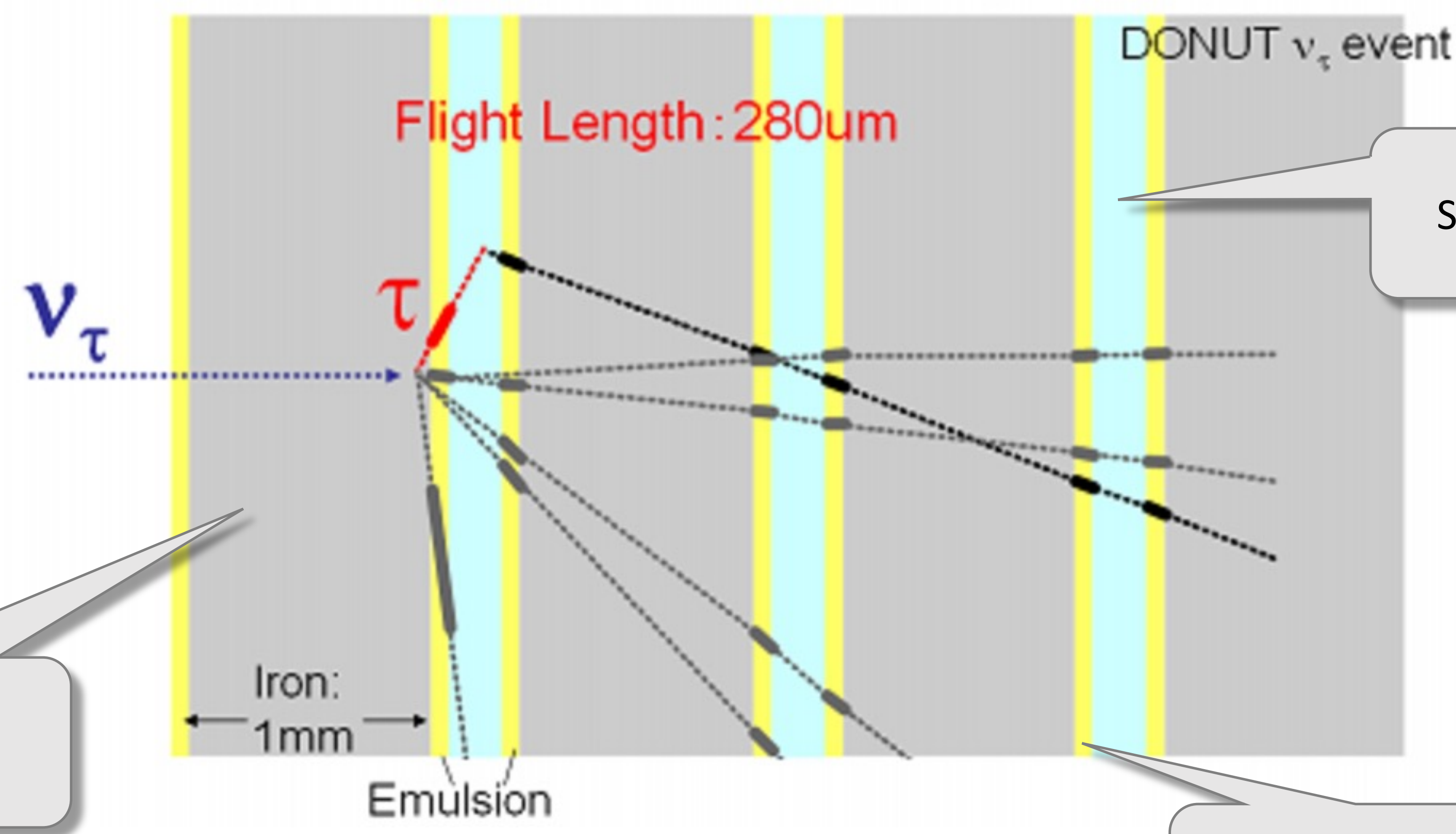
- Protons accelerated by the Tevatron produce tau neutrinos via decay of charmed mesons
- Shielding and magnetic deflection stops/removes all particles but the neutrinos
- Tau neutrino interacts in steel target and produces a tau
- Tau travels for 1mm, leaves a track in the emulsion, then decays into a neutrino and charged particles
- Charged particles leave a track in the emulsion

➢ Famous kink-signal*





Tau neutrino discovery

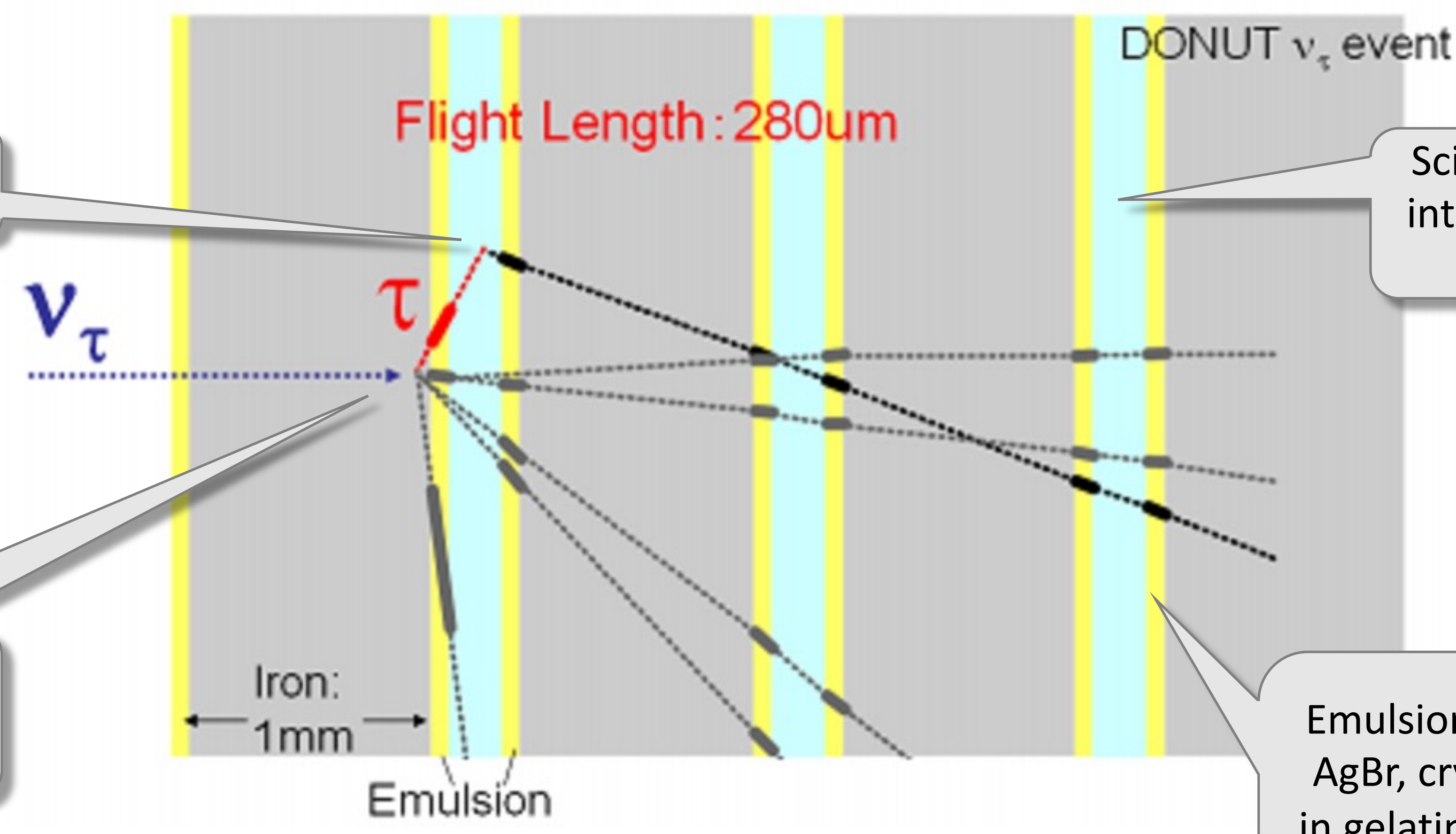


Scintillator: why?

Iron: why?

Emulsion: why?

Tau neutrino discovery



Famous kink

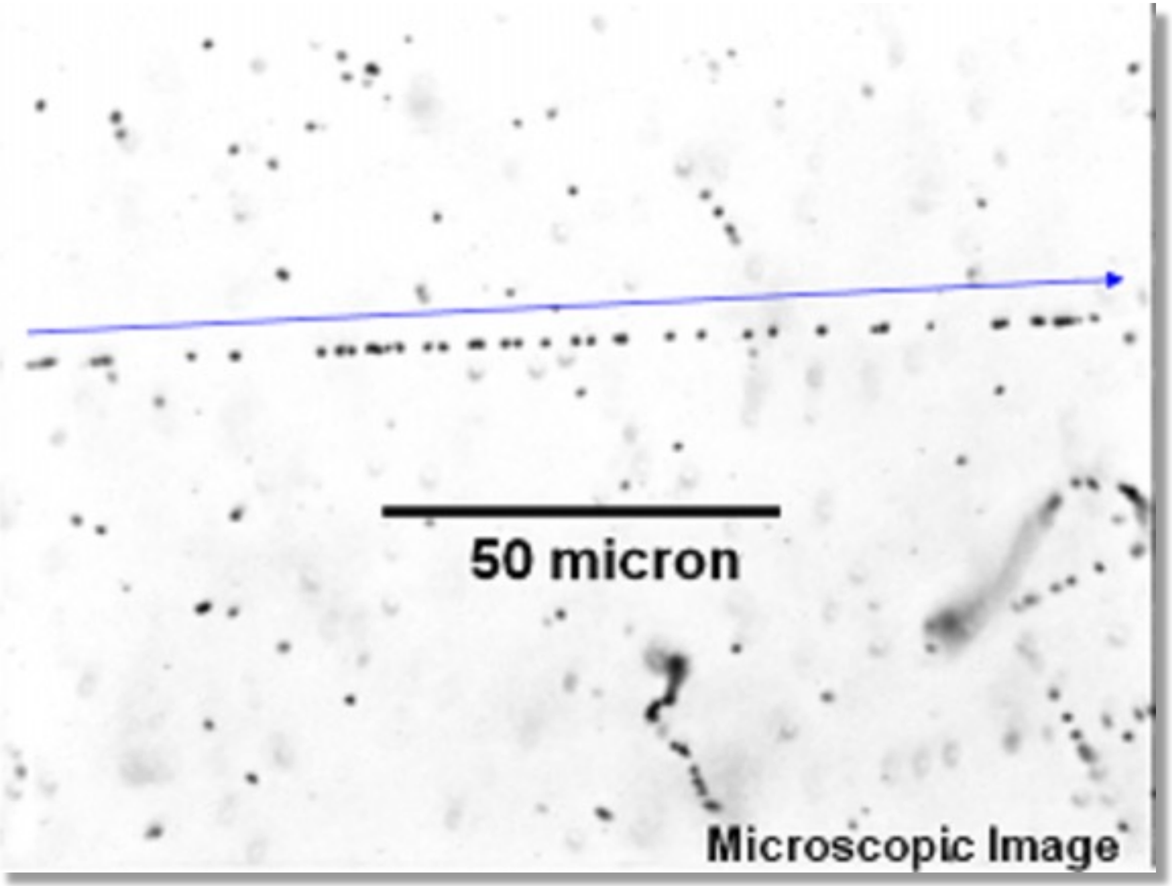
Scintillator to locate interesting emulsion sheets

