Neutrinos

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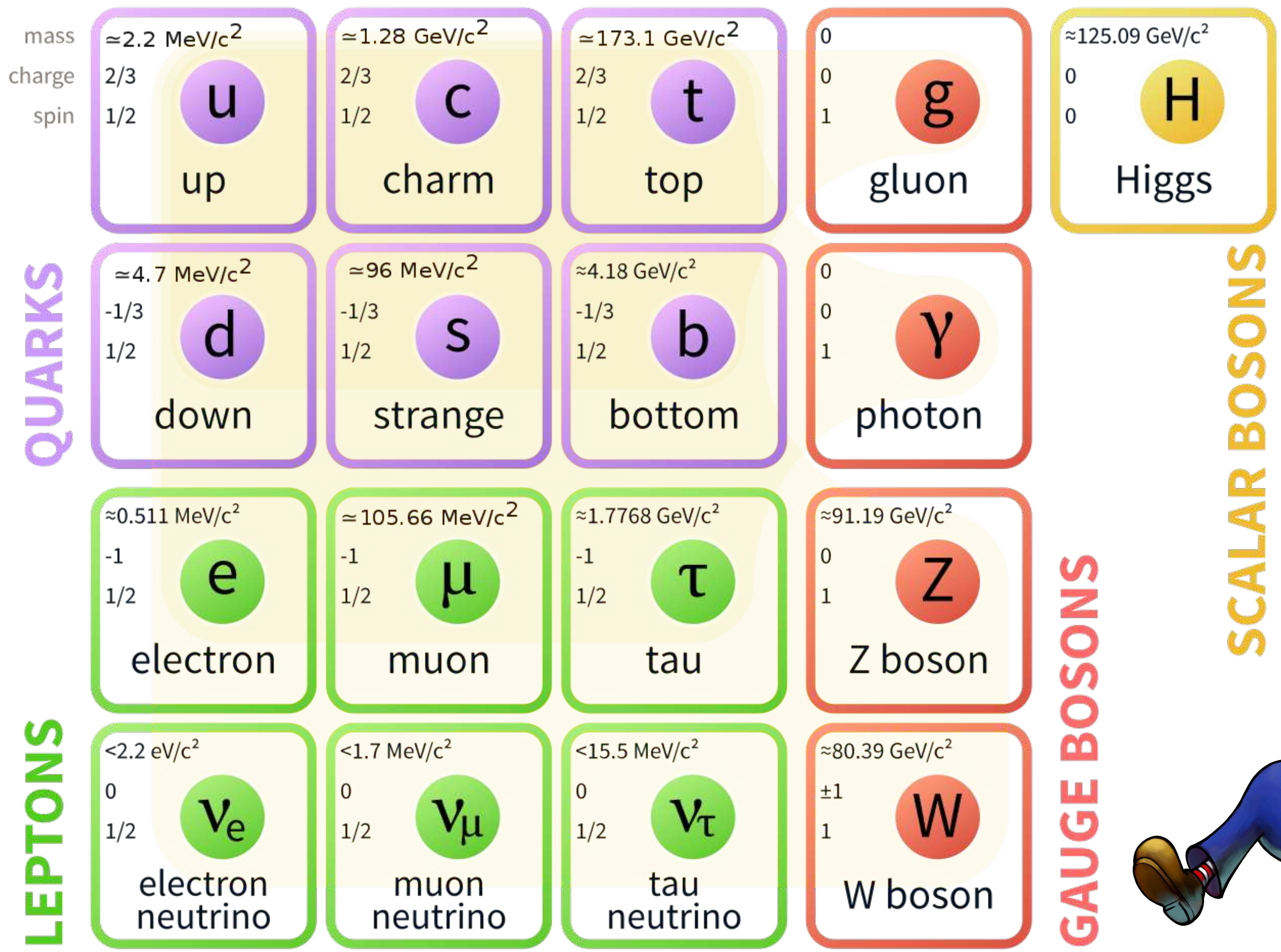
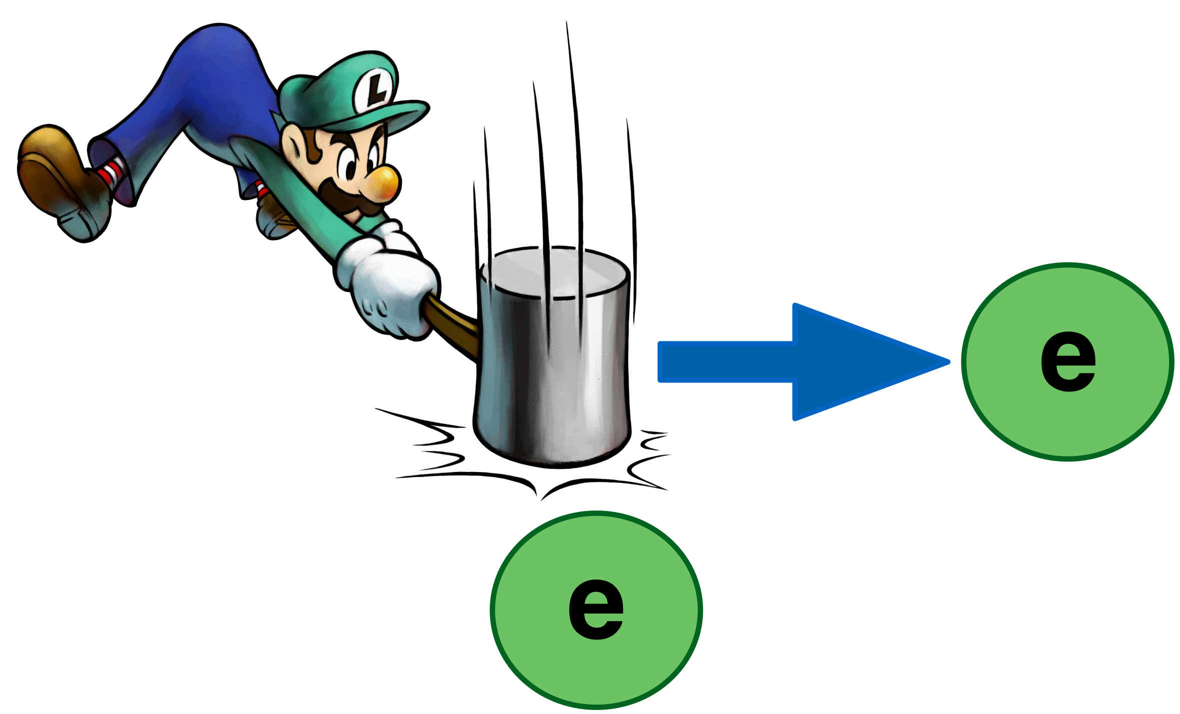
Saturday Morning Physics

November 4, 2018

Introduction

Standard Model of elementary particles

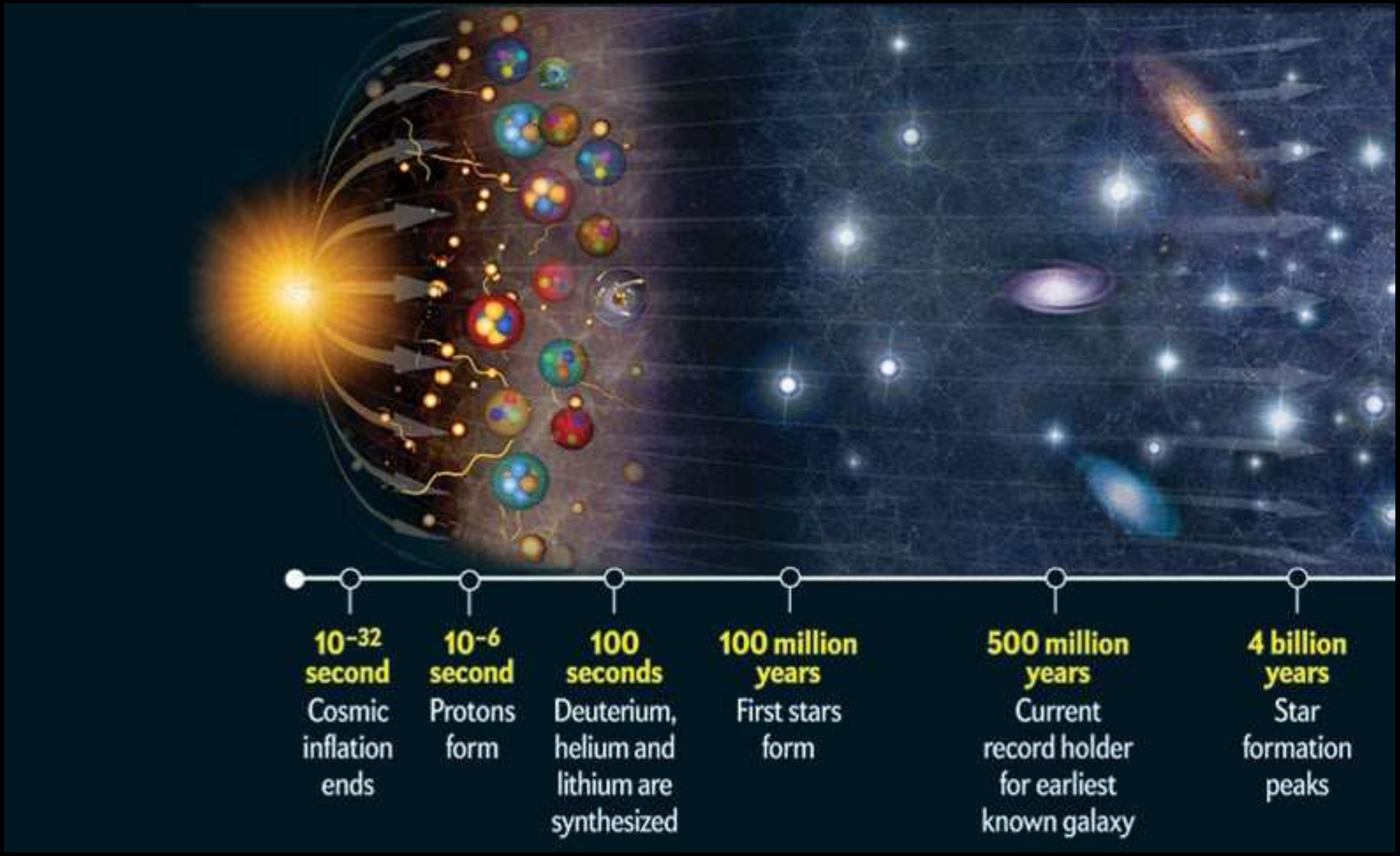




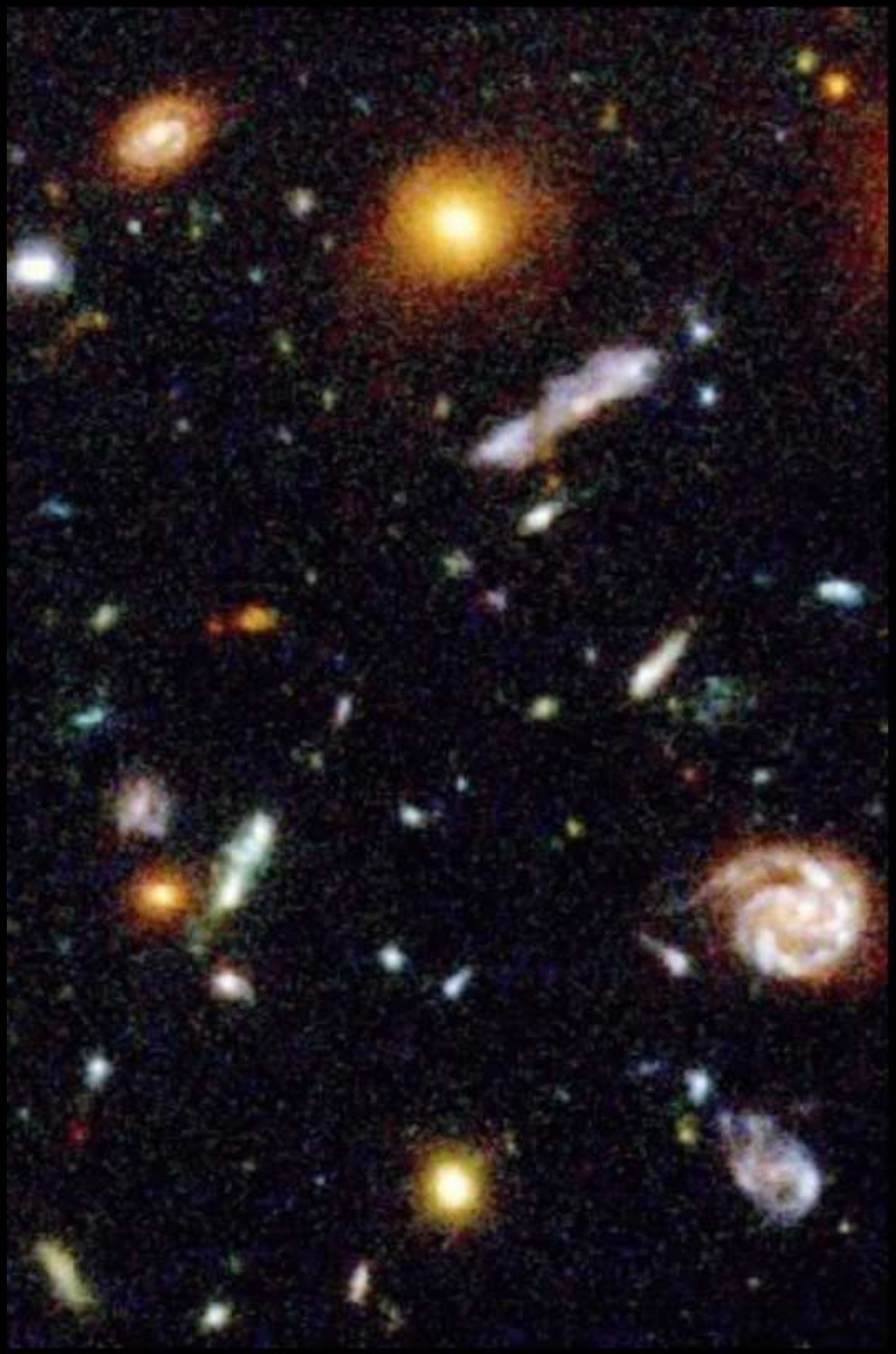
+

antiparticles

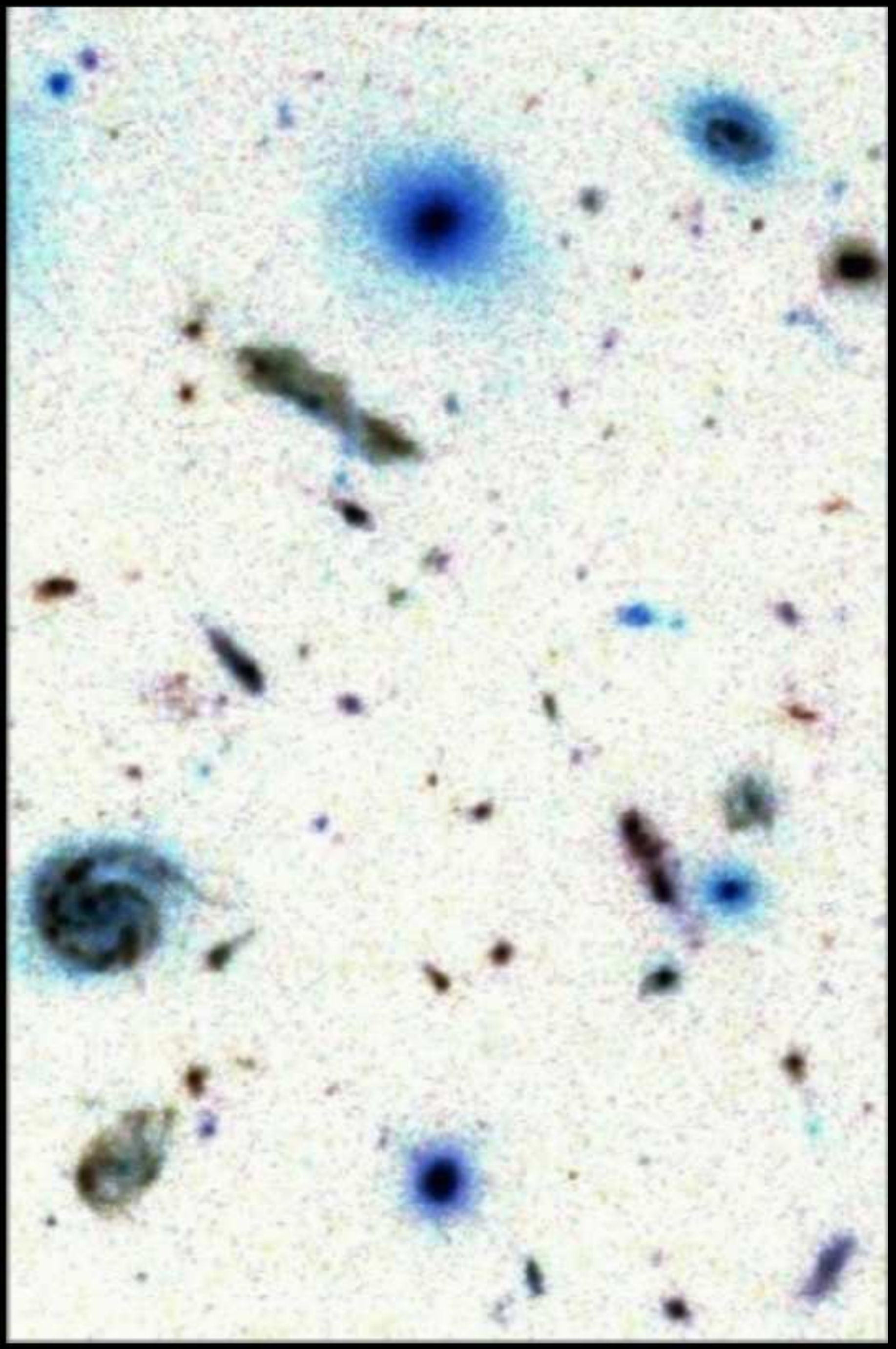
At the beginning of the universe, these particles existed in abundance