Neutrino interacts in iron (high Z)

Emulsion (silver bromide, AgBr, crystals suspended in gelatin solution) takes a photo (developed later)

Tau neutrino discovery

- The DONUT (Direct Observation of the Nu Tau) experiment recorded a total of six million potential interactions.
- Four events provided evidence for the tau neutrino in 2000
- Last particle to be discovered before the Higgs boson in 2012



Discovery of the neutrinos (Overview)

	Electron ν	Muon ν	Tau ν
Source	Reactor: Electron Anti-neutrinos	Accelerator: Pions → Muon neutrinos	Accelerator: Charmed mesons → tau neutrinos
Detector	Water with Cadmium + Scintillator	Aluminum Plates + Spark Chamber	Lead + Scintillator + Emulsion sheet layers
Signature	Coincidence signal	Long tracks	Kink
Location	Hanford reactor site, USA	Brookhaven, USA	Tevatron @ Fermilab, USA
People/Group	Reines, Cowan	Ledermann, Schwartz, Steinberger	DONUT Collaboration
Year	1957 	1962 	2000

Neutrino Oscillation

Neutrino Flavours und Masses

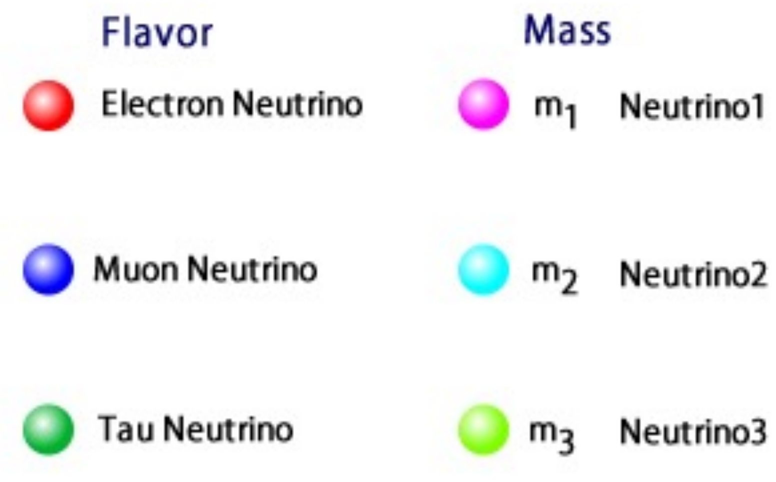
Key ingredient 1:

- A neutrino with a specific **mass** has no specific **flavor**
- A neutrino with a specific **flavor** has no specific **mass**

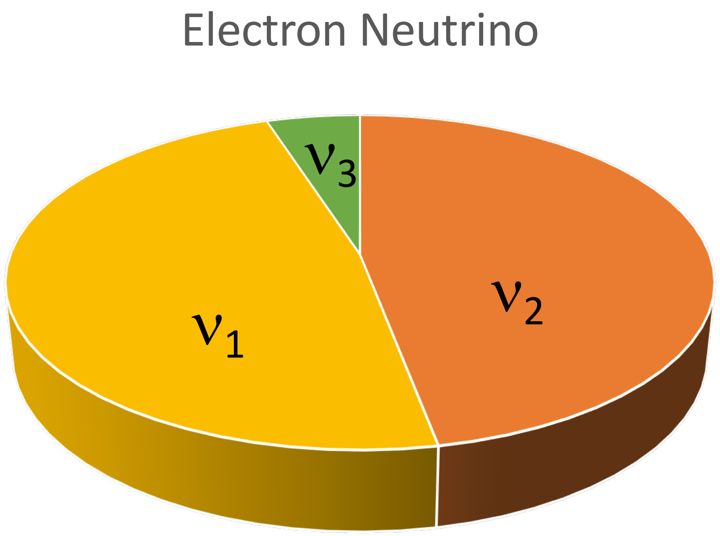
Key ingredient 2:

- Neutrino is born in a flavor eigenstate, but propagates as mass eigenstate
- Neutrino mass eigenstates evolve differently with time

$$e^{-i\hat{H}t/\hbar}\left|v_e\right\rangle = U_{e1}\cdot e^{-iE_1t/\hbar}\left|v_1\right\rangle + U_{e2}\cdot e^{-iE_2t/\hbar}\left|v_2\right\rangle + U_{e3}\cdot e^{-iE_3t/\hbar}\left|v_3\right\rangle$$



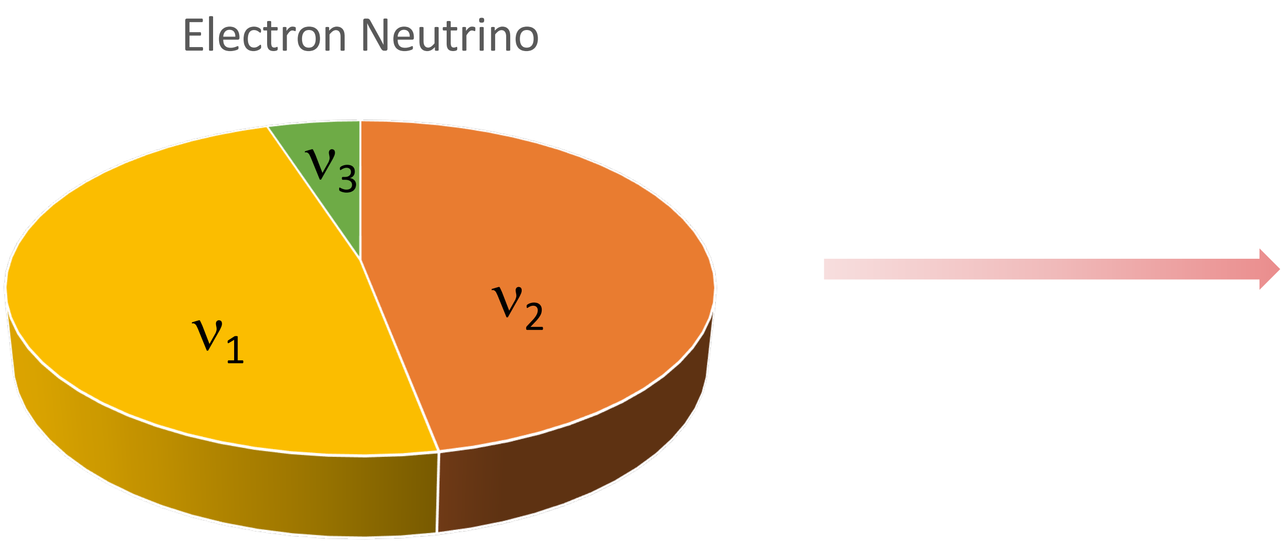
Neutrino Oscillations



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

t=0 $$|\nu_e\rangle = U_{e1} \cdot |\nu_1\rangle + U_{e2} \cdot |\nu_2\rangle + U_{e3} \cdot |\nu_3\rangle$$

Neutrino Oscillations



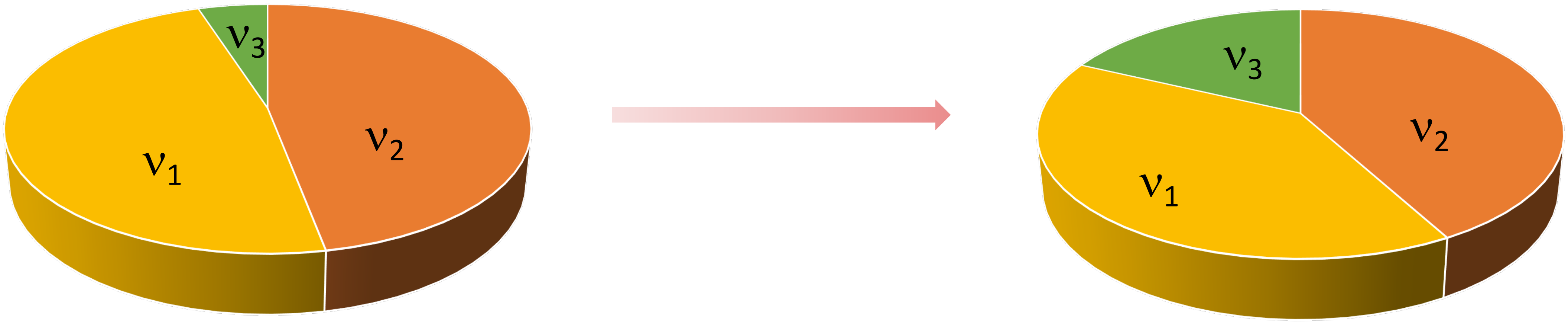
t=0 $$|\nu_e\rangle = U_{e1}\cdot|\nu_1\rangle + U_{e2}\cdot|\nu_2\rangle + U_{e3}\cdot|\nu_3\rangle$$

t>0 $$e^{-i\hat{H}t/\hbar}|\nu_e\rangle = U_{e1}\cdot e^{-i\hat{H}t/\hbar}|\nu_1\rangle + U_{e2}\cdot e^{-i\hat{H}t/\hbar}|\nu_2\rangle + U_{e3}\cdot e^{-i\hat{H}t/\hbar}|\nu_3\rangle$$