Matter and anti-matter almost completely annihilated

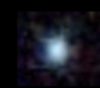


10,000,000,001



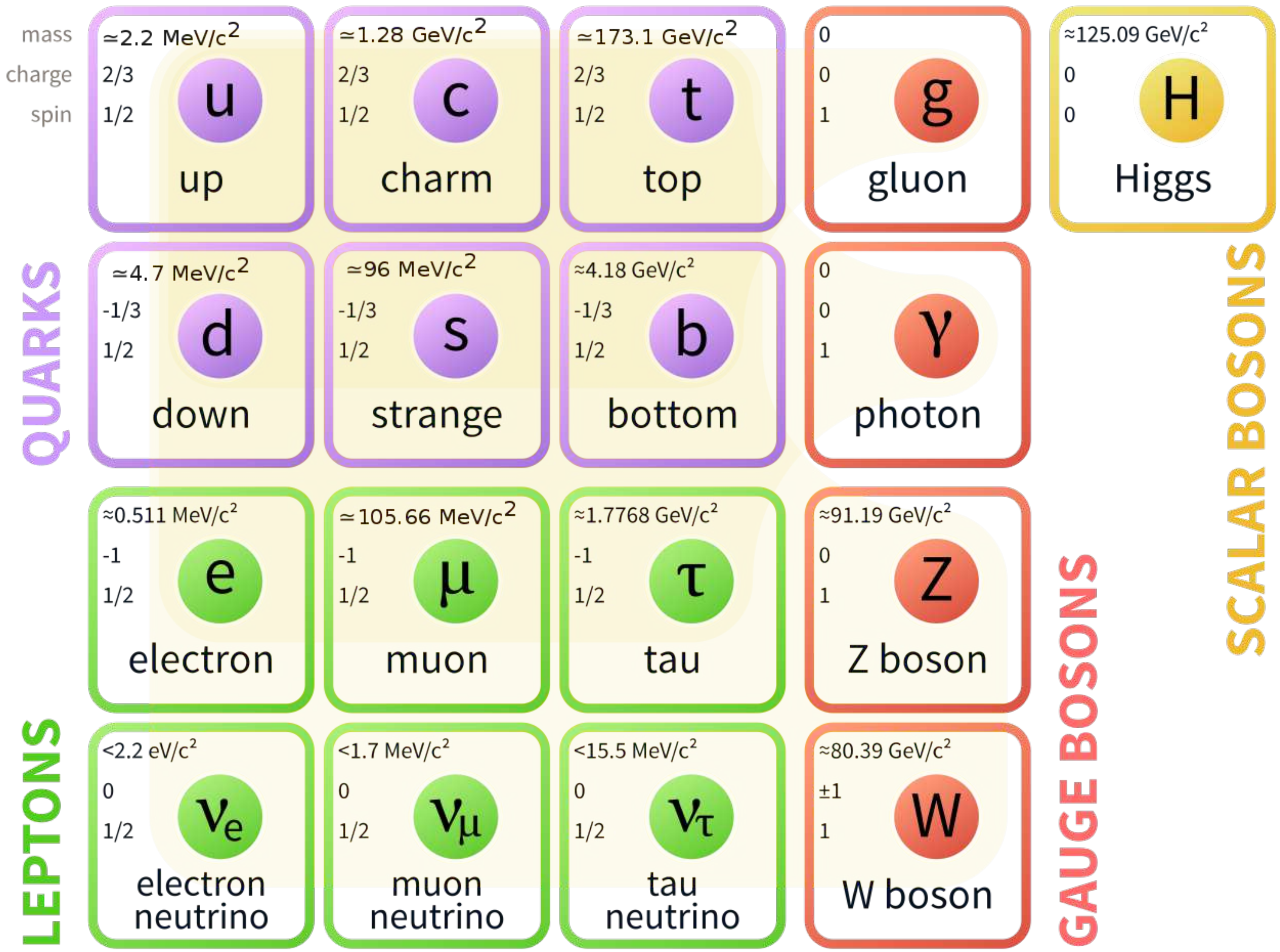
10,000,000,000

Leaving behind a universe dominated by matter

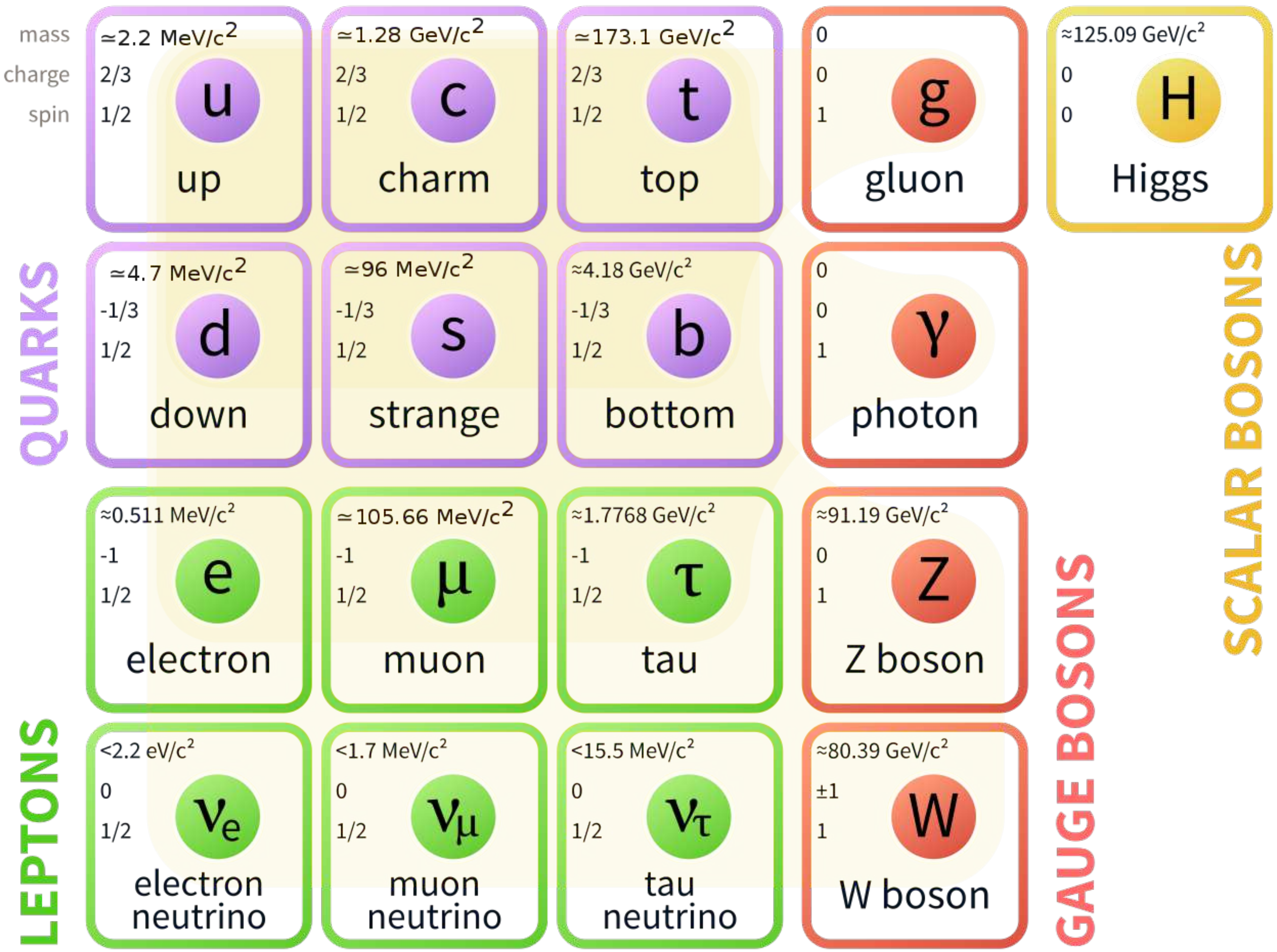


1 0

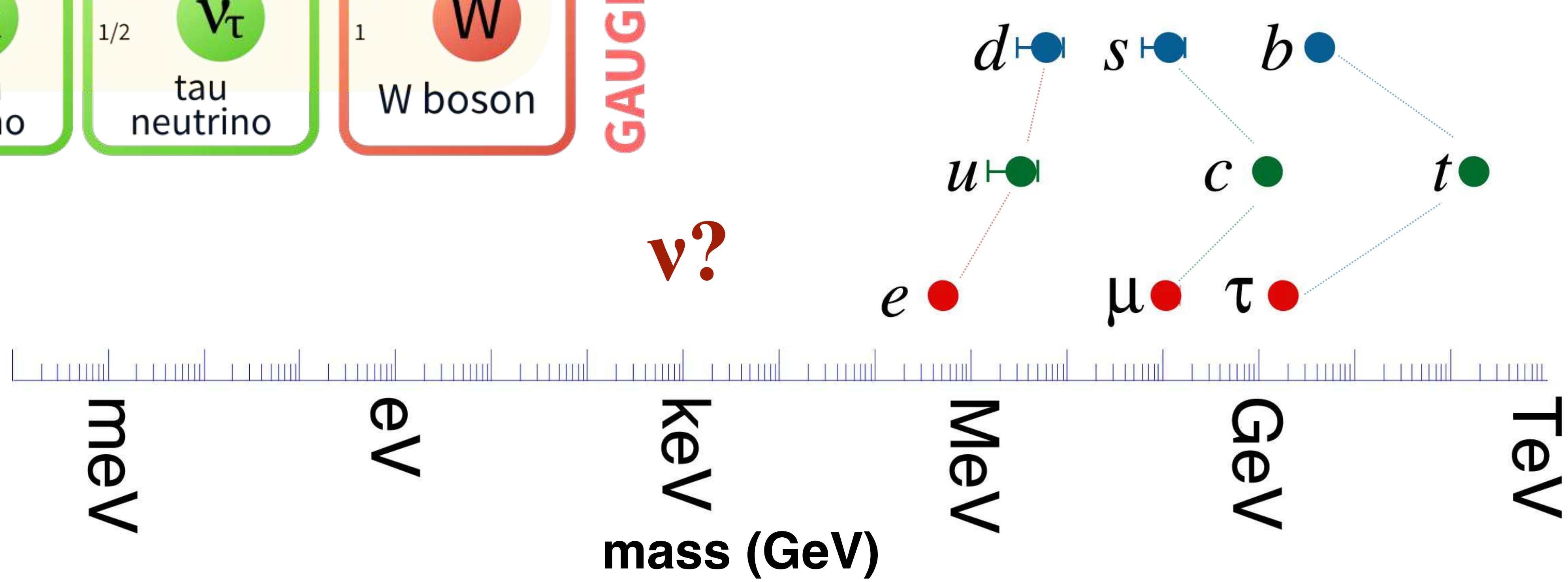
Standard Model of elementary particles



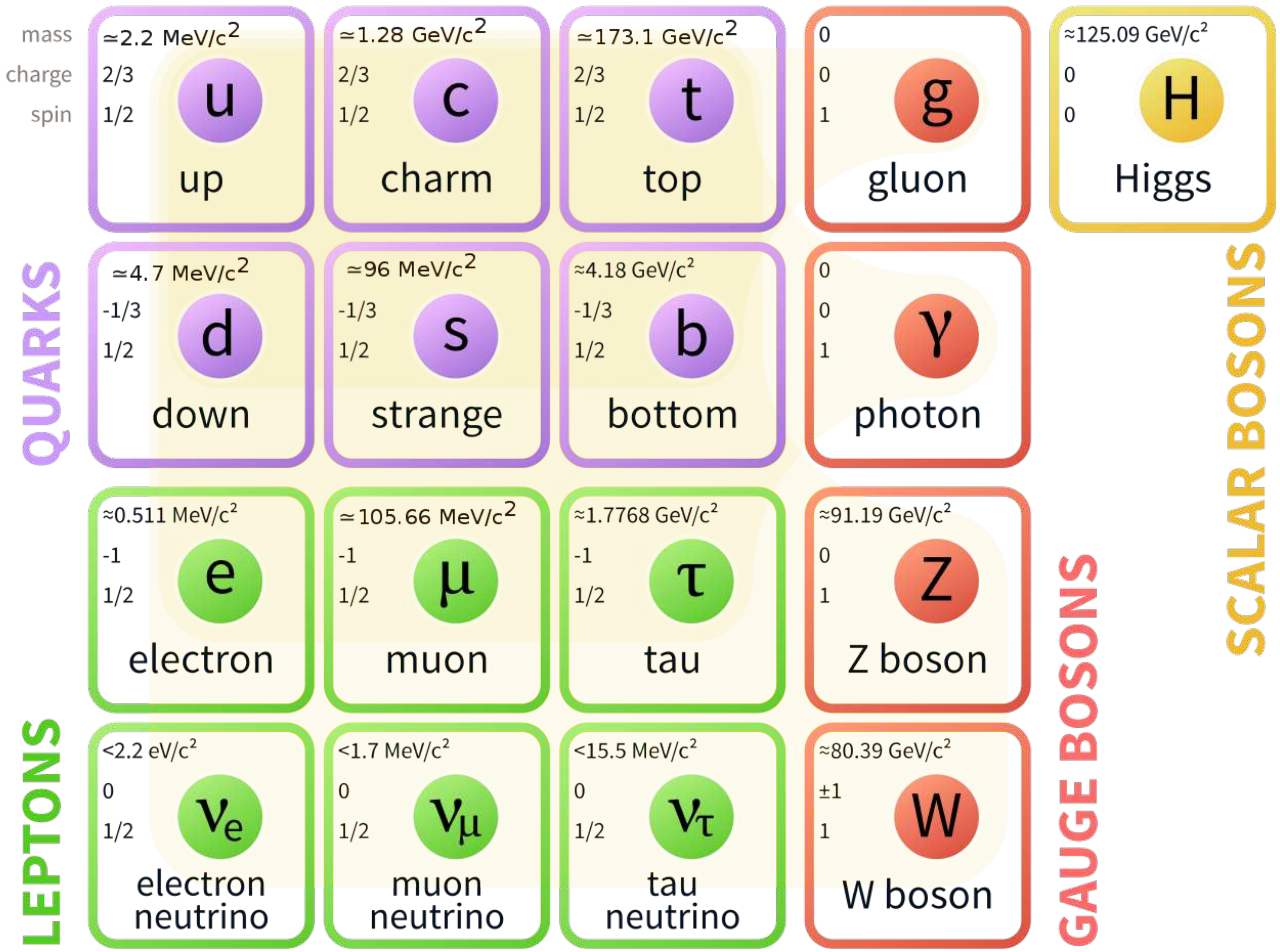
Standard Model of elementary particles

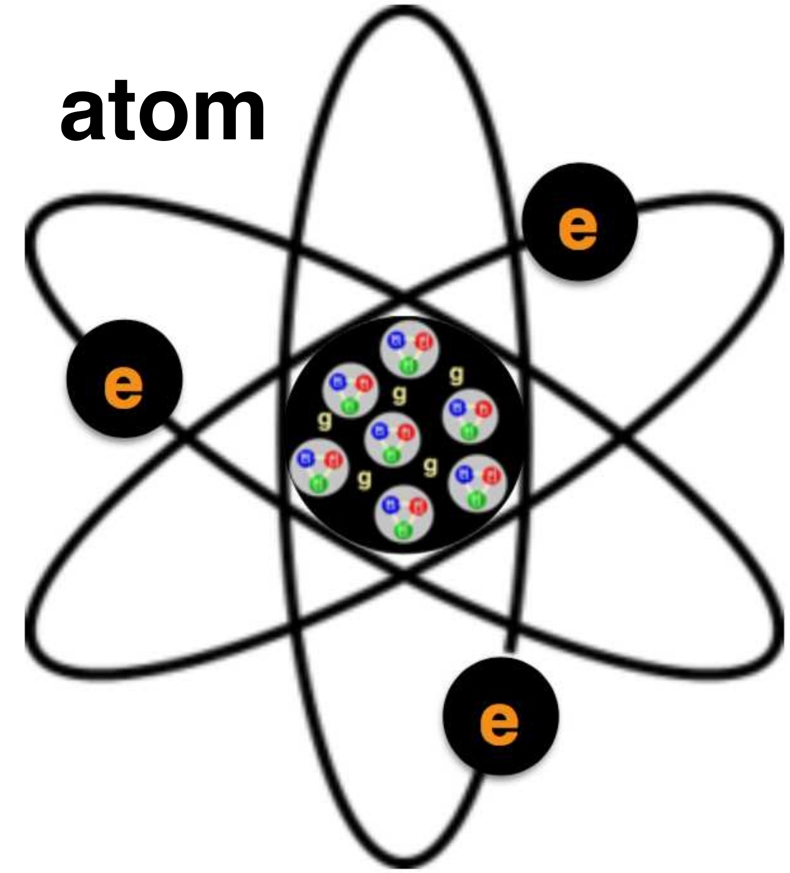


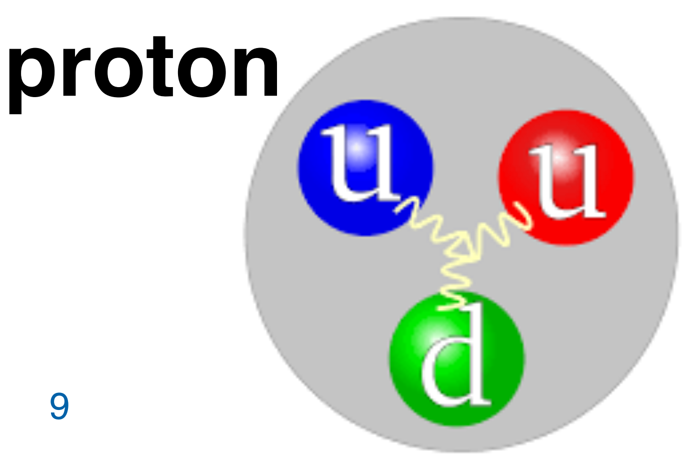
The difference between the generations is the mass.

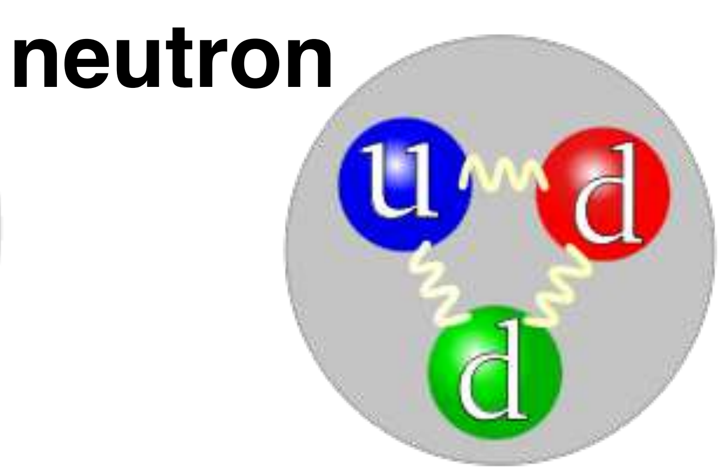


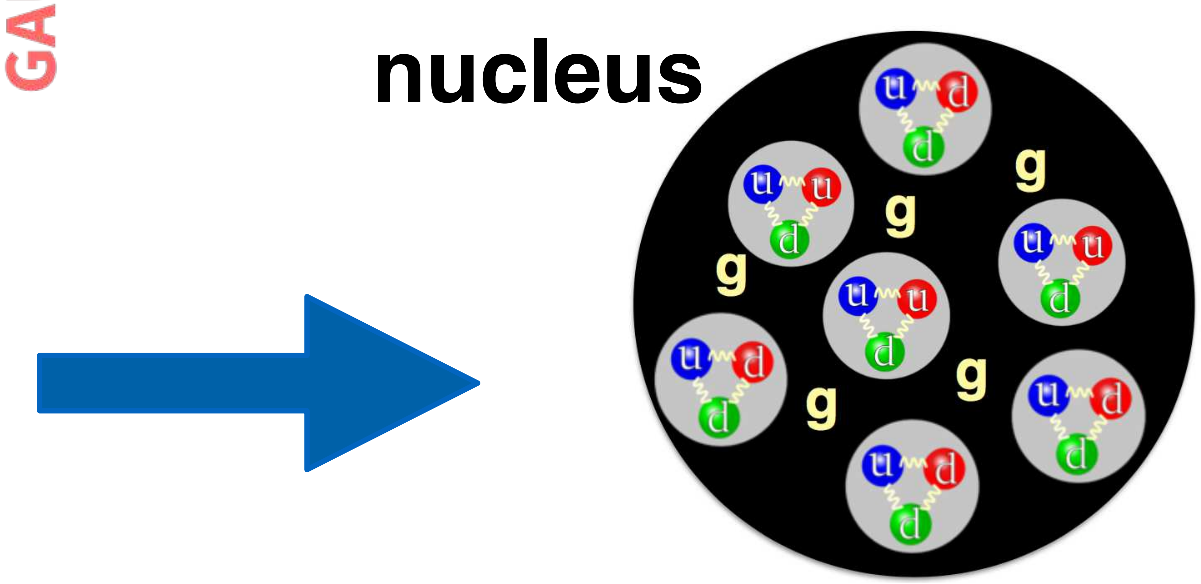
Standard Model of elementary particles











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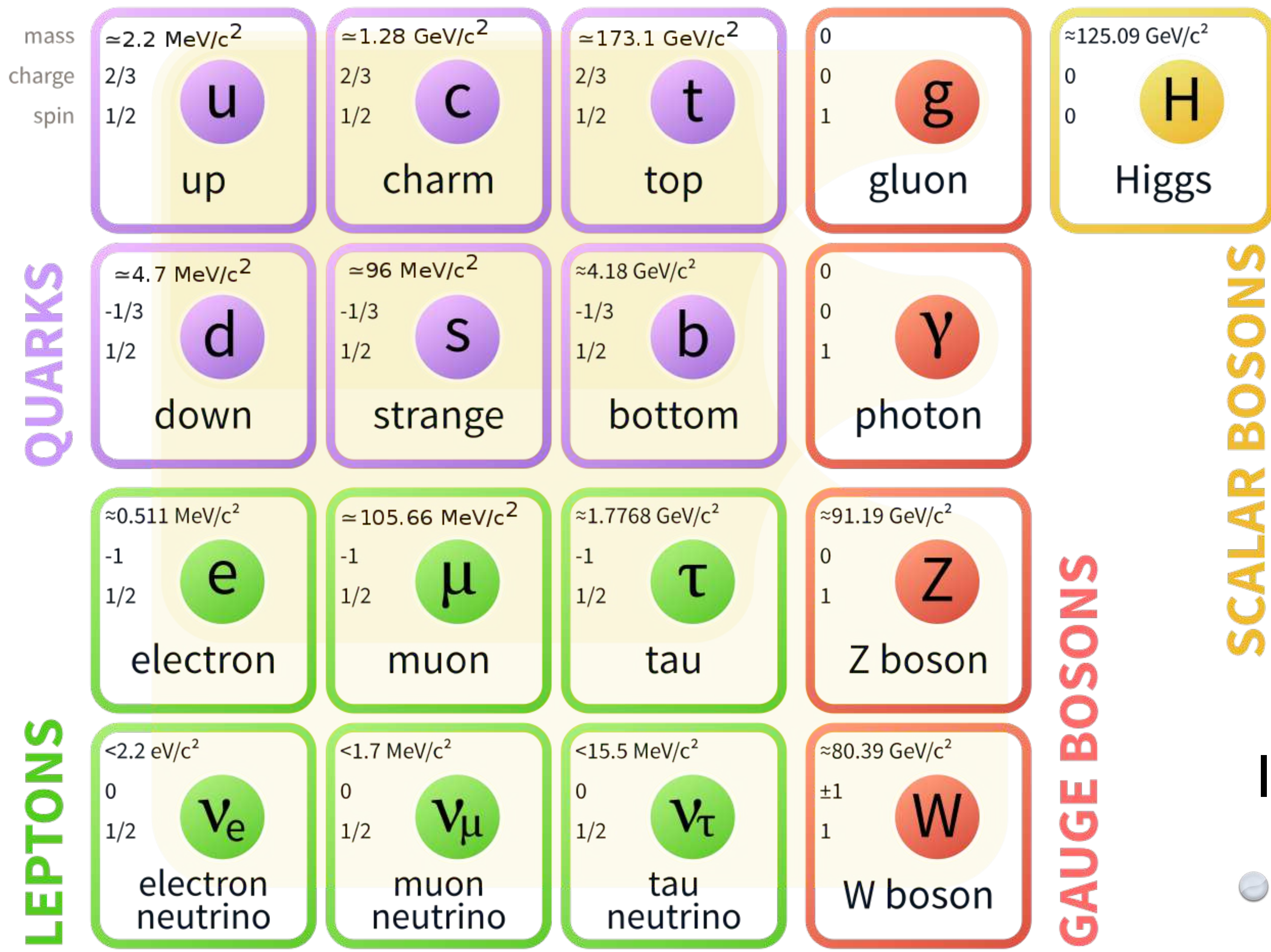
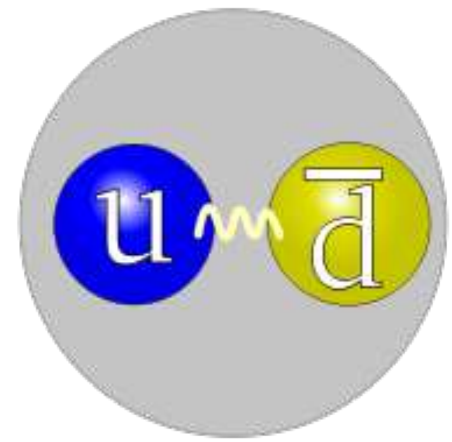


pion (π^+)



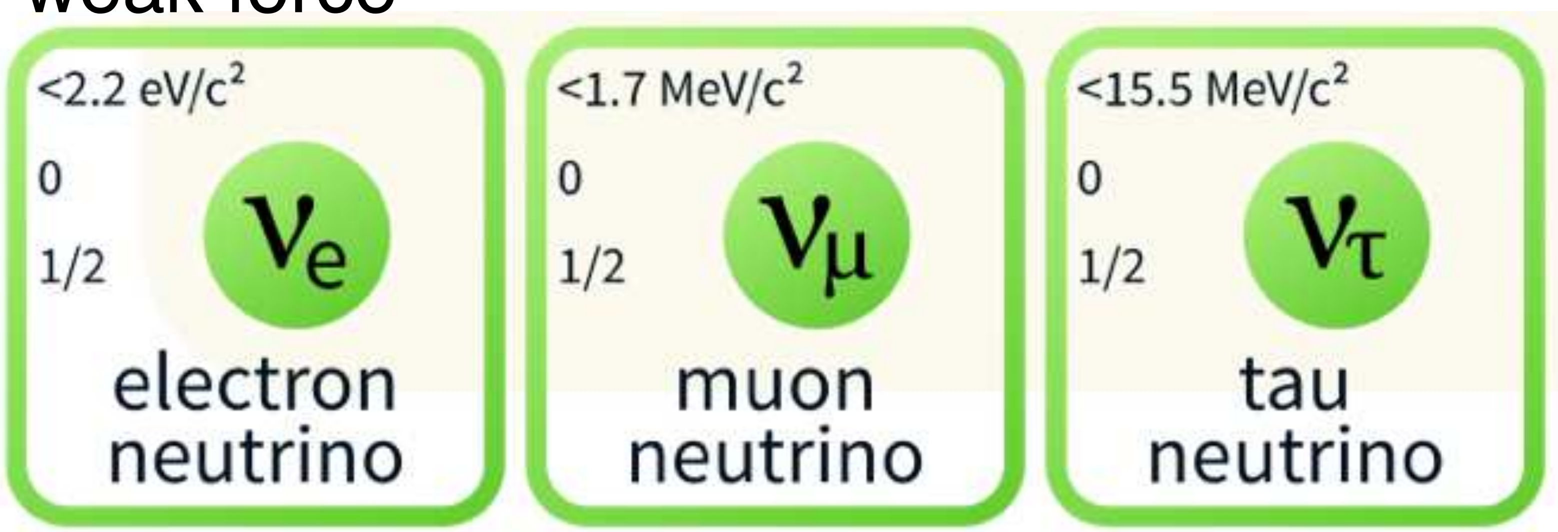
Inestable particles

- Decay lifetime: ~ 26 ns
- Decay almost 100% via:

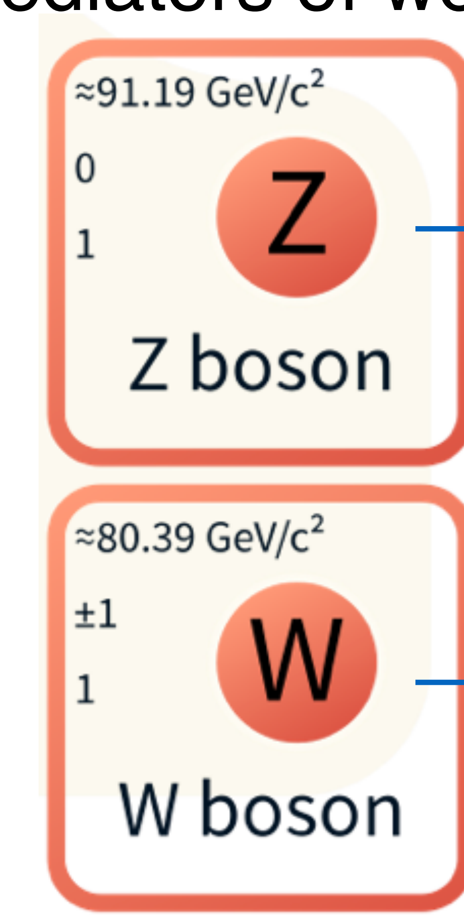
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

Neutrino and weak interactions

3 neutrino types (flavors), no charge, only interact by weak force



2 mediators of weak force



charge: 0

charge: +-1

Neutrino and weak interactions

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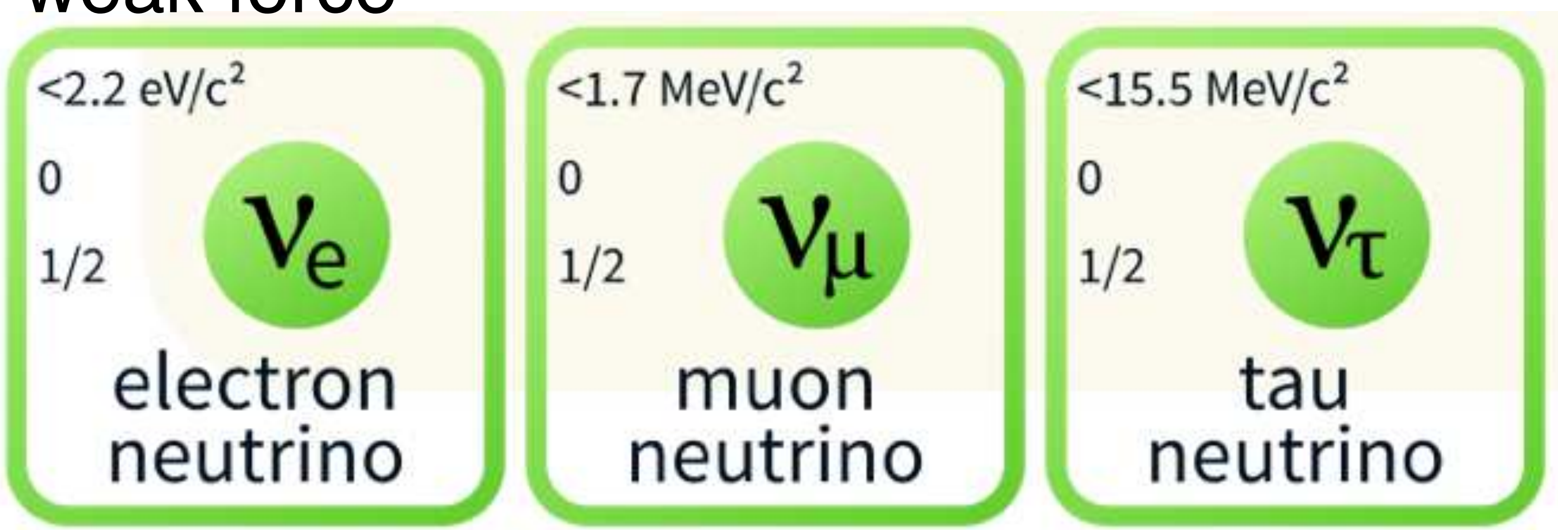
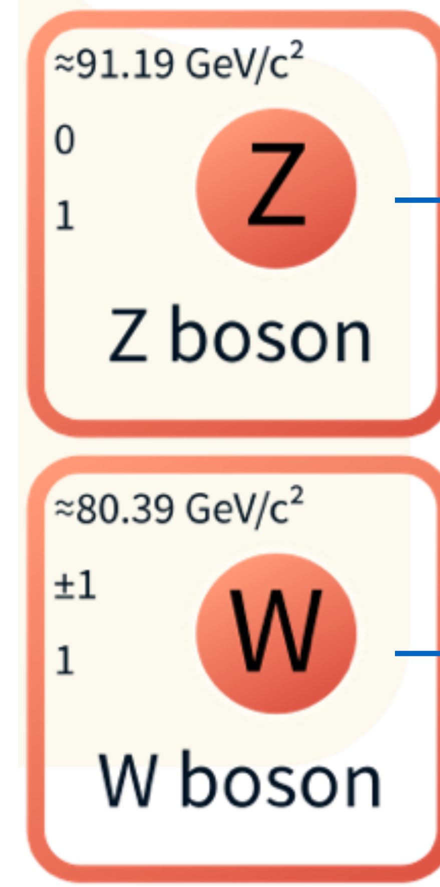


2 mediators of weak force

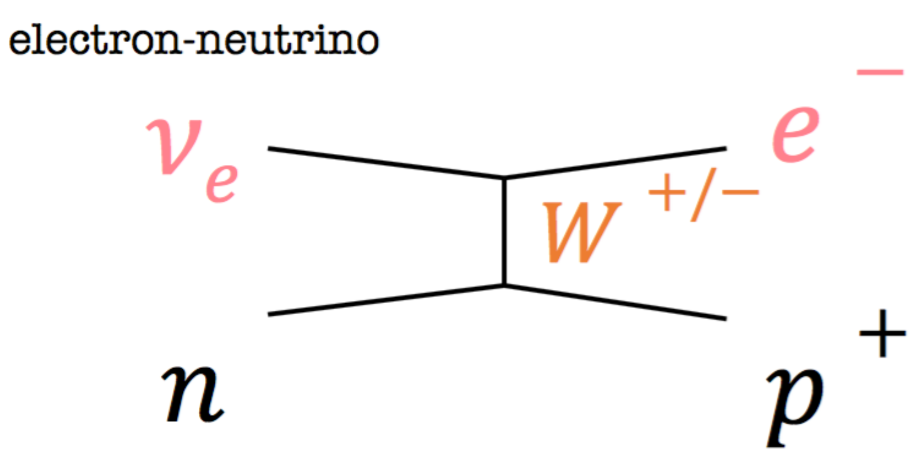


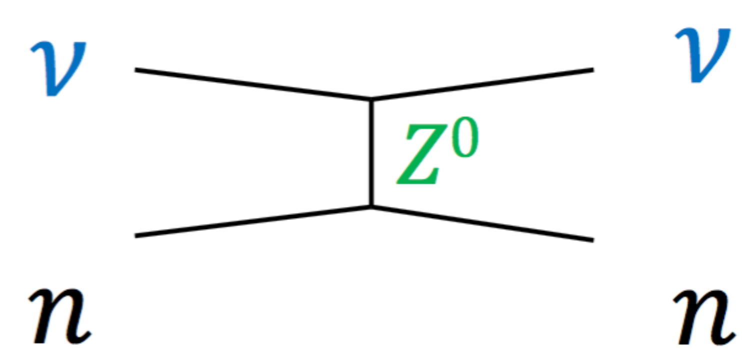
charge: 0

charge: +-1

charged-current

neutral-current



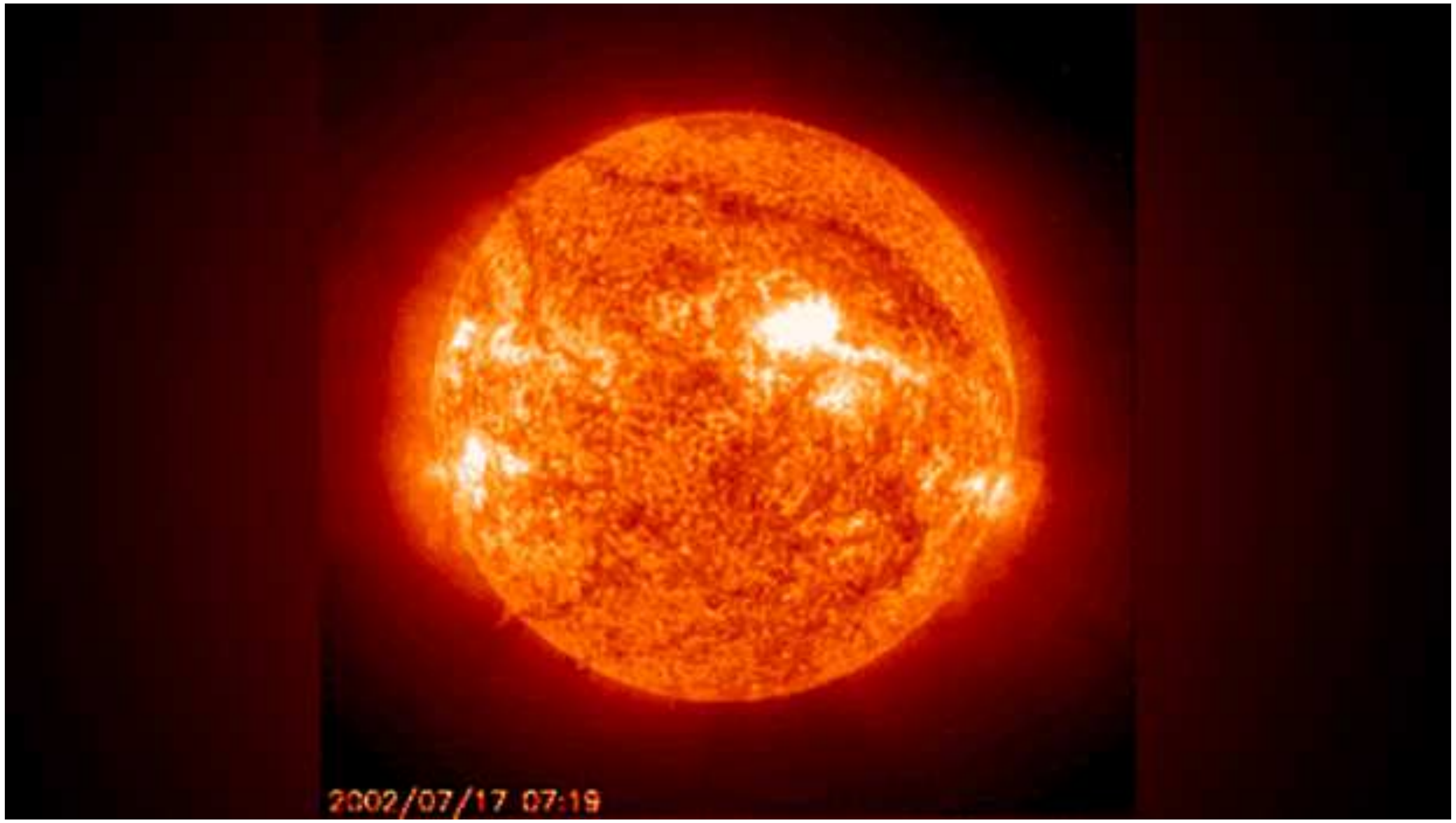


$W^{+/-}$ = charged boson

Z^0 = neutral boson

What do we know about neutrinos

They are abundant: emitted from the sun, other stars, and including the Big Bang are traveling through out space

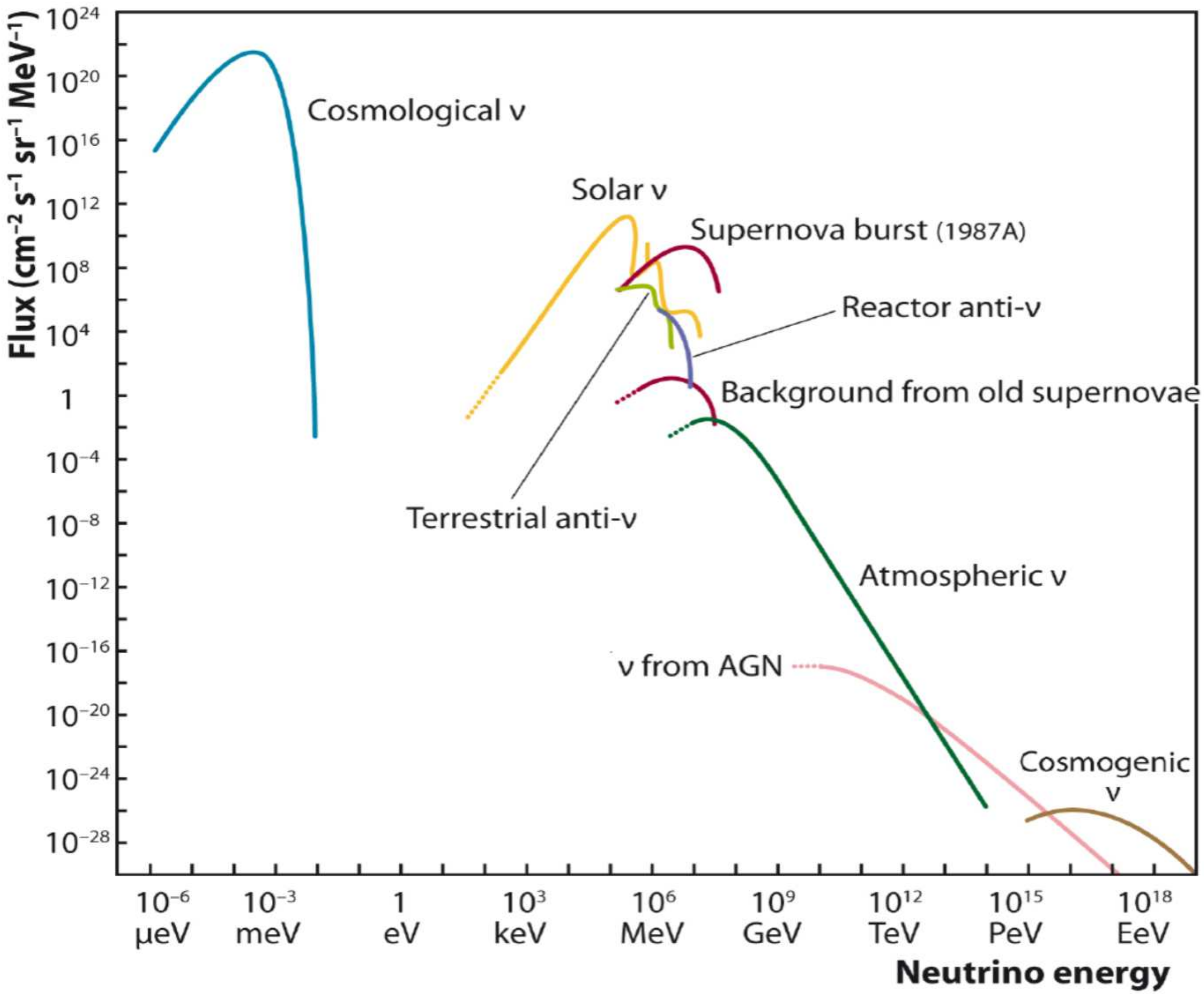


Millions and millions and millions of neutrinos are also passing through YOU at this very MOMENT!

65 billion of neutrinos / cm2 / sec from the Sun.

What do we know about neutrinos

They are abundant and are produced in a wide range of energies!