Neutrino Oscillations

Electron Neutrino

??? Neutrino



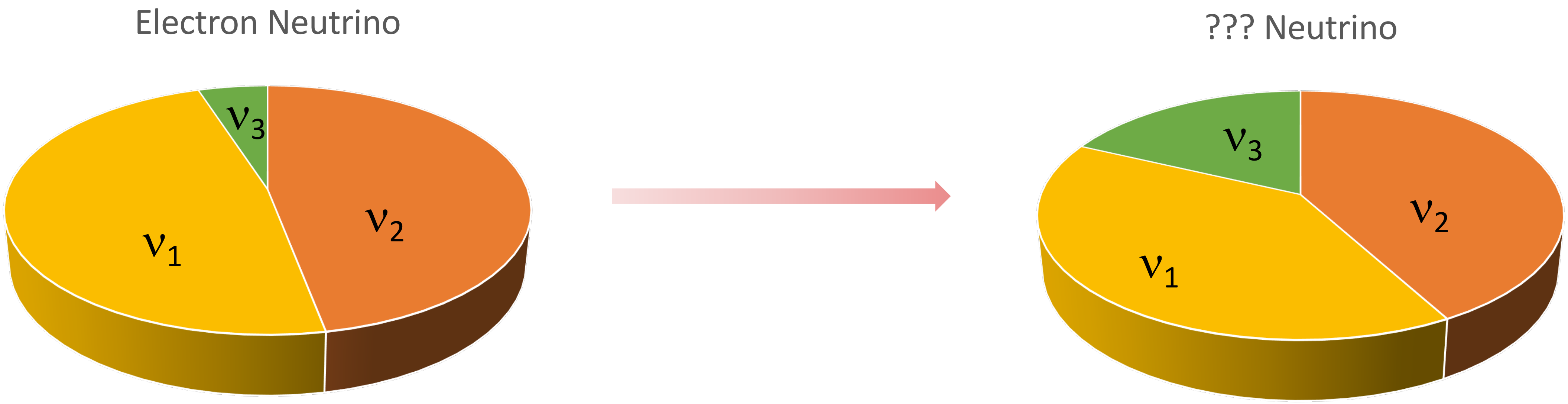
t=0 $$|\nu_e\rangle = U_{e1}\cdot|\nu_1\rangle + U_{e2}\cdot|\nu_2\rangle + U_{e3}\cdot|\nu_3\rangle$$

t>0 $$e^{-i\hat{H}t/\hbar}|\nu_e\rangle = U_{e1}\cdot e^{-i\hat{H}t/\hbar}|\nu_1\rangle + U_{e2}\cdot e^{-i\hat{H}t/\hbar}|\nu_2\rangle + U_{e3}\cdot e^{-i\hat{H}t/\hbar}|\nu_3\rangle$$

$$e^{-i\hat{H}t/\hbar}|\nu_e\rangle = U_{e1}\cdot e^{-iE_1t/\hbar}|\nu_1\rangle + U_{e2}\cdot e^{-iE_2t/\hbar}|\nu_2\rangle + U_{e3}\cdot e^{-iE_3t/\hbar}|\nu_3\rangle$$

The three mass eigenstates evolve differently in time

Neutrino Oscillations



t=0 $$|\nu_e\rangle = U_{e1}\cdot|\nu_1\rangle + U_{e2}\cdot|\nu_2\rangle + U_{e3}\cdot|\nu_3\rangle$$

t>0 $$e^{-i\hat{H}t/\hbar}|\nu_e\rangle = U_{e1}\cdot e^{-i\hat{H}t/\hbar}|\nu_1\rangle + U_{e2}\cdot e^{-i\hat{H}t/\hbar}|\nu_2\rangle + U_{e3}\cdot e^{-i\hat{H}t/\hbar}|\nu_3\rangle$$

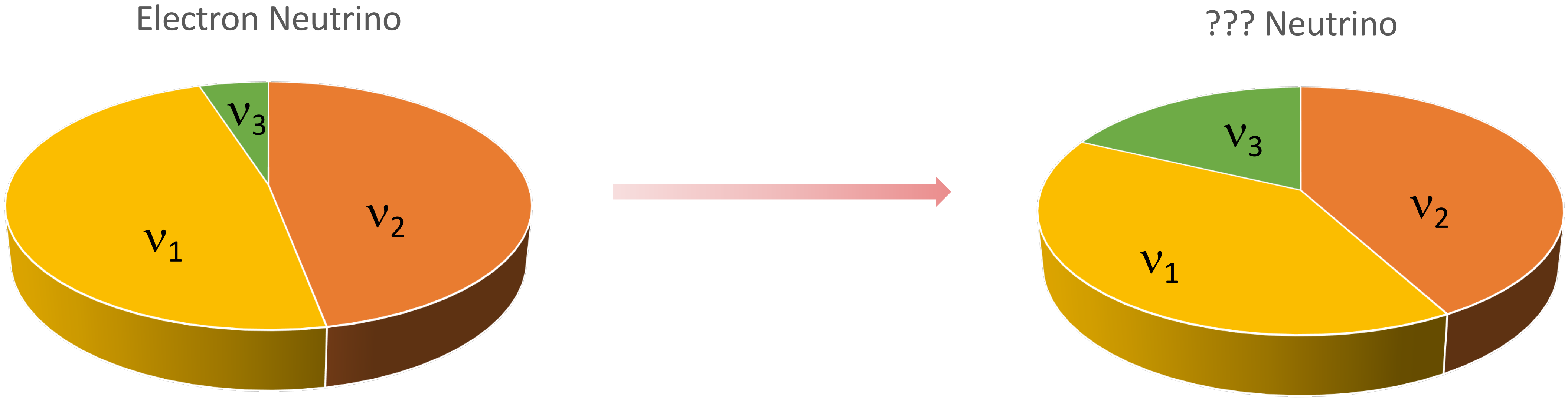
$$|\nu_x\rangle = U_{e1}\cdot e^{-iE_1t/\hbar}|\nu_1\rangle + U_{e2}\cdot e^{-iE_2t/\hbar}|\nu_2\rangle + U_{e3}\cdot e^{-iE_3t/\hbar}|\nu_3\rangle$$

The neutrino is no longer a pure electron neutrino

Neutrino Oscillations

Projection onto the electron flavor gives us the probability to detect an electron neutrino

$$P = \left|\langle \nu_e | \nu_x \rangle\right|^2$$



t=0

$$|\nu_e\rangle = U_{e1} \cdot |\nu_1\rangle + U_{e2} \cdot |\nu_2\rangle + U_{e3} \cdot |\nu_3\rangle$$

t>0

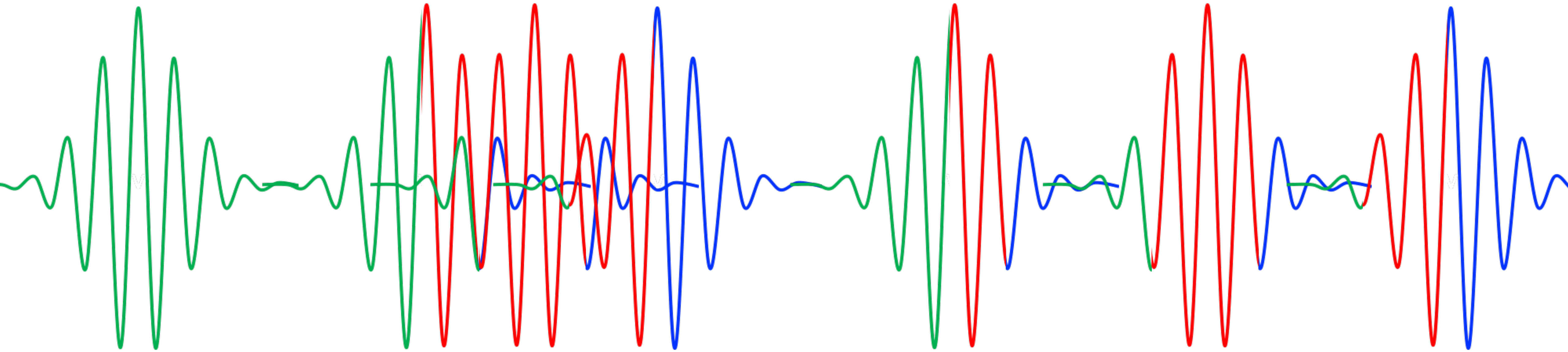
$$e^{-i\hat{H}t/\hbar}|\nu_e\rangle = U_{e1} \cdot e^{-i\hat{H}t/\hbar}|\nu_1\rangle + U_{e2} \cdot e^{-i\hat{H}t/\hbar}|\nu_2\rangle + U_{e3} \cdot e^{-i\hat{H}t/\hbar}|\nu_3\rangle$$

$$|\nu_x\rangle = U_{e1} \cdot e^{-iE_1 t/\hbar}|\nu_1\rangle + U_{e2} \cdot e^{-iE_2 t/\hbar}|\nu_2\rangle + U_{e3} \cdot e^{-iE_3 t/\hbar}|\nu_3\rangle$$