What do we know about neutrinos

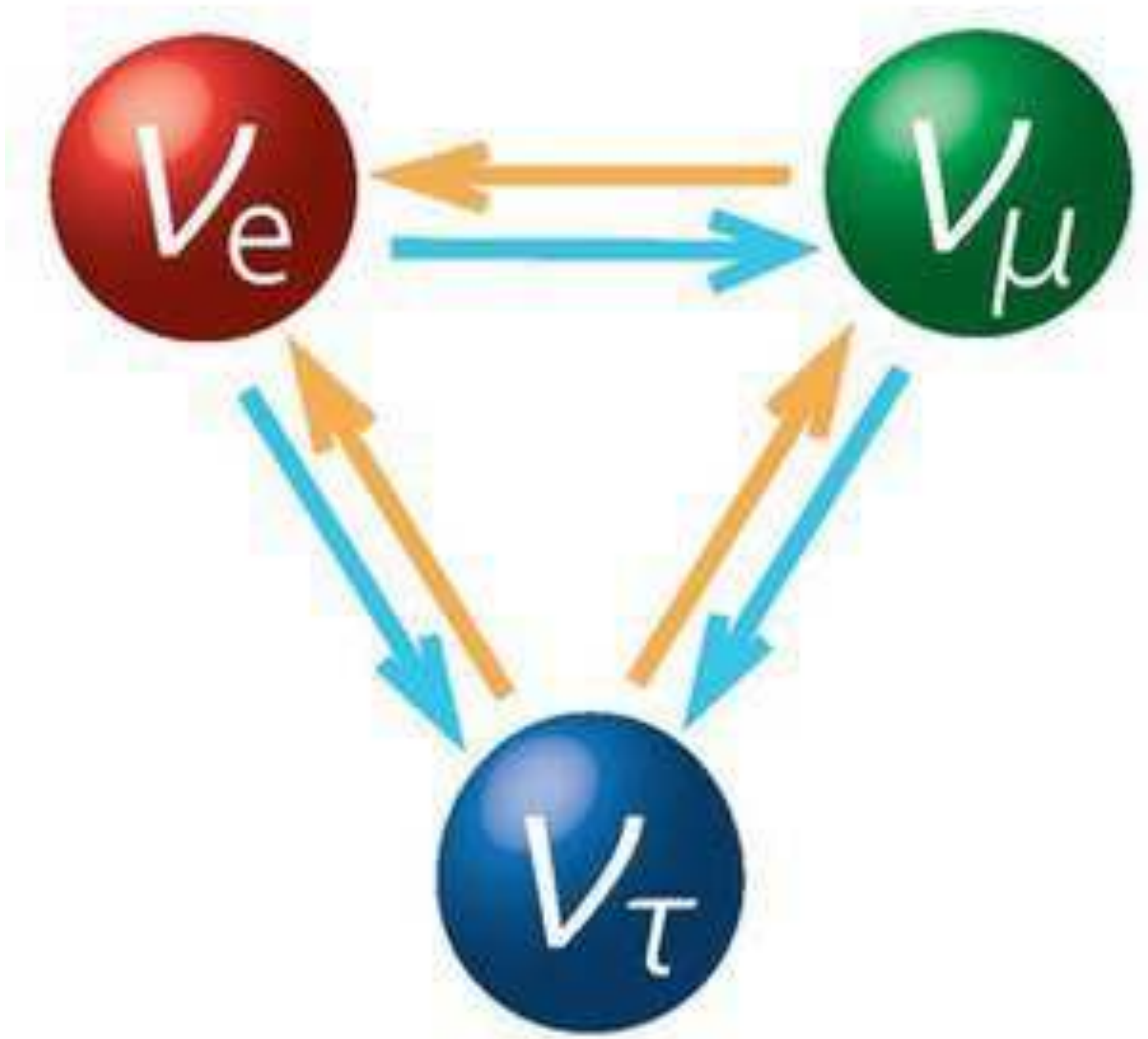
Neutrino interactions are extremely rare!

The probability of their interactions is very small

(neutrinos at Fermilab can travel up to 200 Earths before interacting)

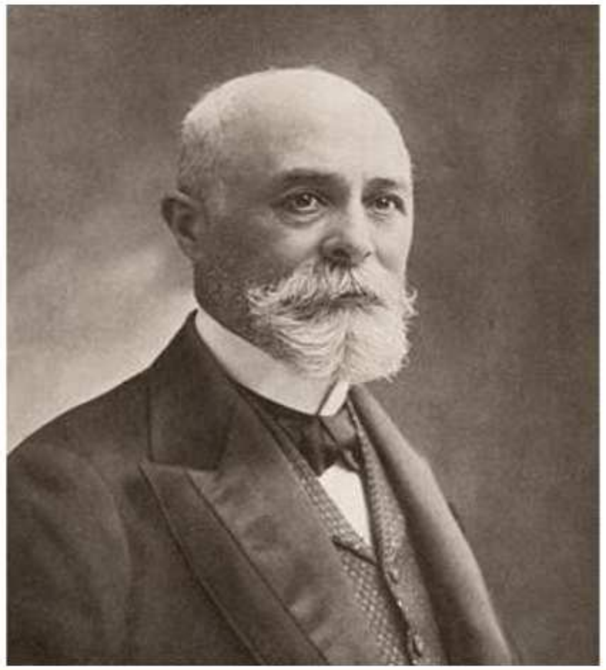
What do we know about neutrinos

They have very small masses and they oscillates



The Discovery of neutrinos

Antoine Henri Becquerel



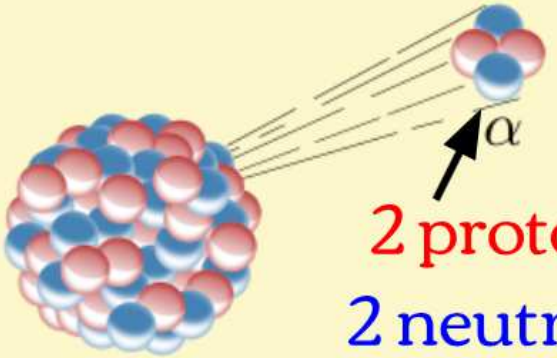
Marie Curie and Pierre Curie

Radioactive Decay

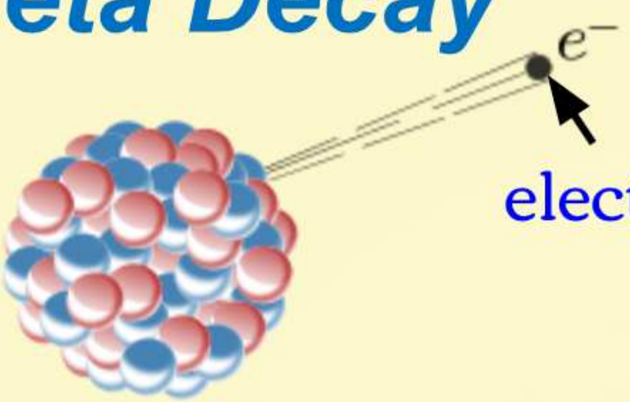
unstable atomic nucleus loses energy by emitting particles

transforms an atom into a different type of atom or into a lower energy

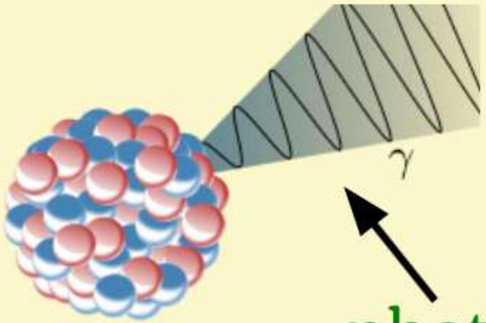
Alpha Decay



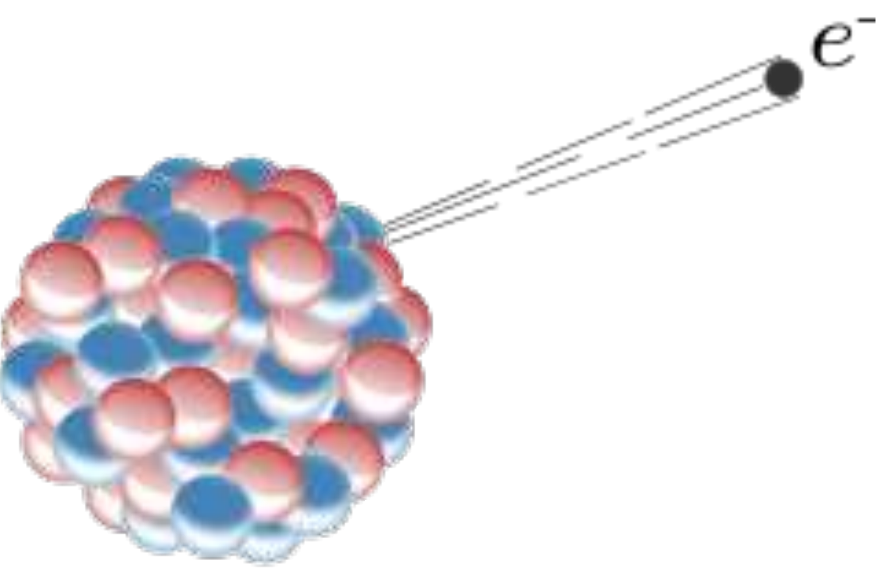
Beta Decay



Gamma Decay



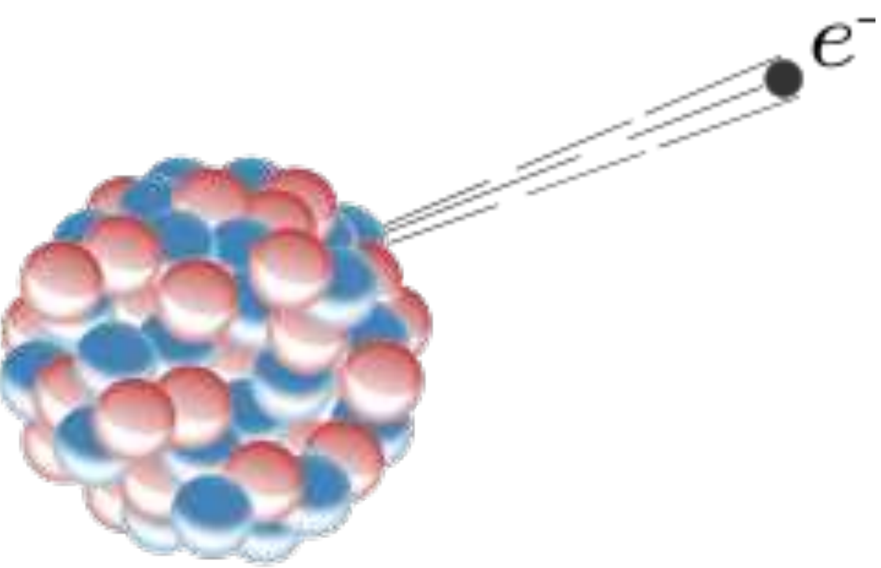
Beta decay problem <= 1930's

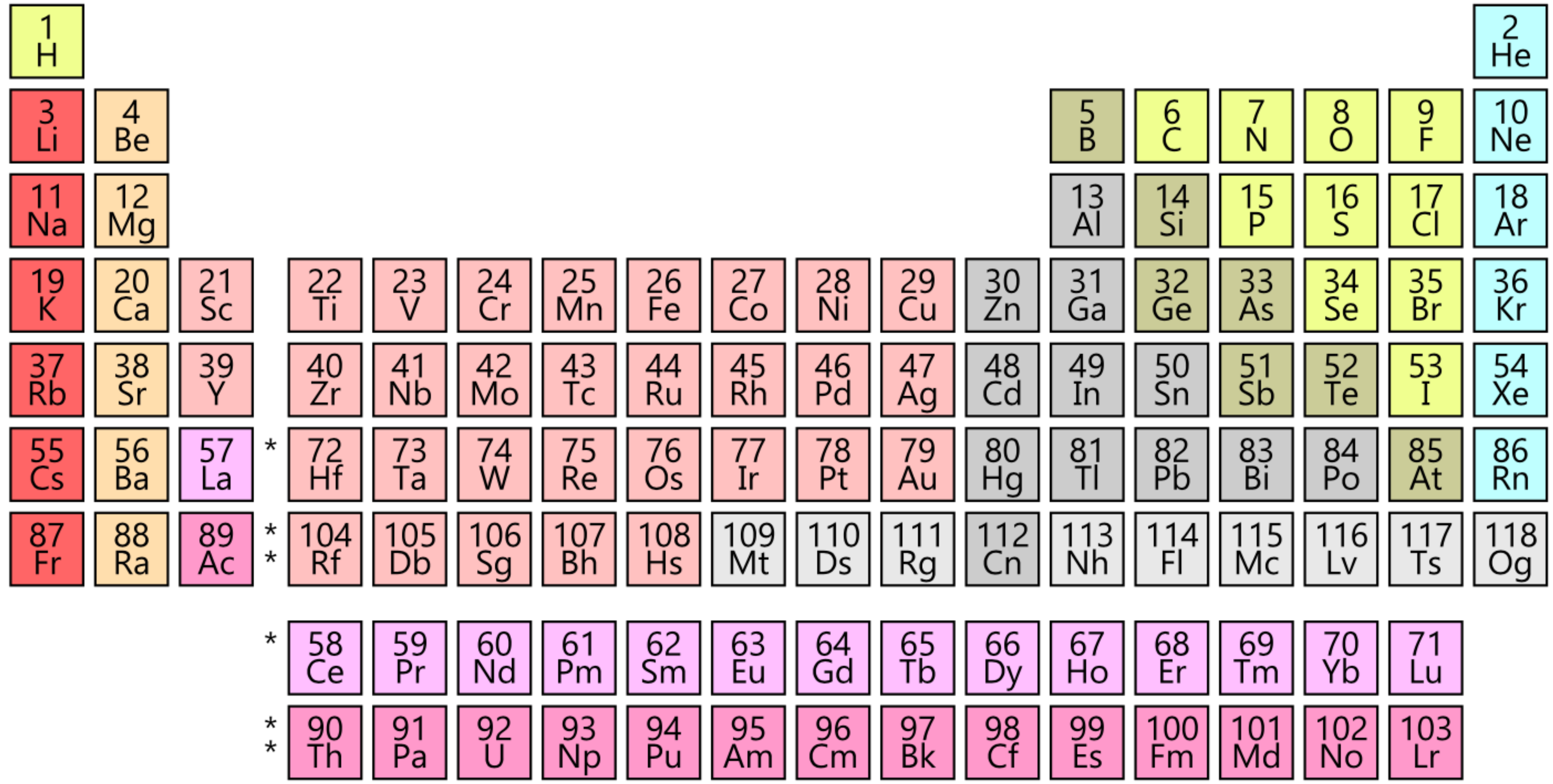


1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	* 72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	** 104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
			* 58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
			** 90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