The neutrino is no longer a pure electron neutrino

Another view…

Production | **Interference → oscillations** | **Dehoherence**

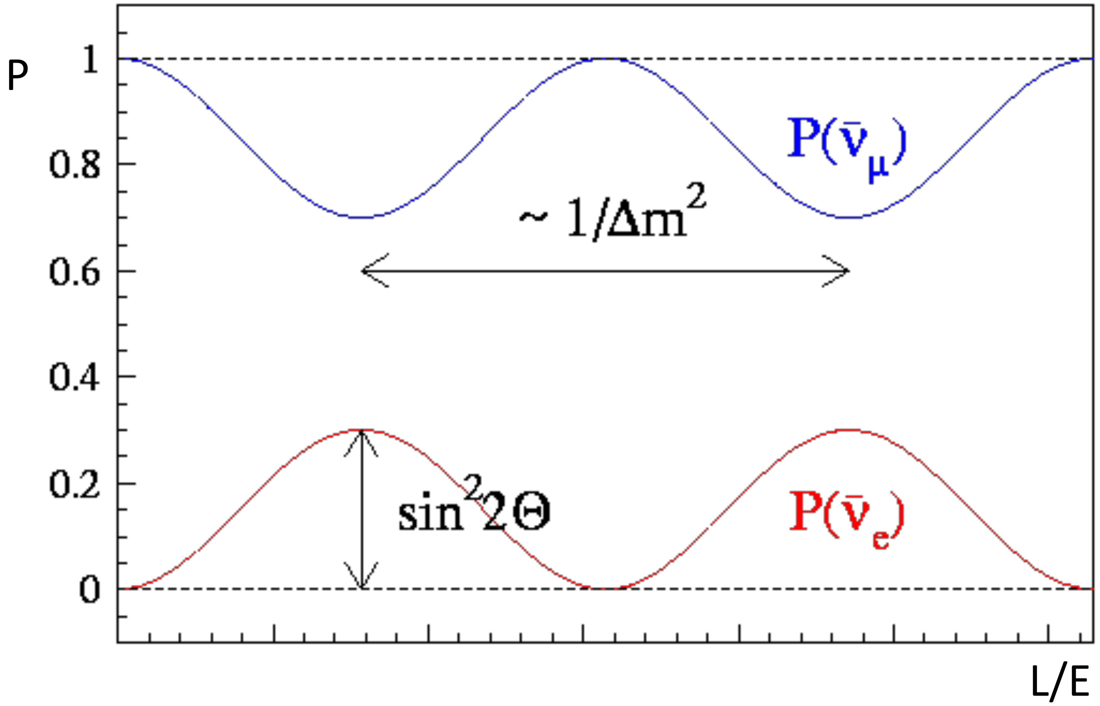


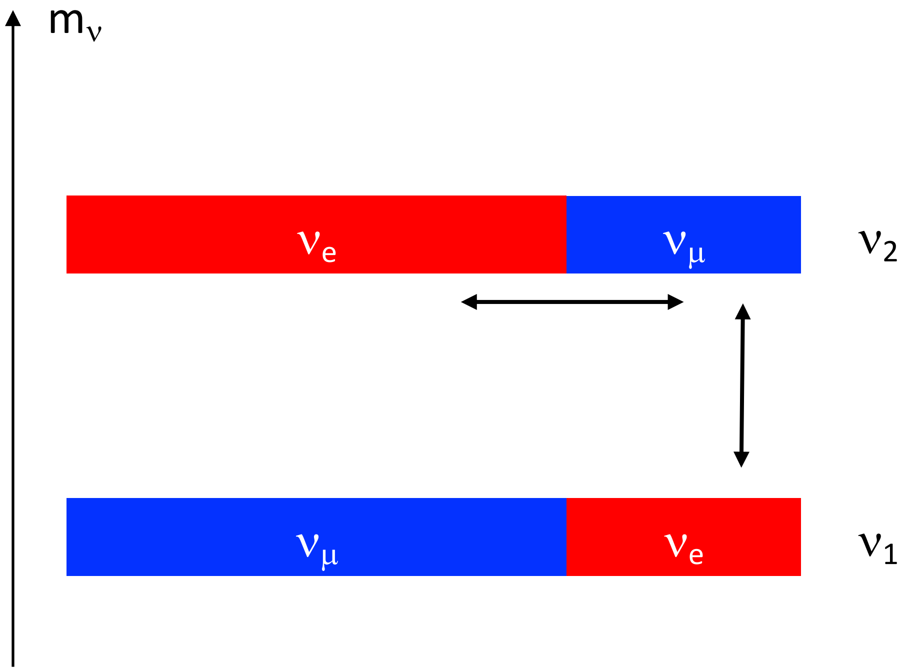
Neutrino produced as flavor eigenstate

Neutrino mass eigenstates propagate. Interference pattern determines probability to detect a specific neutrino flavor

Neutrino mass eigenstates are well separated. No more neutrino oscillations

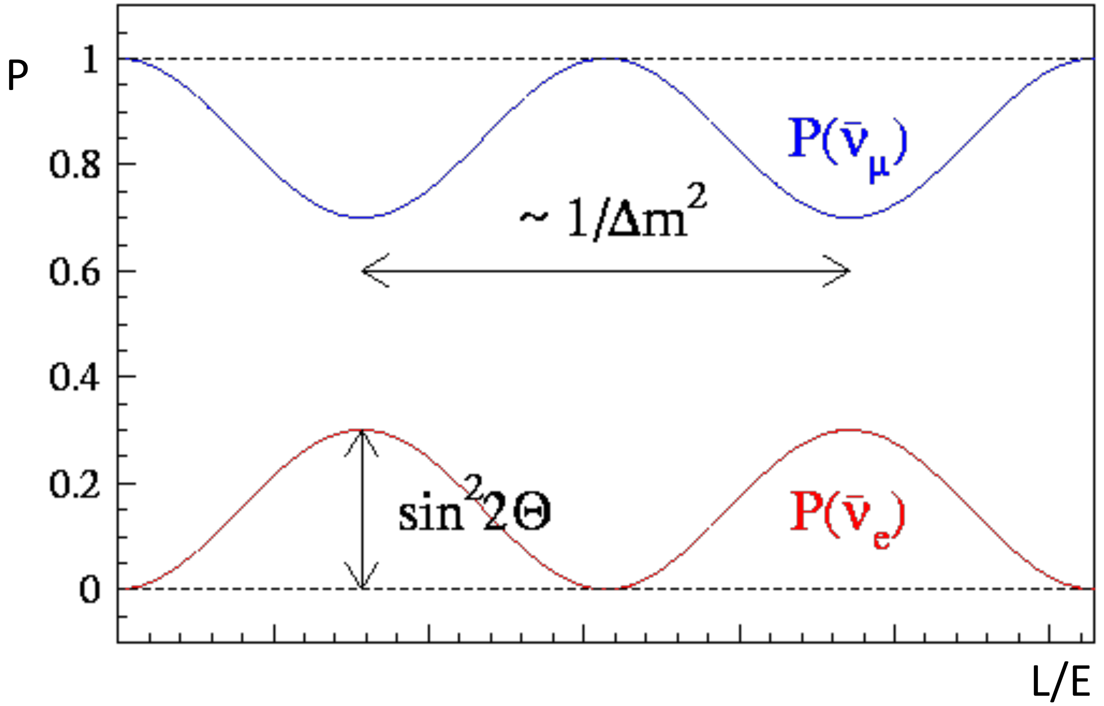
Neutrino Oscillations (for 2 Flavour)

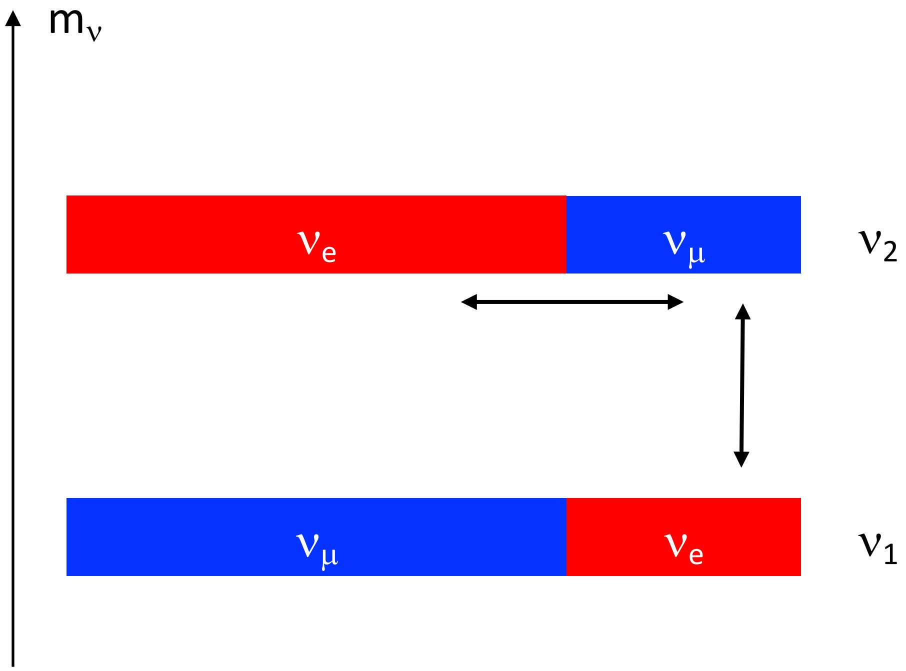




$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \cdot \sin^2(\Delta m^2 \cdot L_\nu / E_\nu)$$

Neutrino Oscillations (for 2 Flavour)





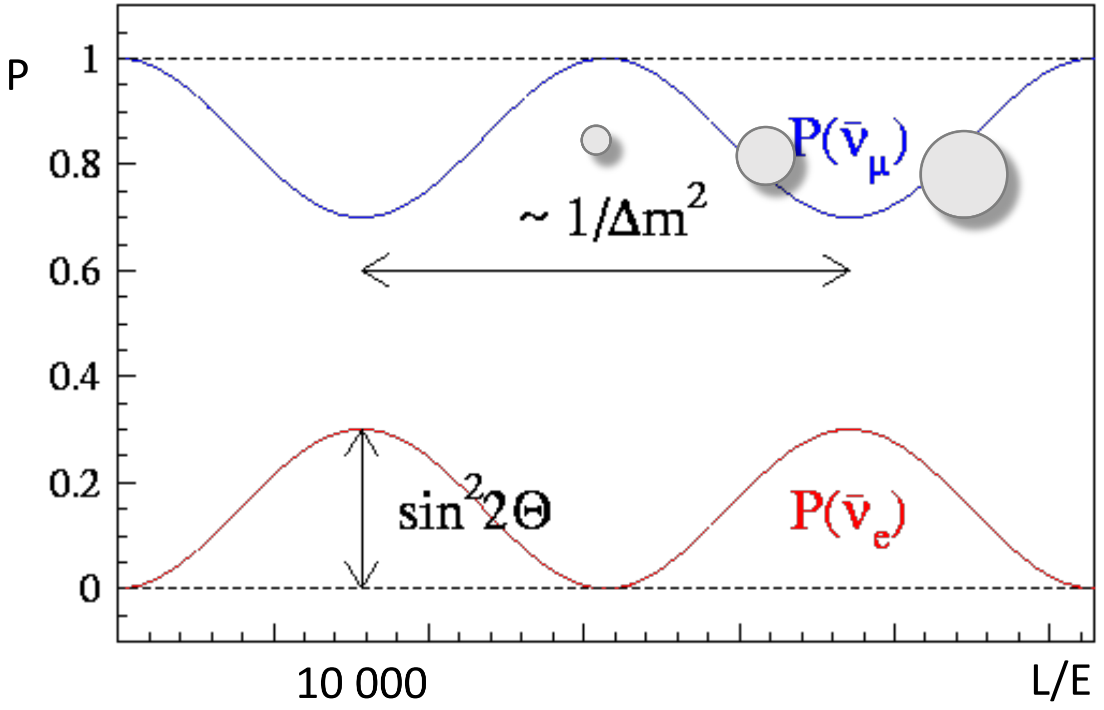
$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \, \sin^2(\Delta m^2 \cdot L_\nu / E_\nu)$$