For instance: Carbon → Nitrogen + Electron

Beta decay problem <= 1930's

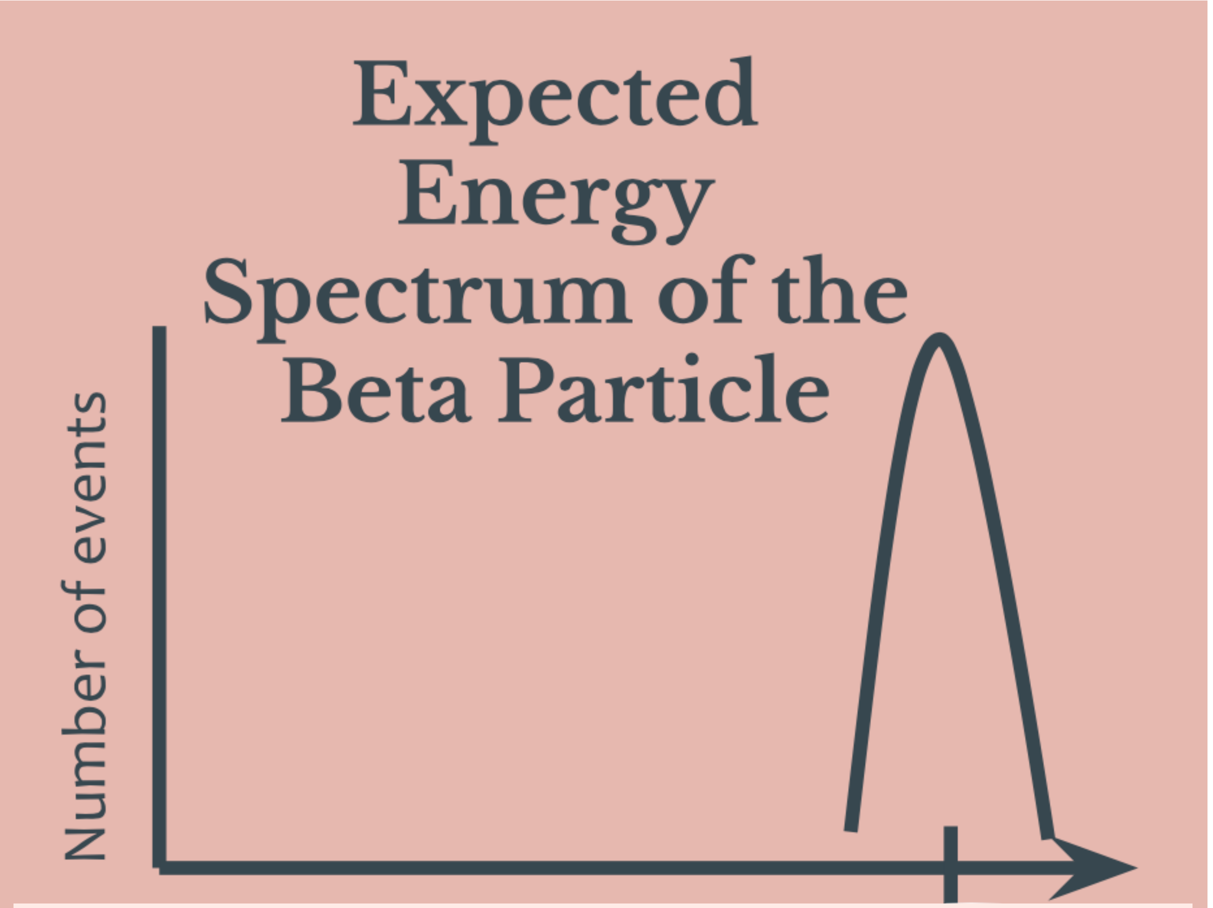




$^{14}_{6}C$ → $^{14}_{7}N$ + e^-

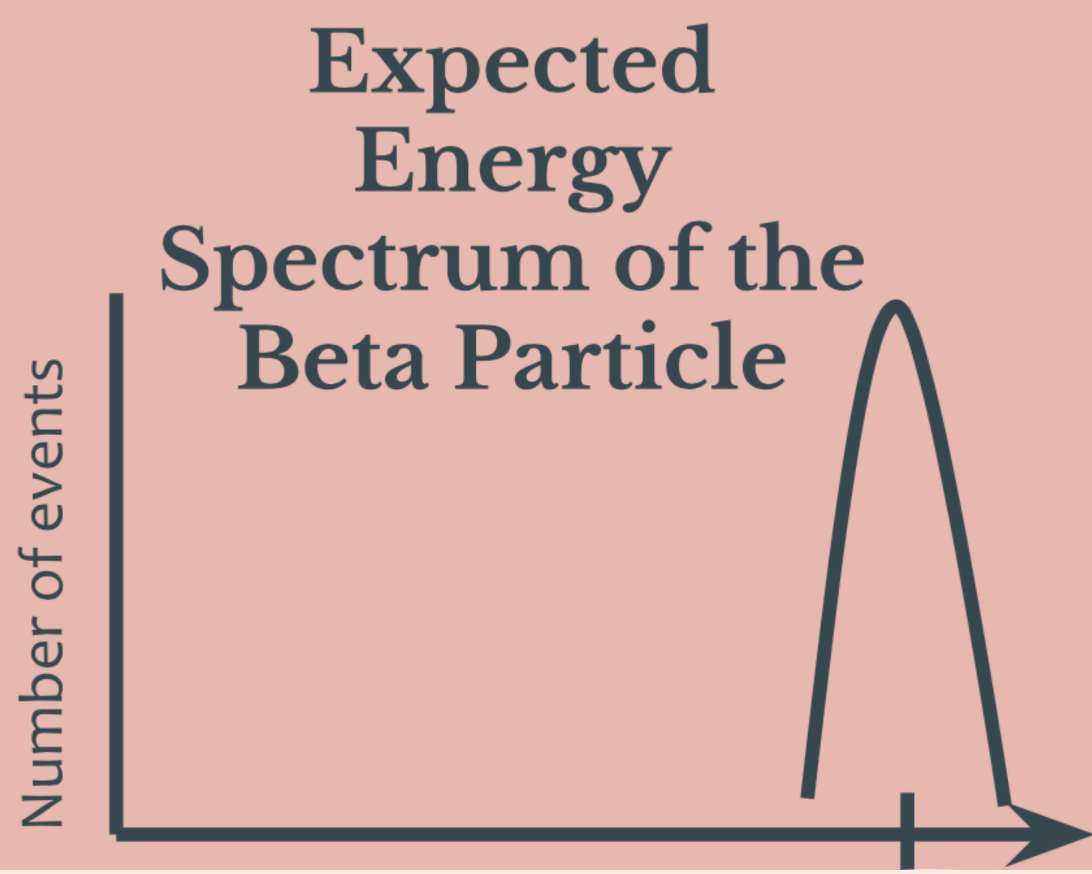
For instance: **Carbon** → **Nitrogen** + **Electron**

13 043.94 MeV/c² | **13 043.27 MeV/c²** | **0.511 MeV/c²**

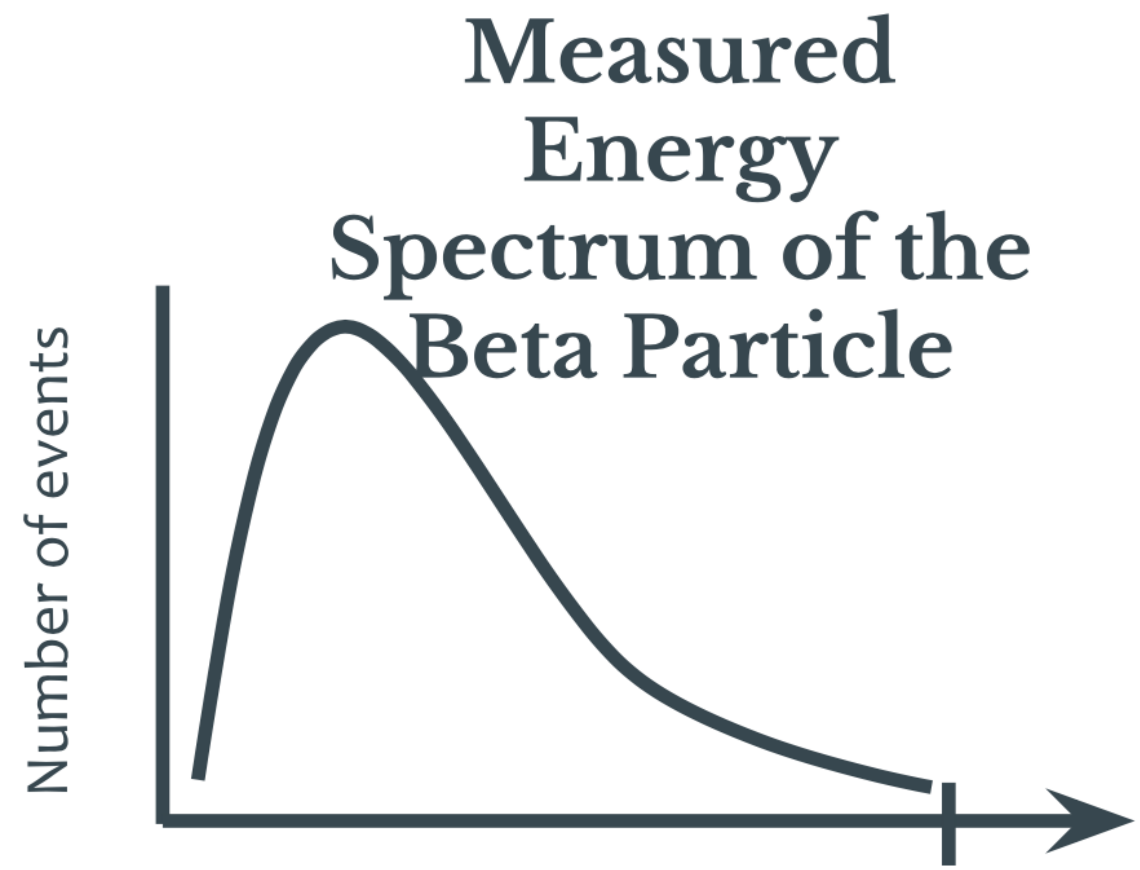


Beta particle: 0.159 MeV/c²

electron kinetic energy: 13 043.94– 13 043.27 – 0.511 = 0.159 MeV/c².



Beta particle: 0.159 MeV/c^2



Beta particle: 0.159 MeV/c^2

Could it be possible?

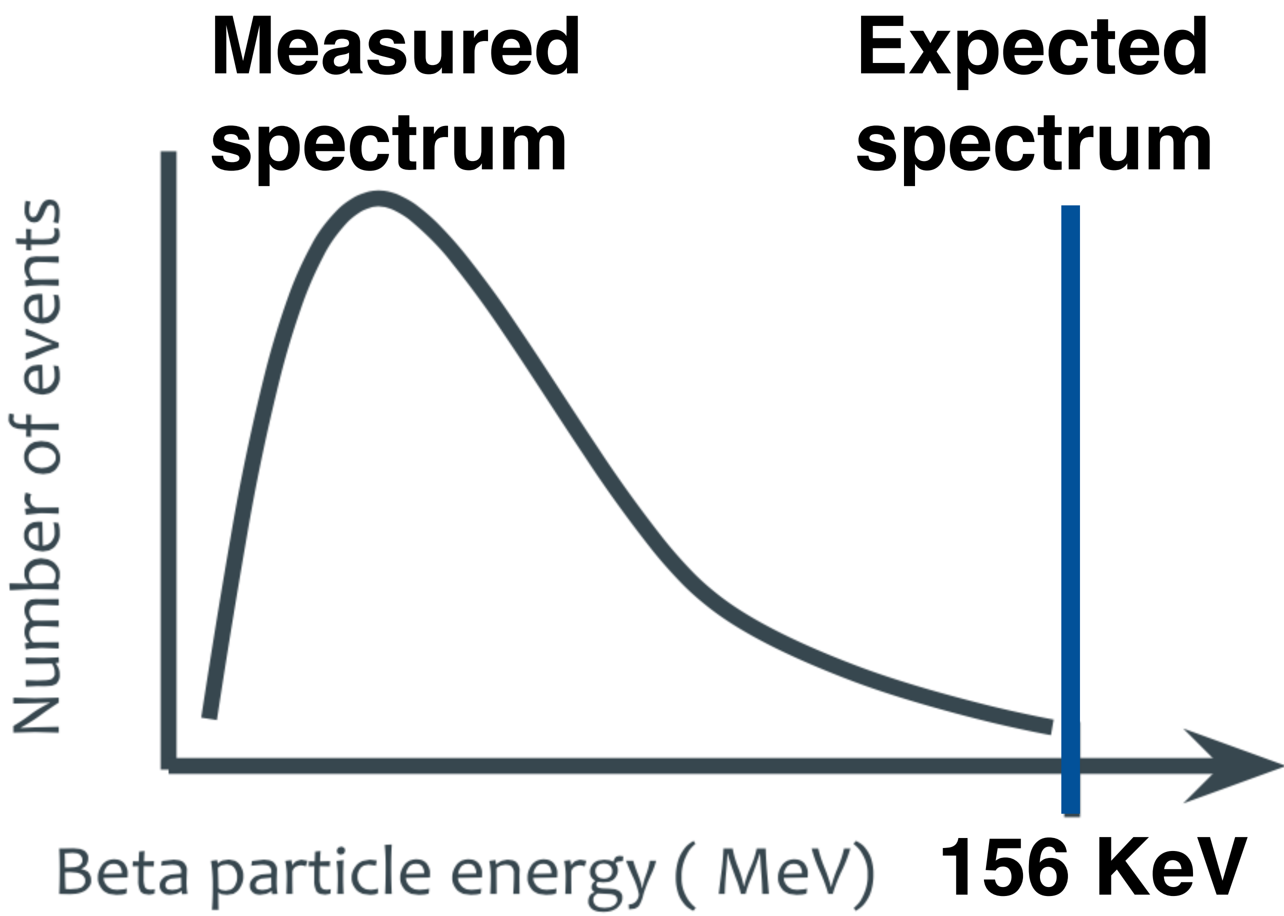
Does the Beat Decay Violate the Law of Energy Conservation?

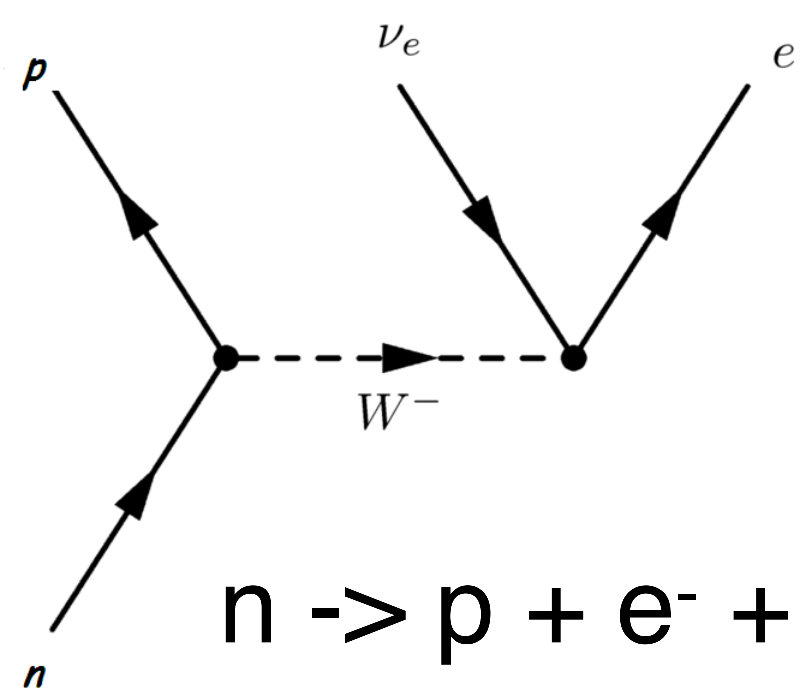
Beta decay problem > 1930's

(1930) Pauli postulated an additional particle (neutral and very small) in beta decays.

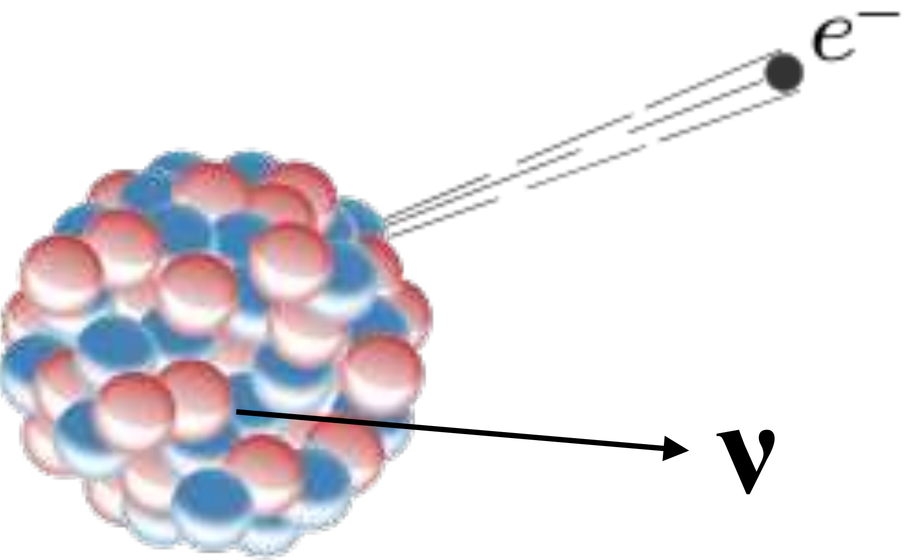
(1933) Fermi formulated the theory the weak force to explain the process.