Amplitude

Frequency

$$\Delta m^2 = m_1^2 - m_2^2$$

Neutrino Oscillations (for 2 Flavour)



In numbers (example):

For **$\Delta m^2 = 10^{-4}$ eV²:**

$1.27 \times 10^{-4} \times$ 10 000 $\approx \pi/2$

→ L/E ~ 10 000 m/MeV

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \, \sin^2(\Delta m^2 \cdot L_\nu / E_\nu)$$

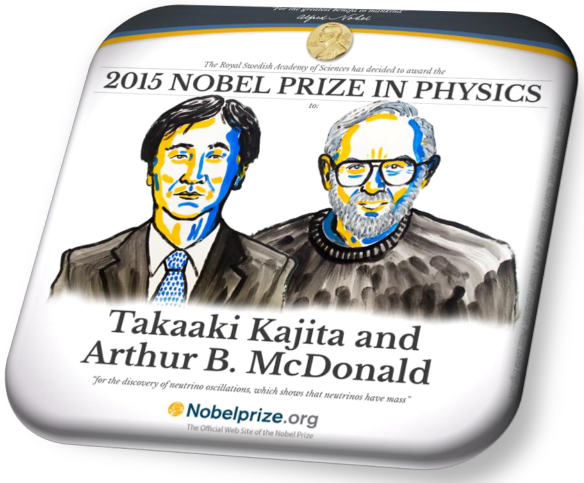
Amplitude   Frequency

$= \sin^2 2\theta \, \sin^2(1.27 \, \Delta m^2 \, L_\nu(\mathrm{km})/E_\nu(\mathrm{GeV}))$

Nobel Prize in Physics 2015

Takaaki Kajita and Arthur B. McDonald:

“for the discovery of neutrino oscillations, which shows that neutrinos have mass”

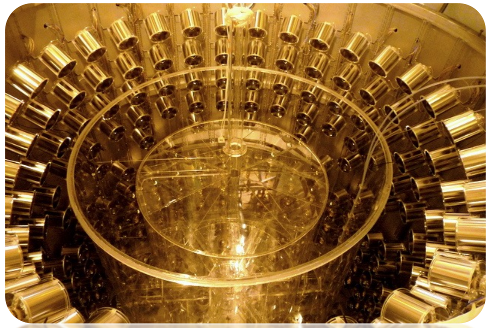


3-Flavour mixing, historically referred as:

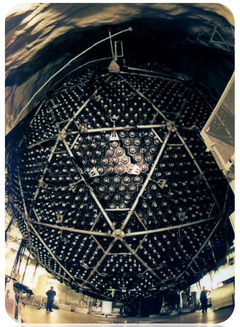
atmospheric mixing (45°) | reactor mixing (small $\theta_{13}\approx 9°$) | solar mixing (34°)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

e.g. Super Kamiokande



e.g. Double Chooz



e.g. SNO

http://demonstrations.wolfram.com/NeutrinoOscillations/

3ν Oscillation Formalism

Atmospheric | Cross-Mixing | Solar | Majorana CP phases (L violating processes)

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

PMNS mixing matrix

$\theta_{23} \sim 45°$: "atm." angle

$\theta_{13} \sim 9°$

$\theta_{12} \sim 34°$: "solar" angle

δ dirac CP phase

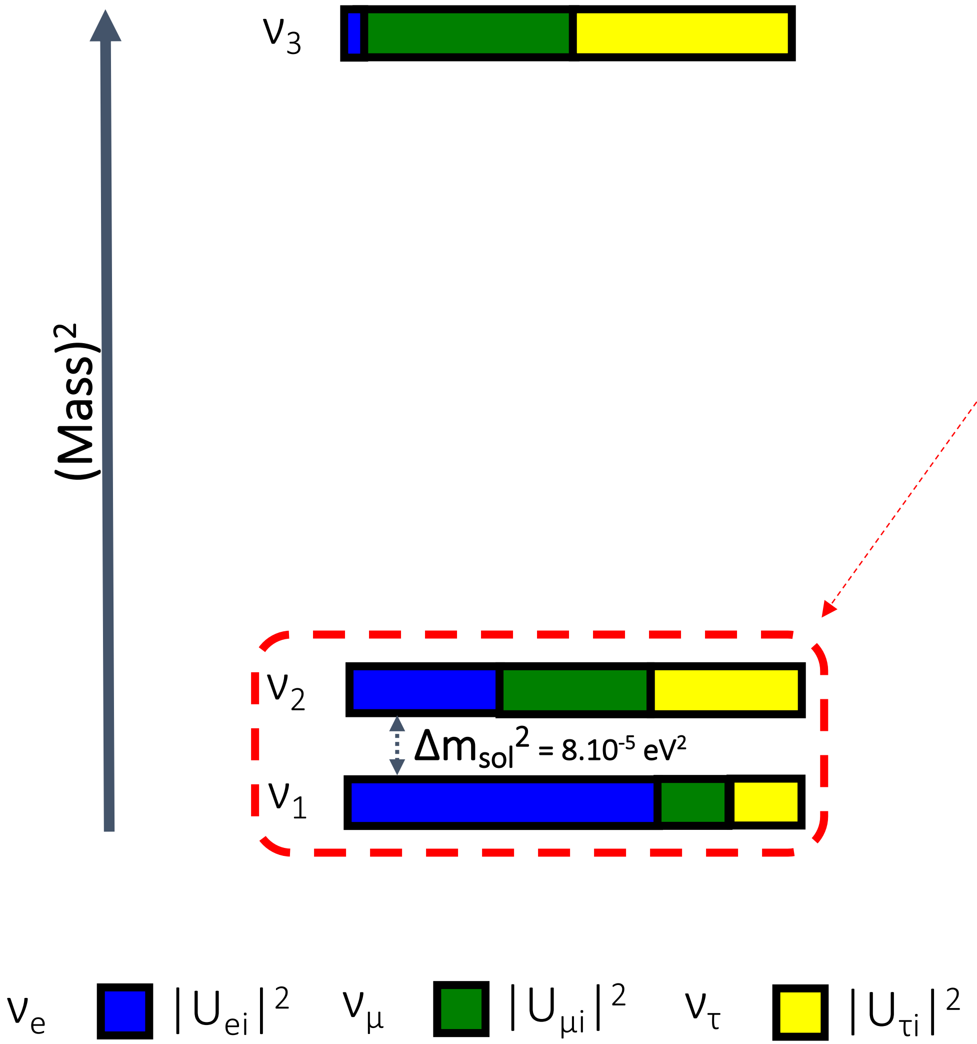
- 3 masses $m_{1,2,3}$: $\Delta m^2_{sol} = m_2^2 - m_1^2 \sim 8\ 10^{-5}\ eV^2$ & $\Delta m^2_{atm} = |m_3^2 - m_1^2| \sim 2\ 10^{-3}\ eV^2$

- Oscillation in vacuum : $P(\nu_x \to \nu_x) \approx 1 - \mathbf{sin^2(2\theta_i)} \times \sin^2\left(1.3 \cdot \boldsymbol{\Delta m_i^2} \cdot \frac{\mathbf{L}}{\mathbf{E}}\right)$

tunable

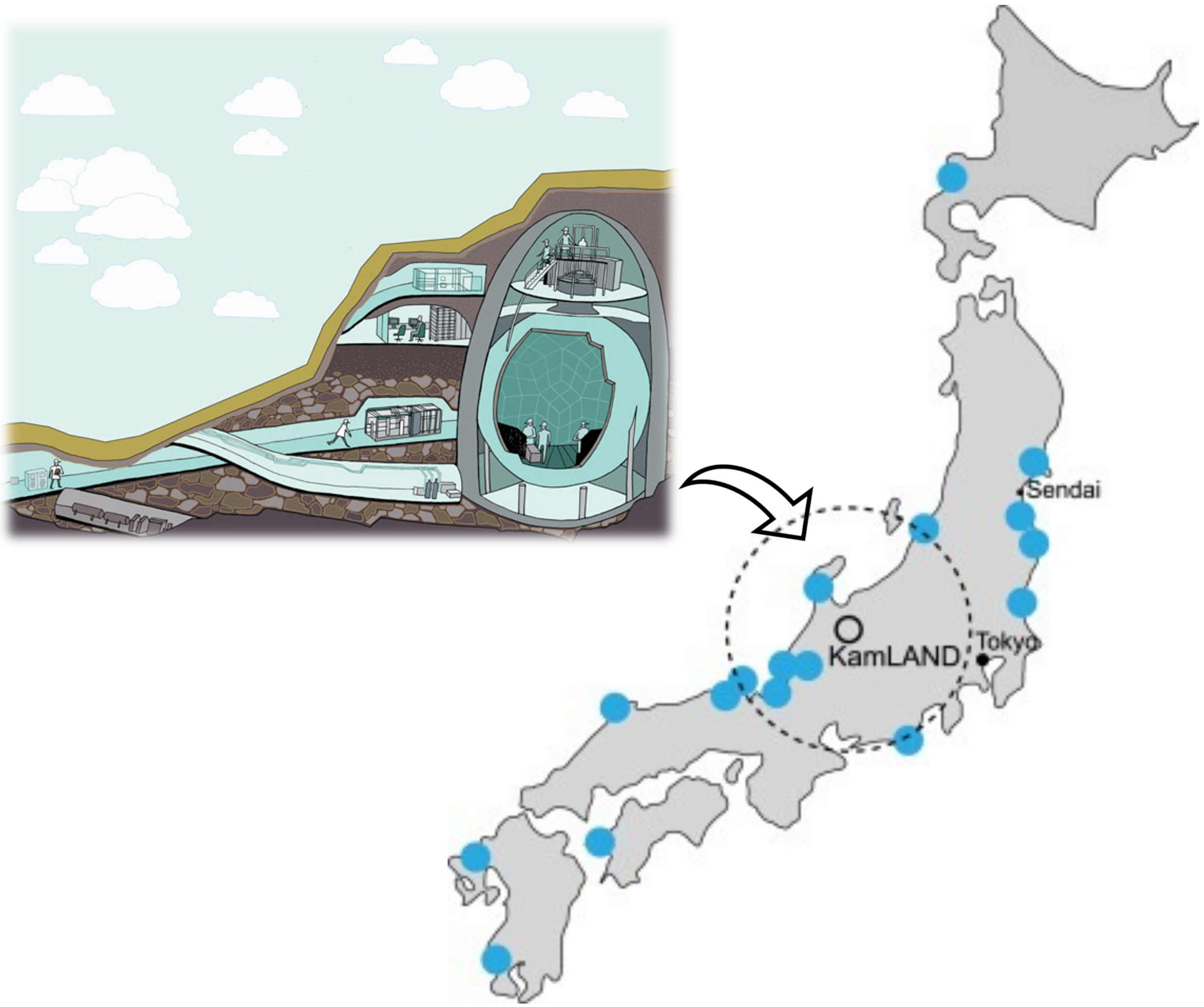
What are the leptonic mixing parameters?

Δm^2_{21} & θ_{12}



- Δm^2 (eV^2) ~ L(km) / E(MeV)
- Reactor
  L ~ 100 km & E ~ MeV
- Solar
  MSW flavor transition

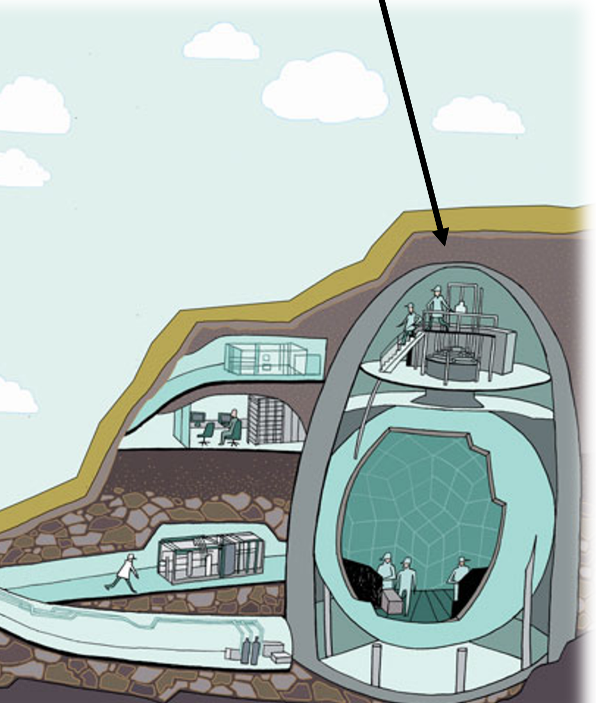
The KamLAND experiment



- KamLAND (Kamioka Liquid scintillator Anti-Neutrino Detector) is so far the largest low-energy antineutrino
- Located on the island of Honshu in Japan, since 2002
- Built to detect hundreds of anti-neutrinos per year from nuclear reactors hundreds of kilometers away

The KamLAND detector

1km overburden



Electronics Hut

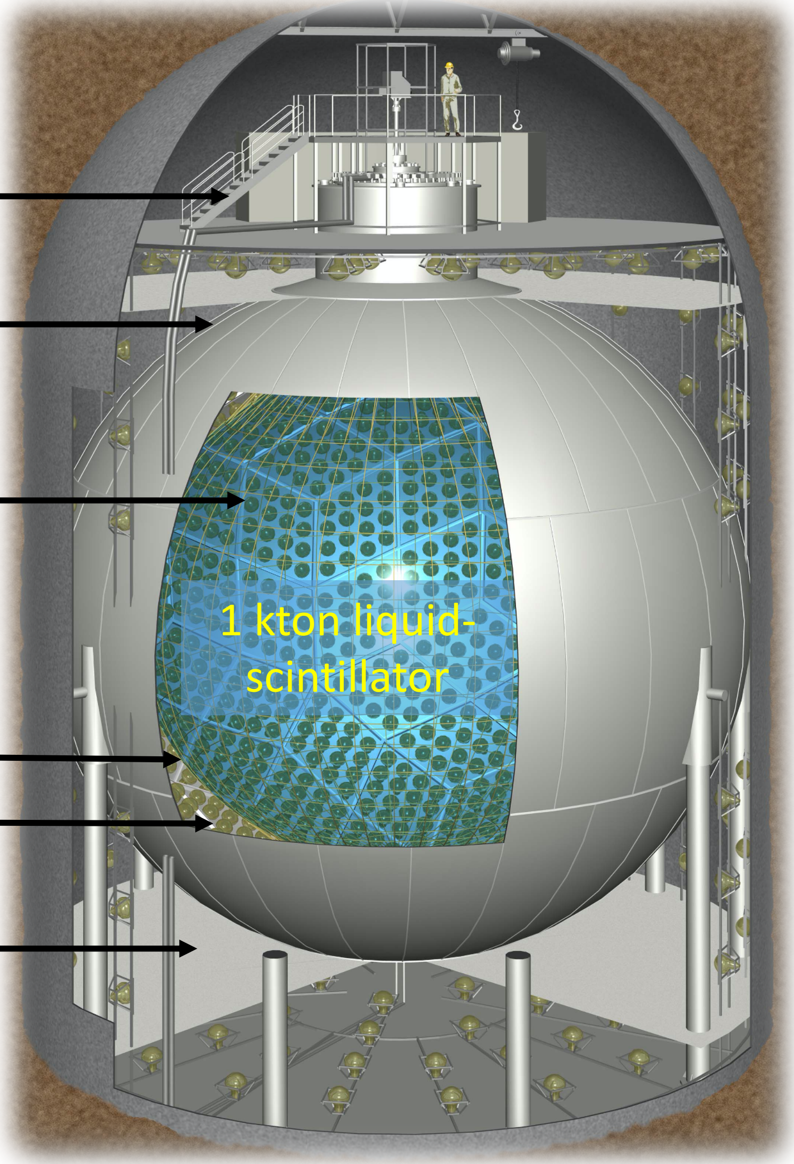
Steel Sphere, 8.5m radius

Inner detector
1325 17” PMT’s
554 20” PMT’s
34% coverage

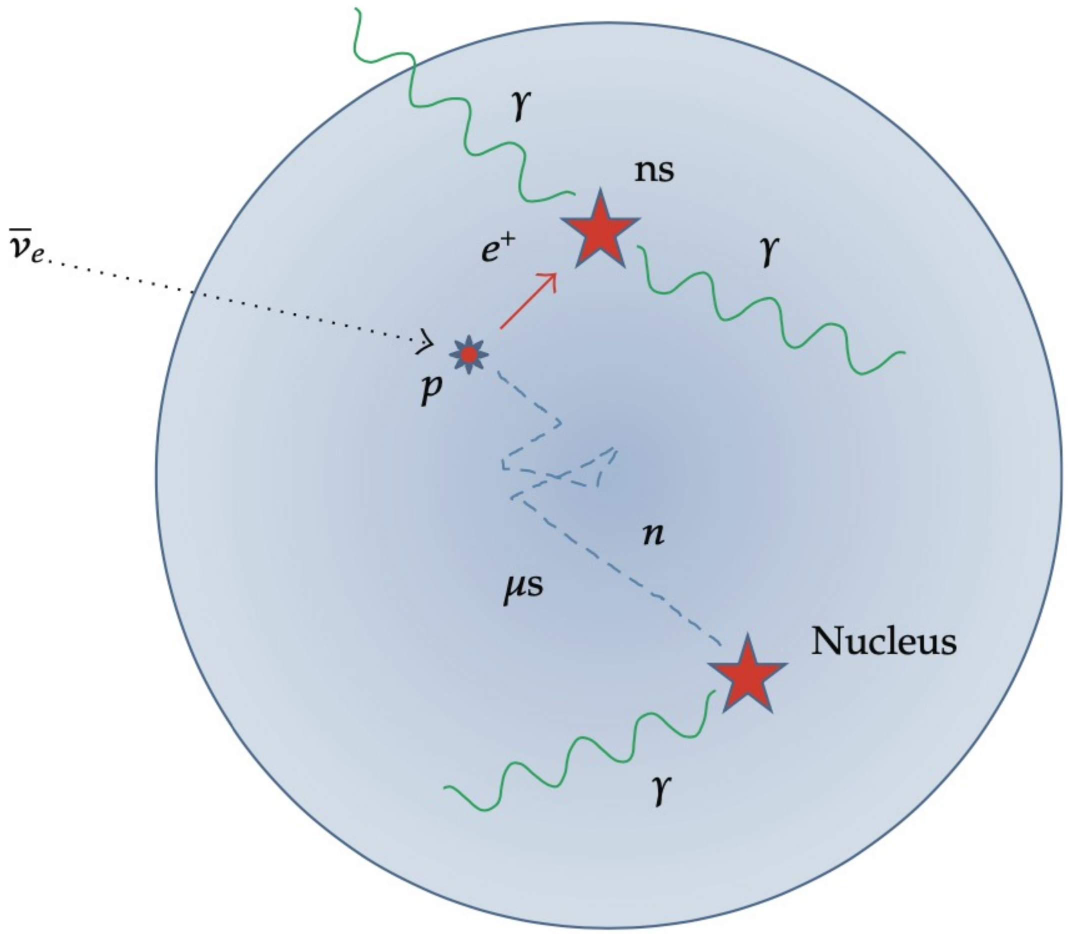
Transparent balloon, 6.5m radius

Buffer oil

Water Cherenkov outer detector
225 20” PMT’s



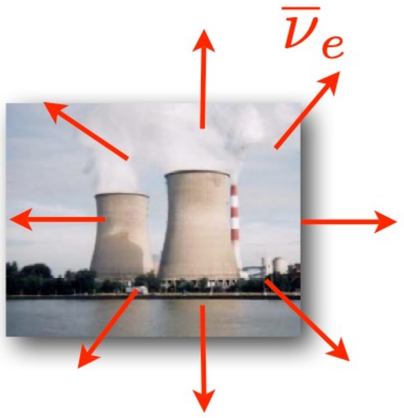
The KamLAND detection principle

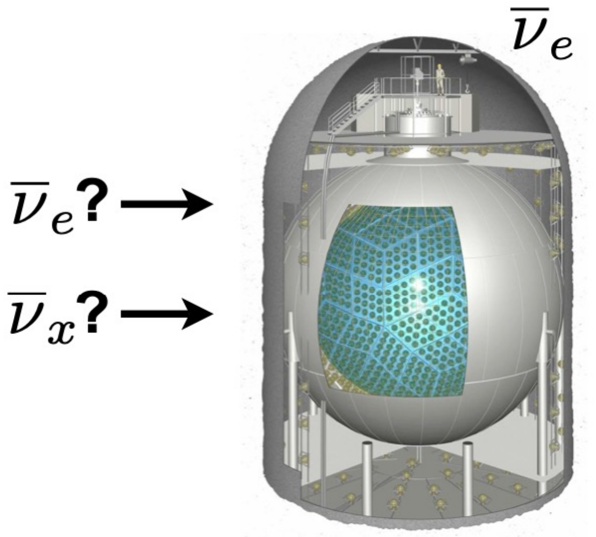


- Inverse beta decay (IBD) reaction
- Prompt signal comes from positron annihilation
- Delayed signal occurs when neutron captures a proton
- Challenge: reduce background
  - Cosmic rays (overburden)
  - Natural radioactivity (pure materials)

The KamLAND reactor neutrino measurement

Question before the year 2001: are there reactor neutrino (MeV) oscillation at a distance >100 km?