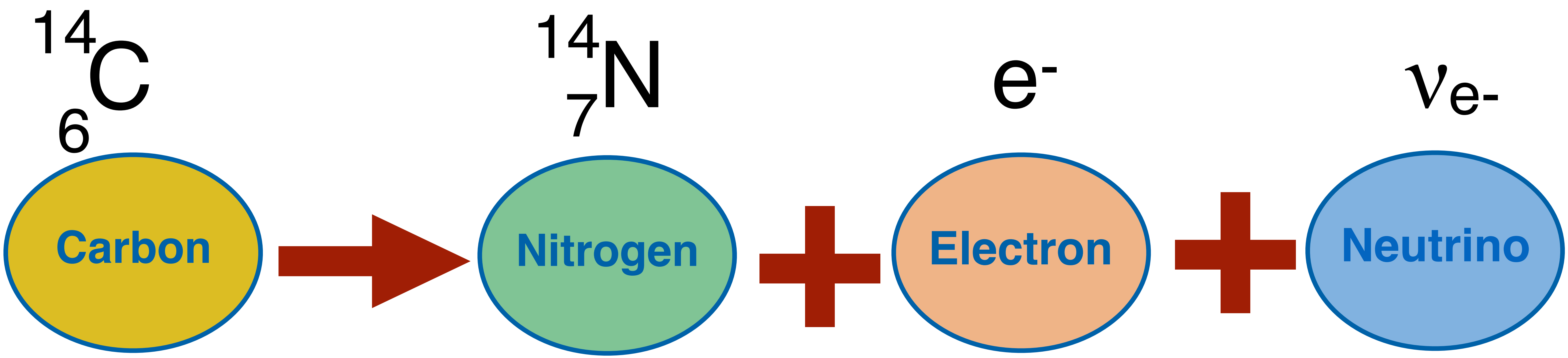
(1936) Yukawa proposed W boson as a carrier of the weak force.

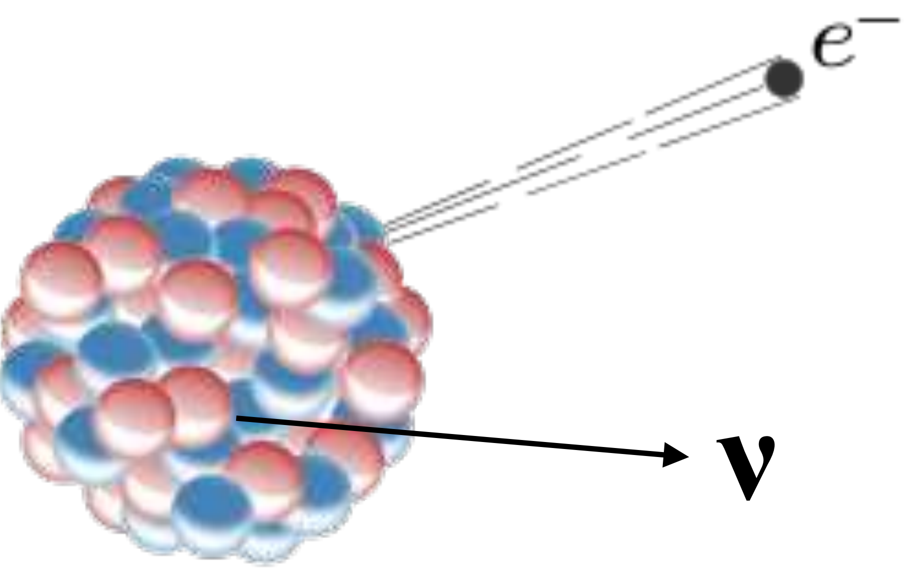




$$n \rightarrow p + e^- + \bar{\nu}_e$$

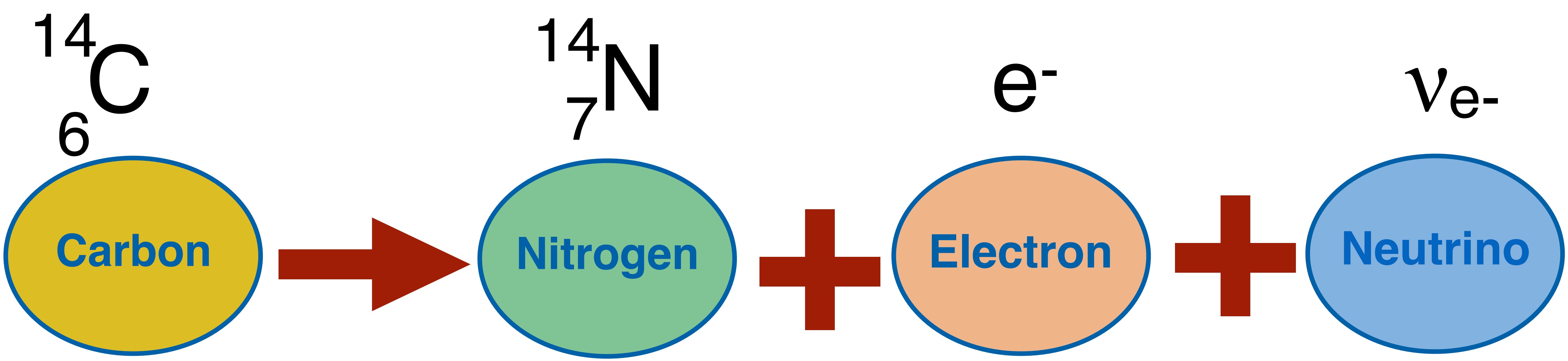

e^-
ν

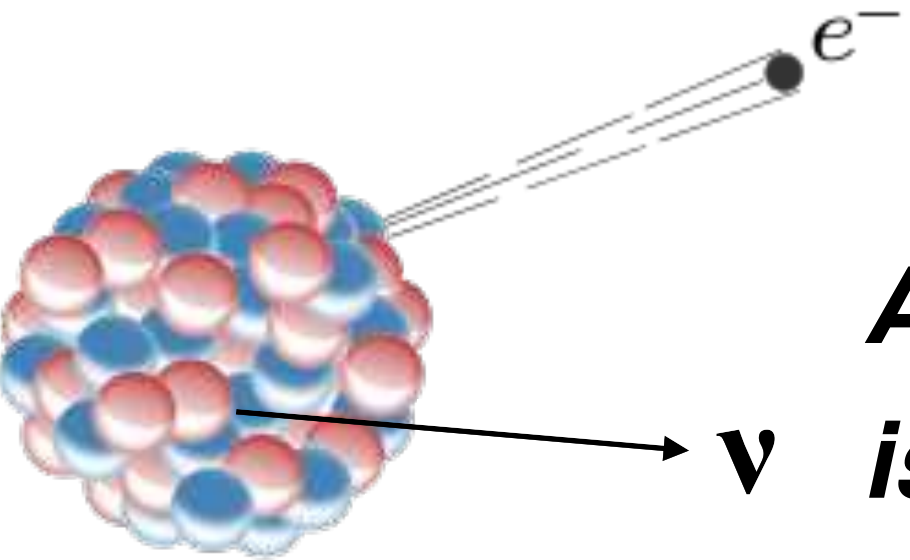

$^{14}_{6}C$
$^{14}_{7}N$
e^-
ν_{e-}
Carbon
Nitrogen
Electron
Neutrino



A new particle, the neutrino, is proposed

The next step is to detect the neutrino





A new particle, the neutrino, is proposed

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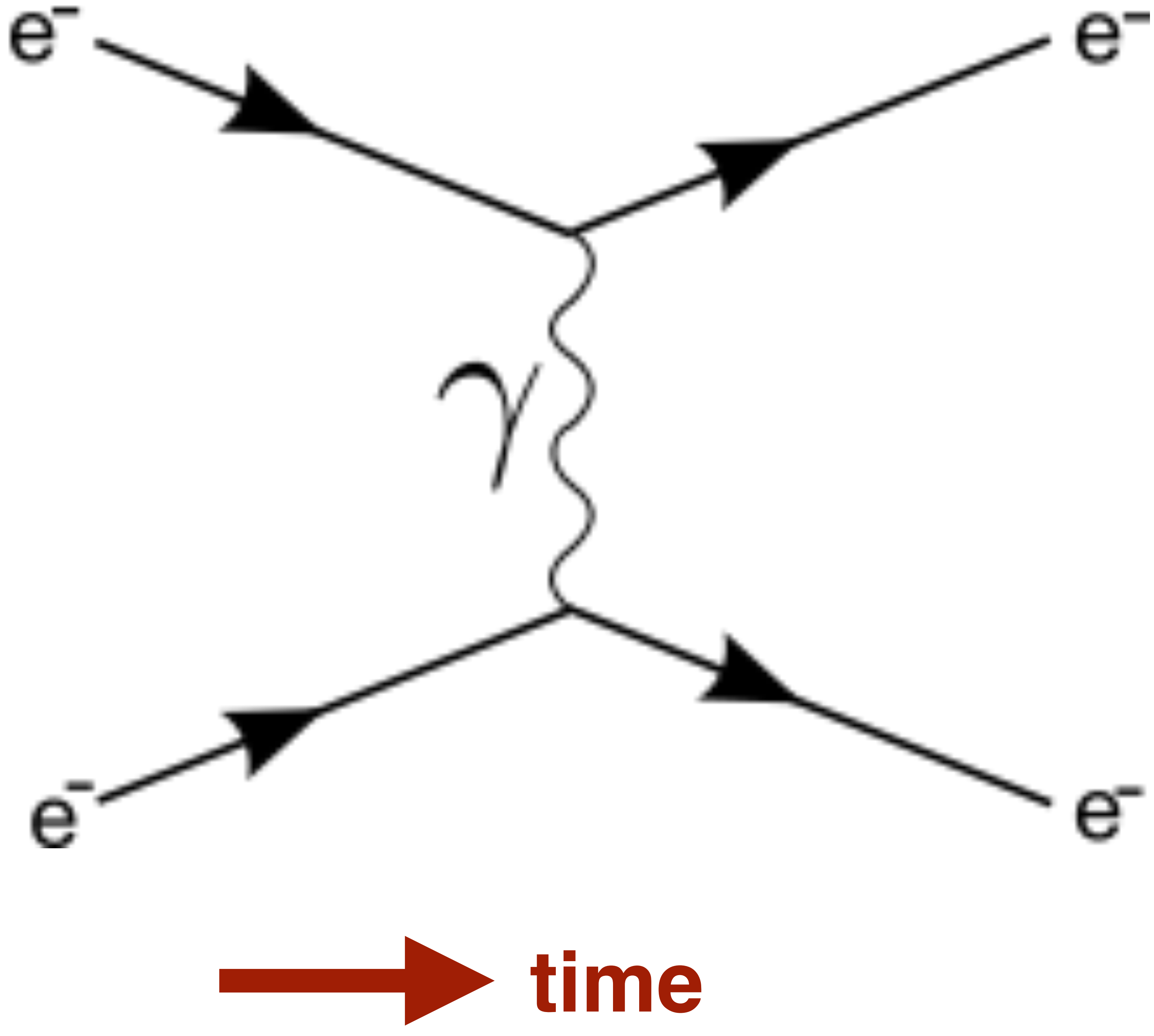
$^{14}_{6}C \rightarrow \, ^{14}_{7}N + e^- + \nu_{e-}$