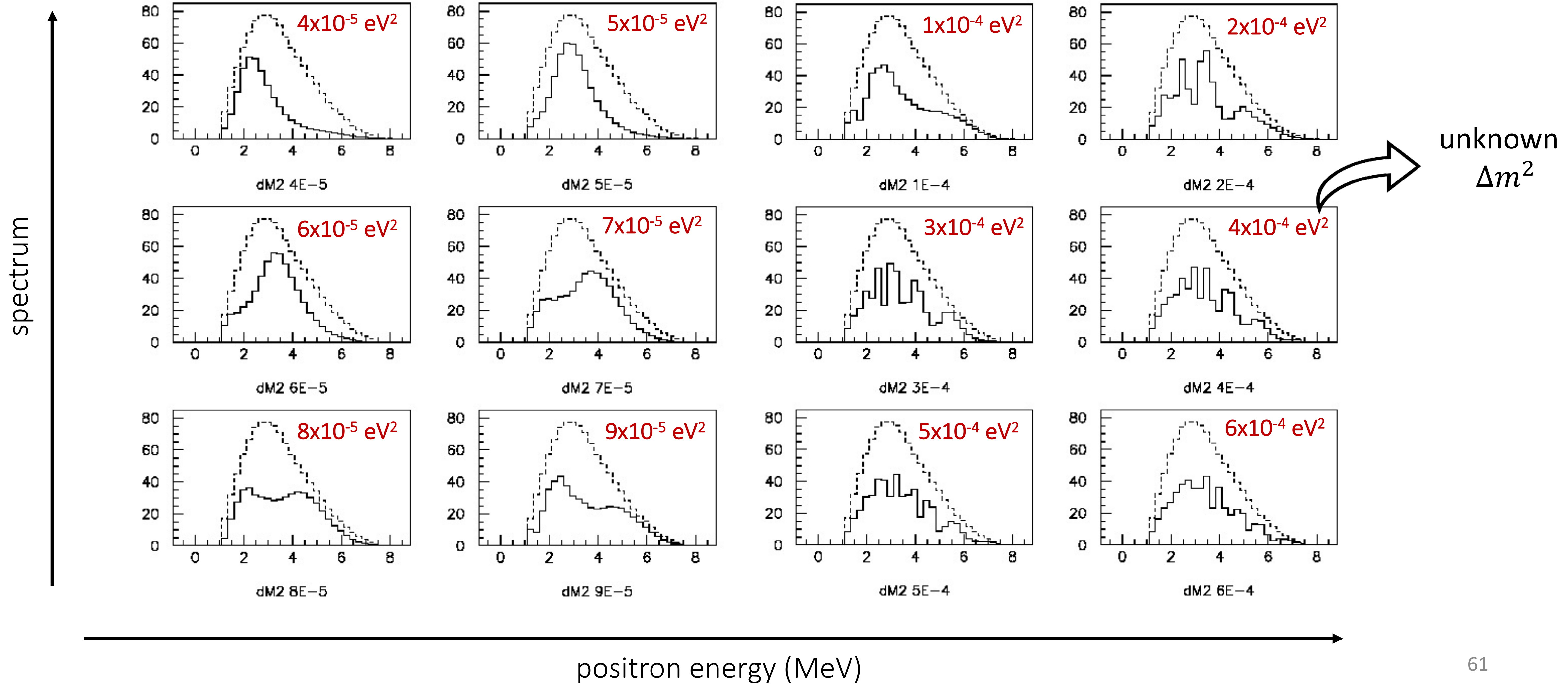




$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2 2\theta \, \sin^2 \frac{1.27 \Delta m^2 L}{E}$$

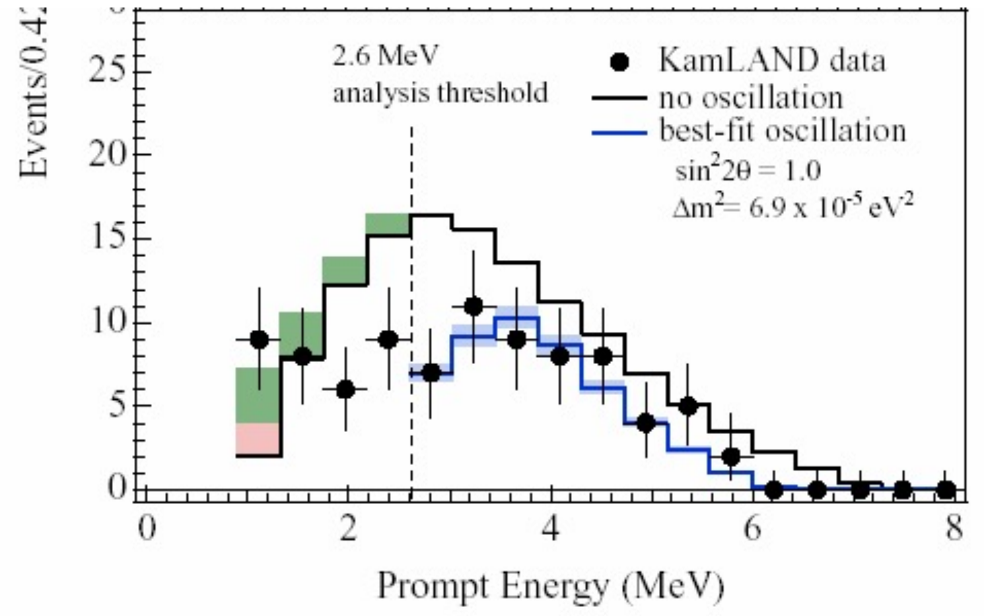
L = 200 km

What KamLAND did we expect in 2001?



The KamLAND reactor neutrino measurement

First results in 2002

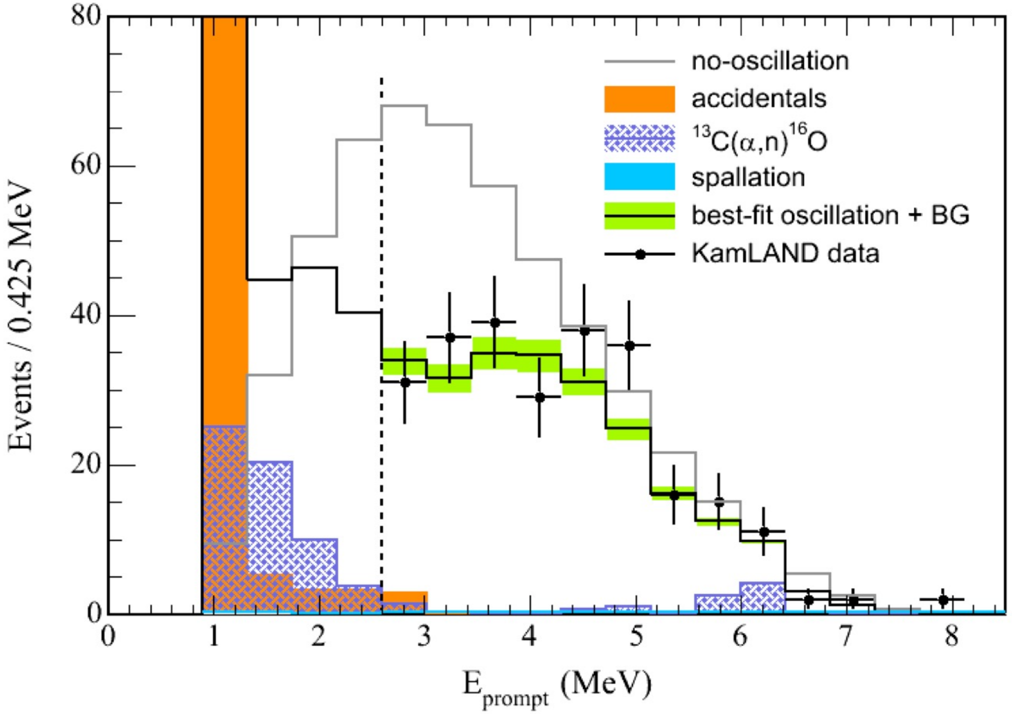


- established reactor antineutrino disappearance, L>>100km, at high significance

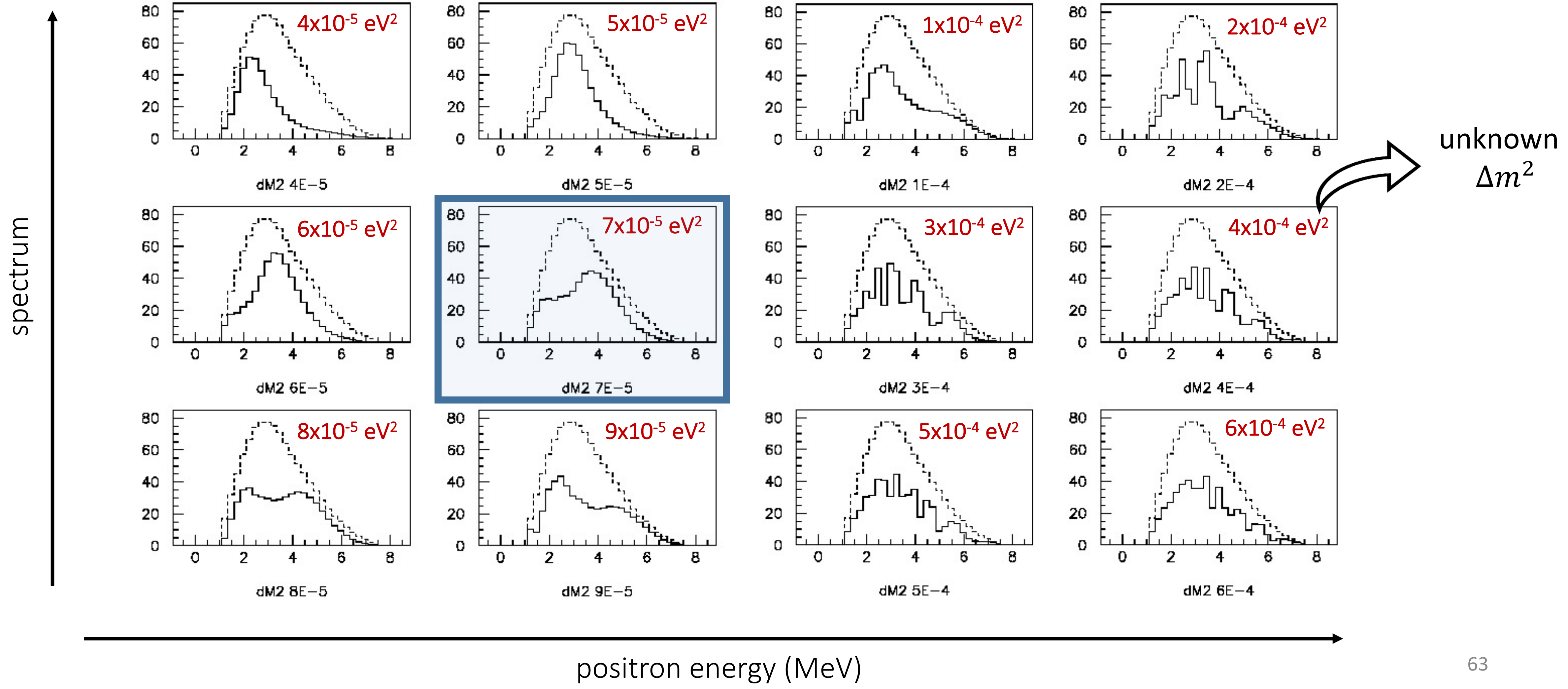
- Energy threshold at 2.6 MeV
  - Backgrounds at low energy
  - Geoneutrinos!

Results around 2010

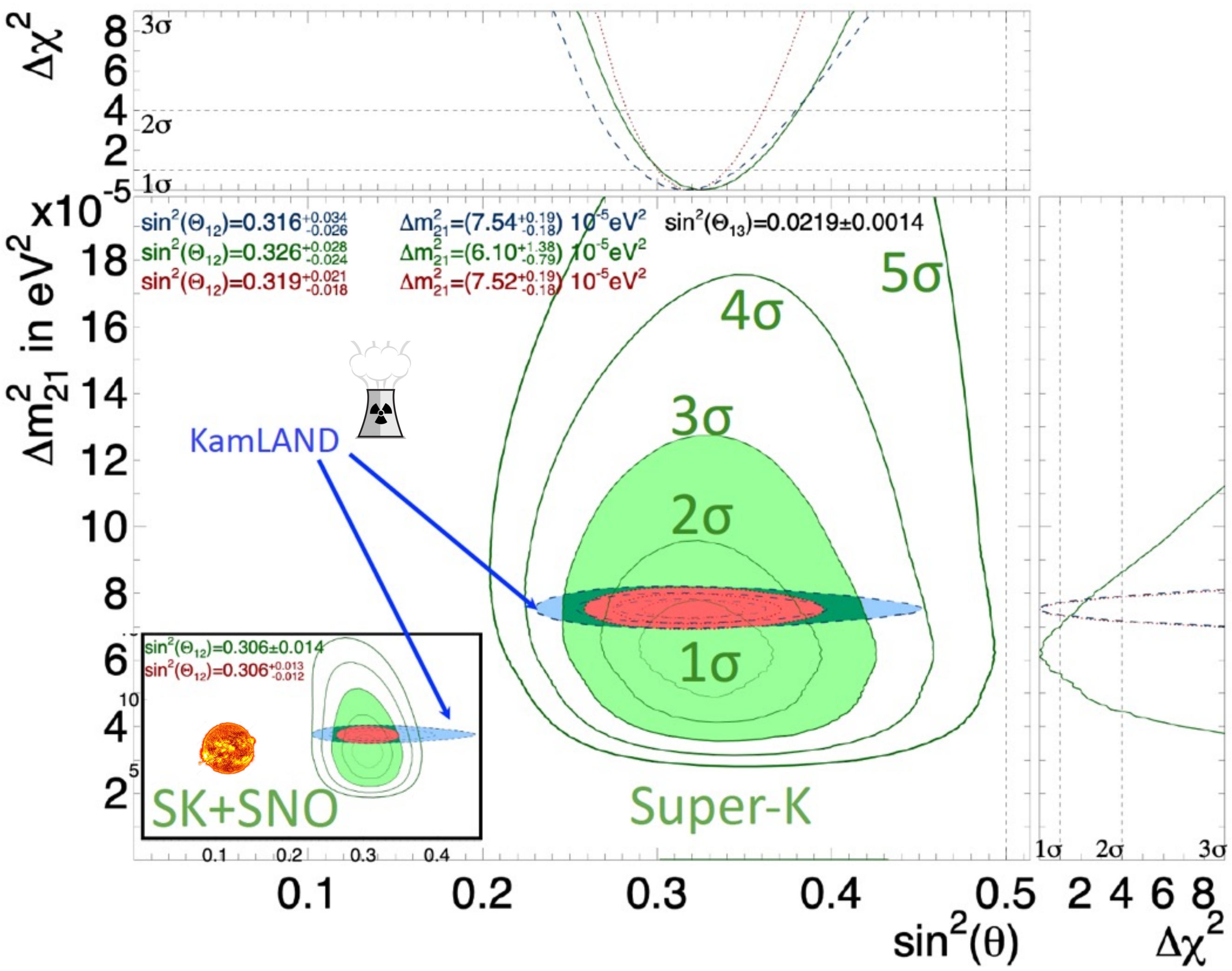
$$\Delta m^2_{21} = 7.59 \pm 0.21 \cdot 10^{-5}\ \mathrm{eV}^2,\ \tan^2\theta_{12} = 0.47^{+0.06}_{-0.05}$$

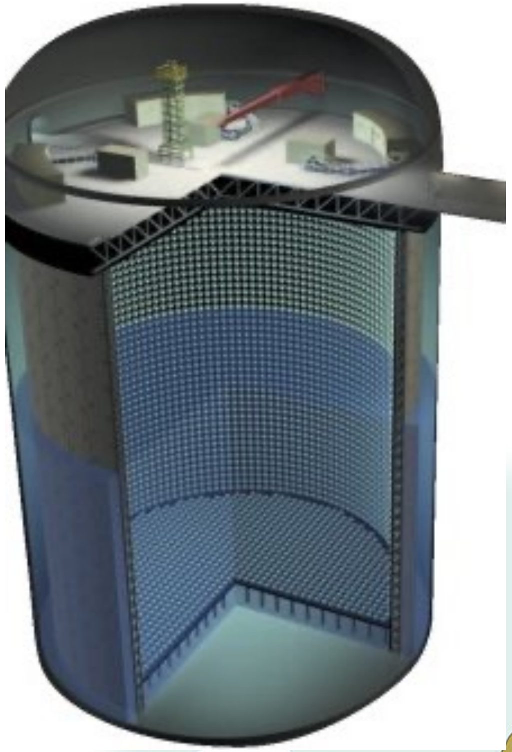


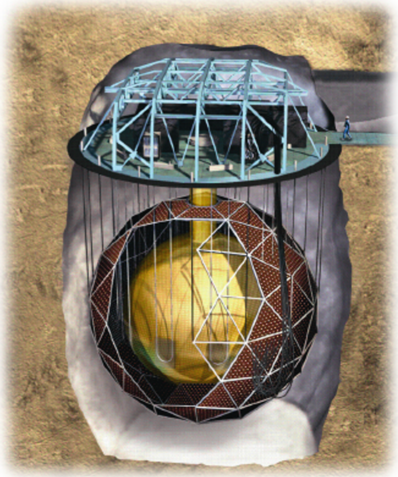
What KamLAND did we expect in 2001?

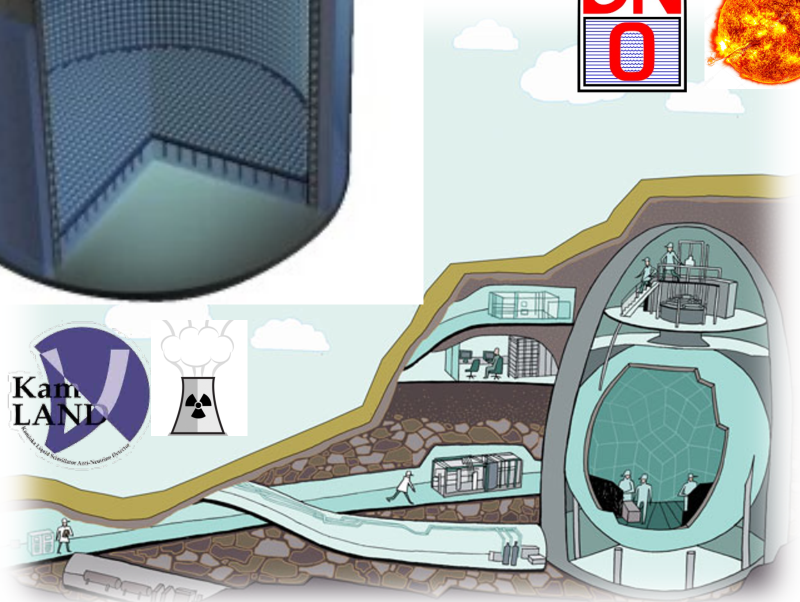


Solar + Reactor Experiments









- Consistent Solar/Reactor Δm^2_{21} & θ_{12}