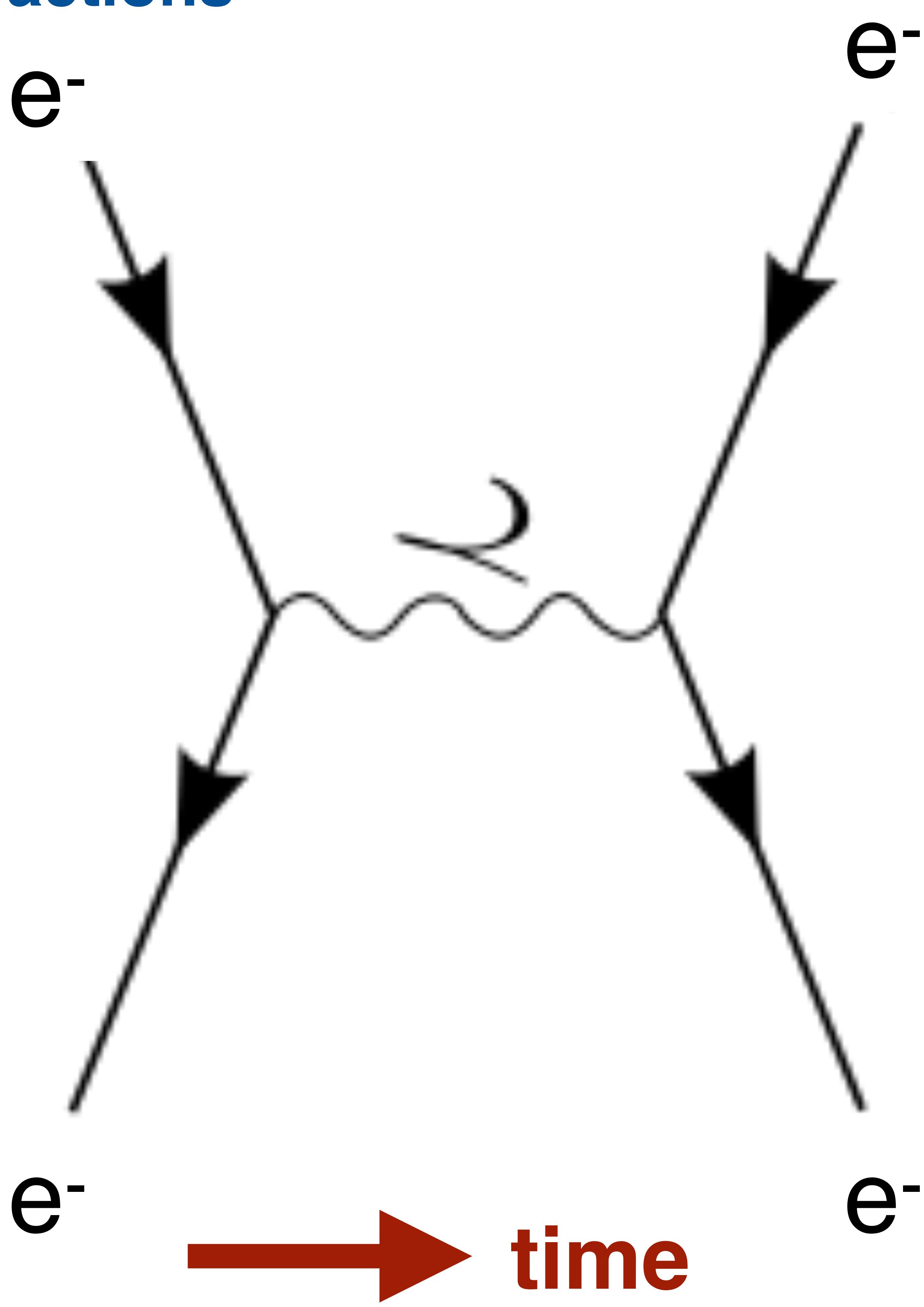
Carbon → Nitrogen + Electron + Neutrino

Nature has many symmetries

Symmetry in interactions



Symmetry in interactions



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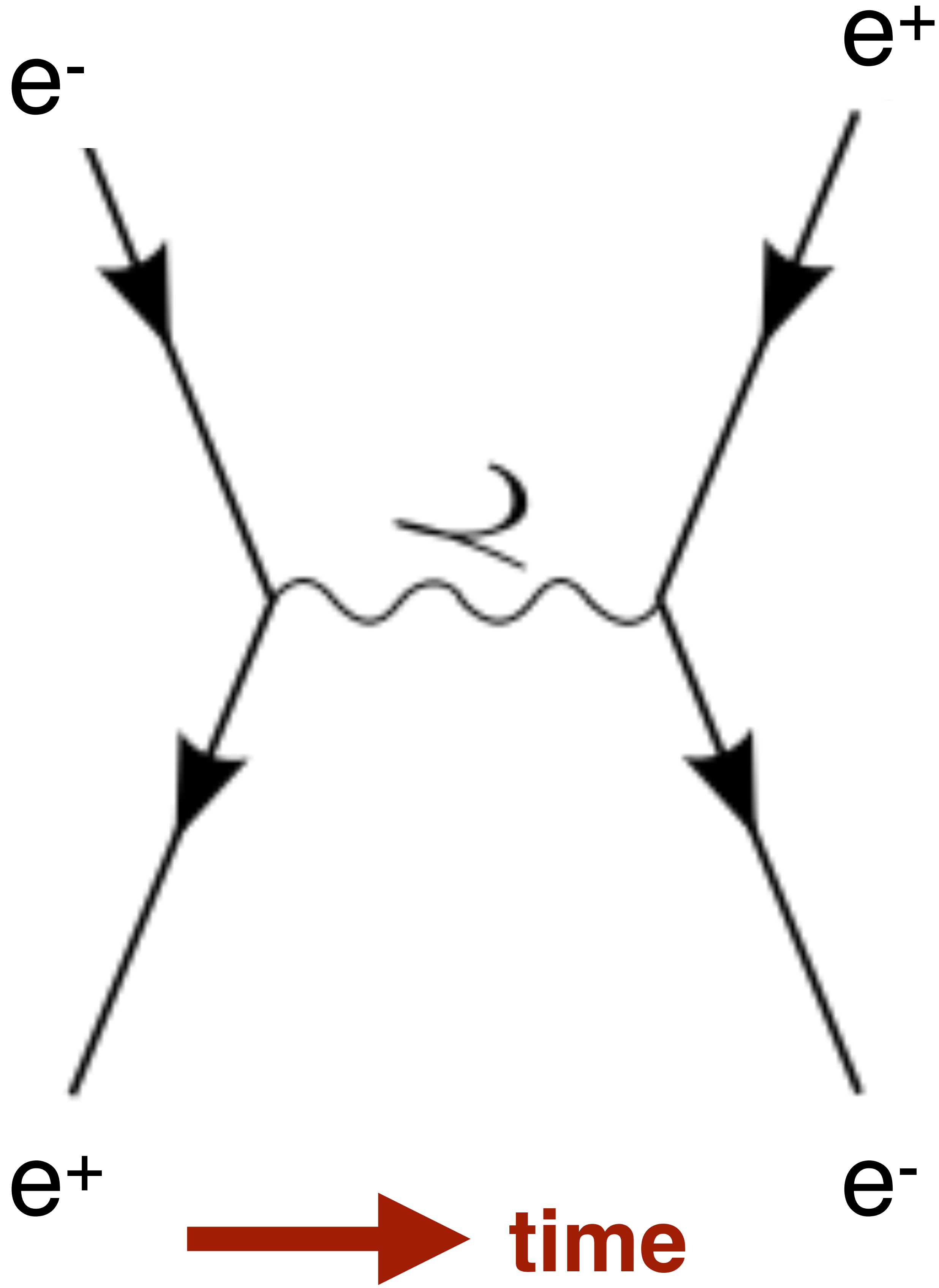
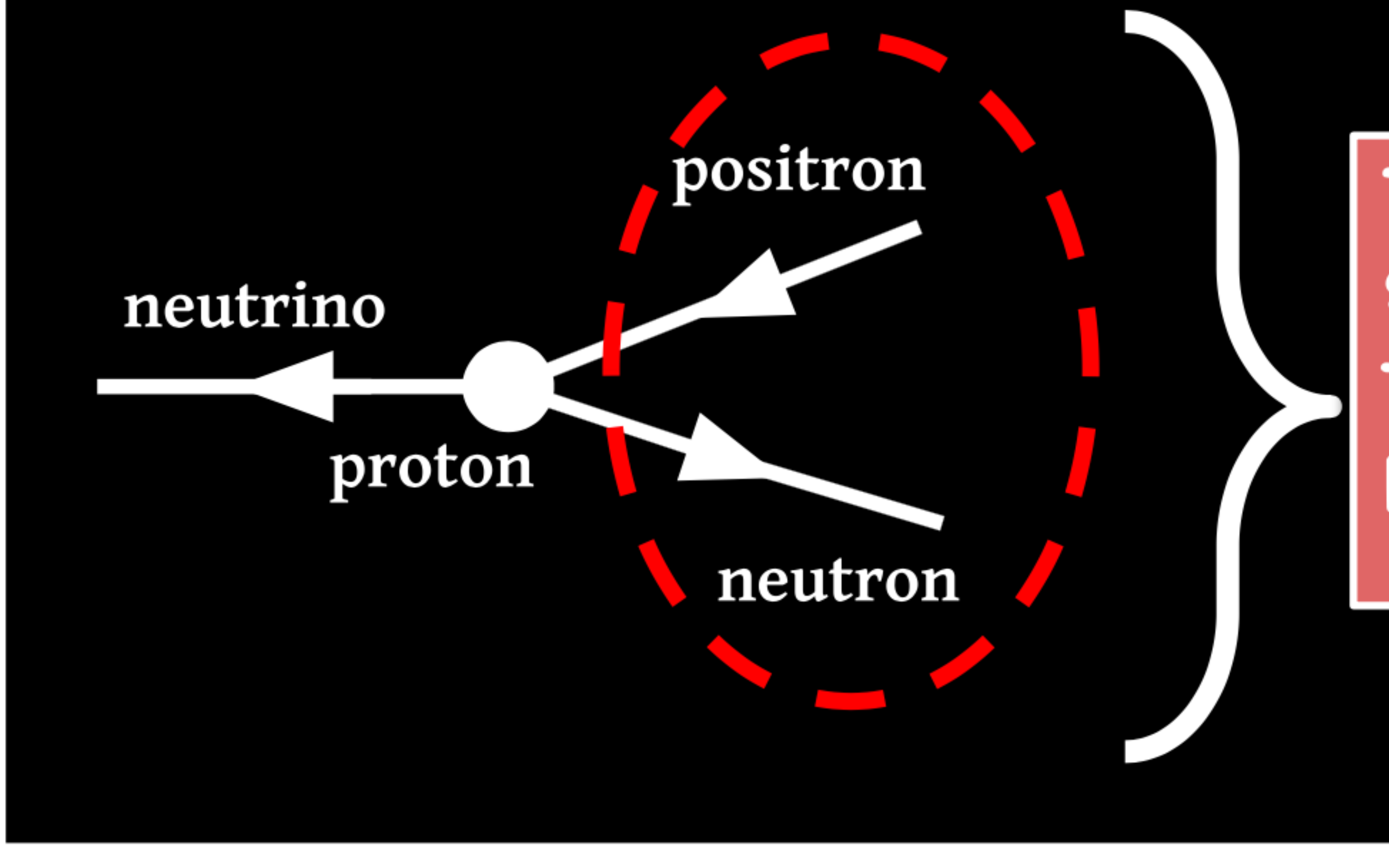


$n \rightarrow p + e^- + \bar{\nu}_e$

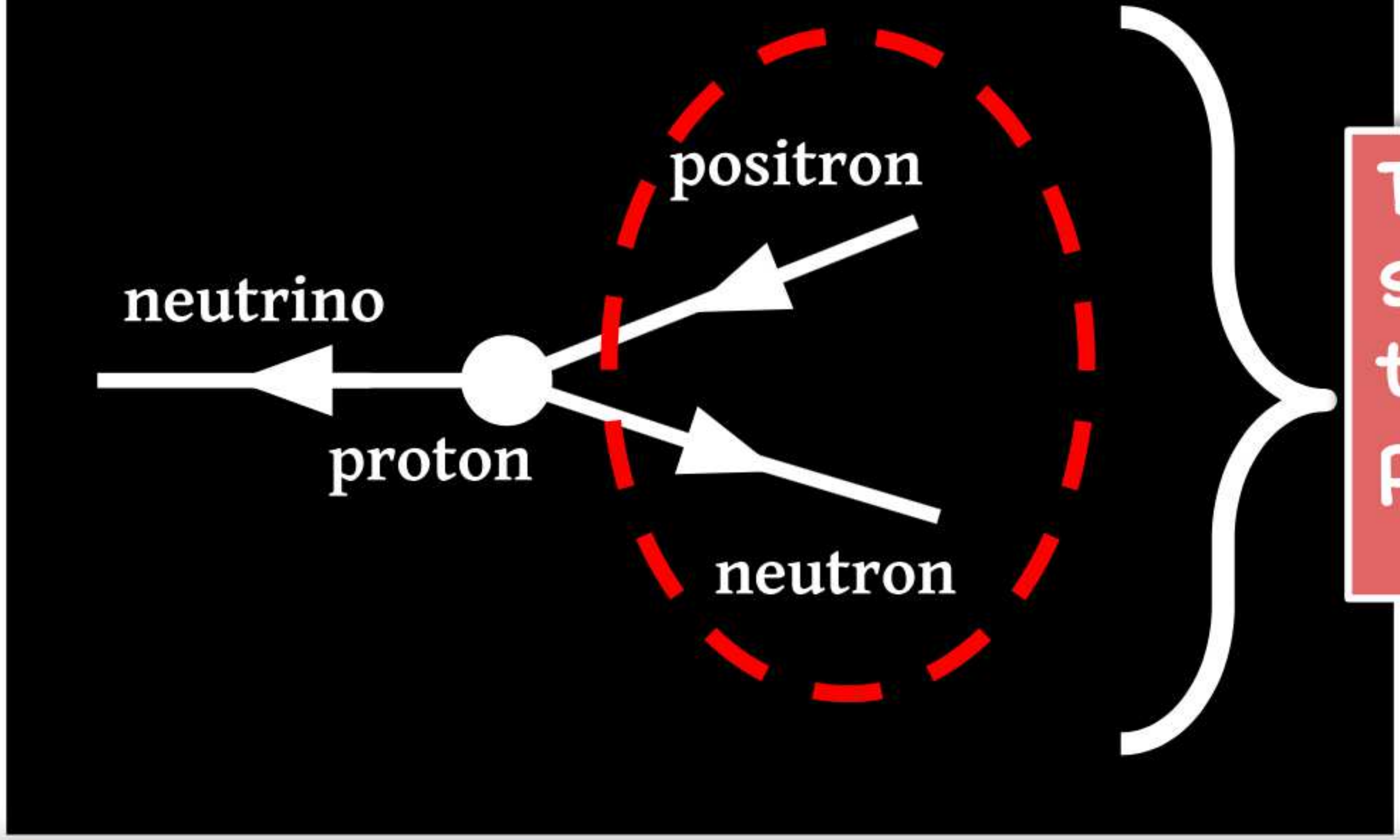
Beta decay

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

Inverse beta decay



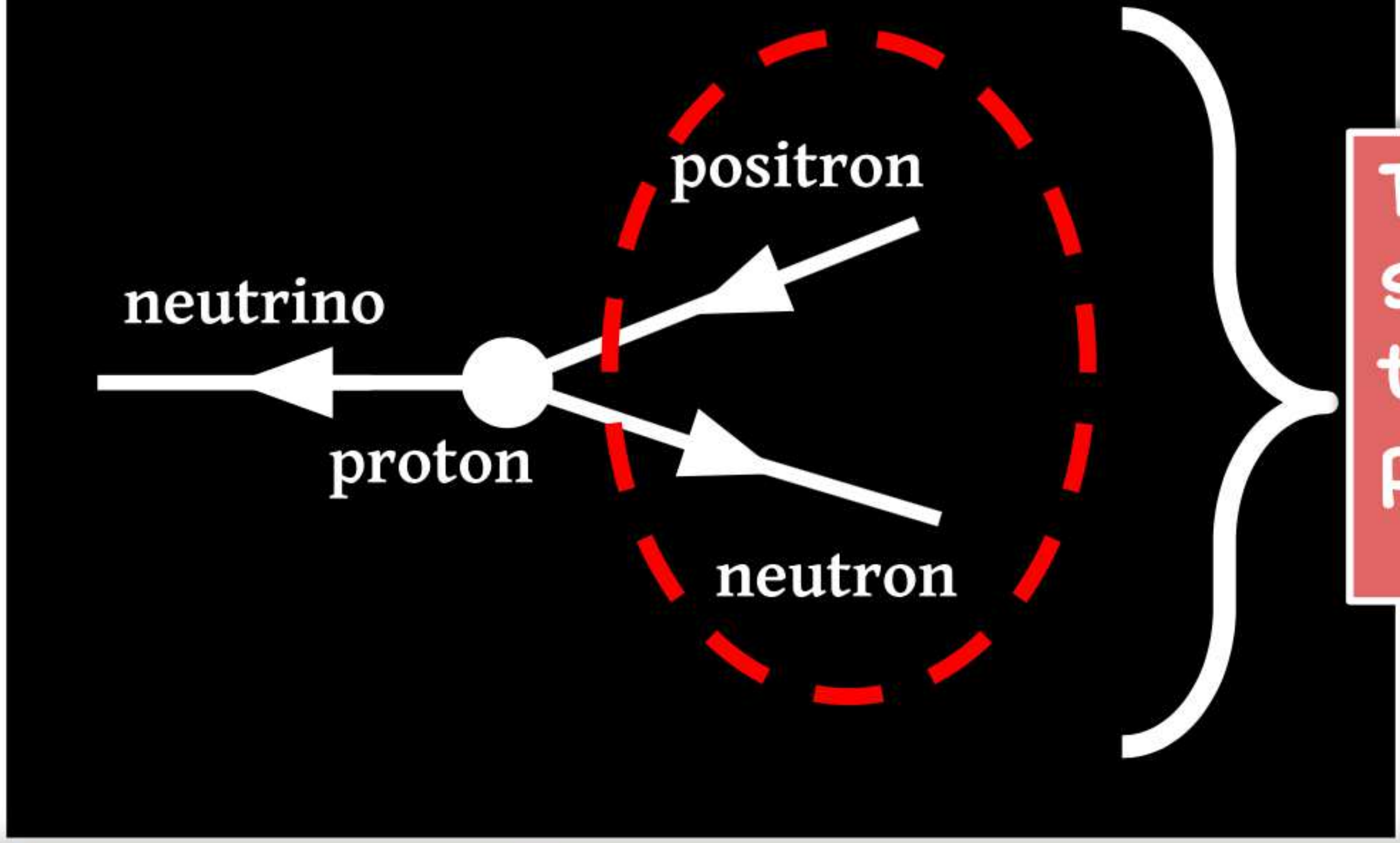
To observe the neutrino, scientists needed to detect the signatures of the positron and neutron.



To observe the neutrino, scientists needed to detect the signatures of the positron and neutron.

positron

is a positive charged electron → interacts via the electromagnetic force → interaction results in emission of gamma rays



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positron

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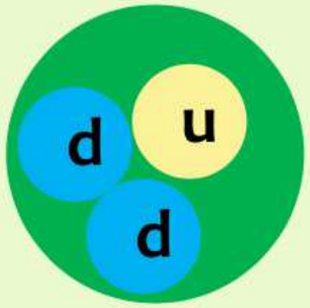
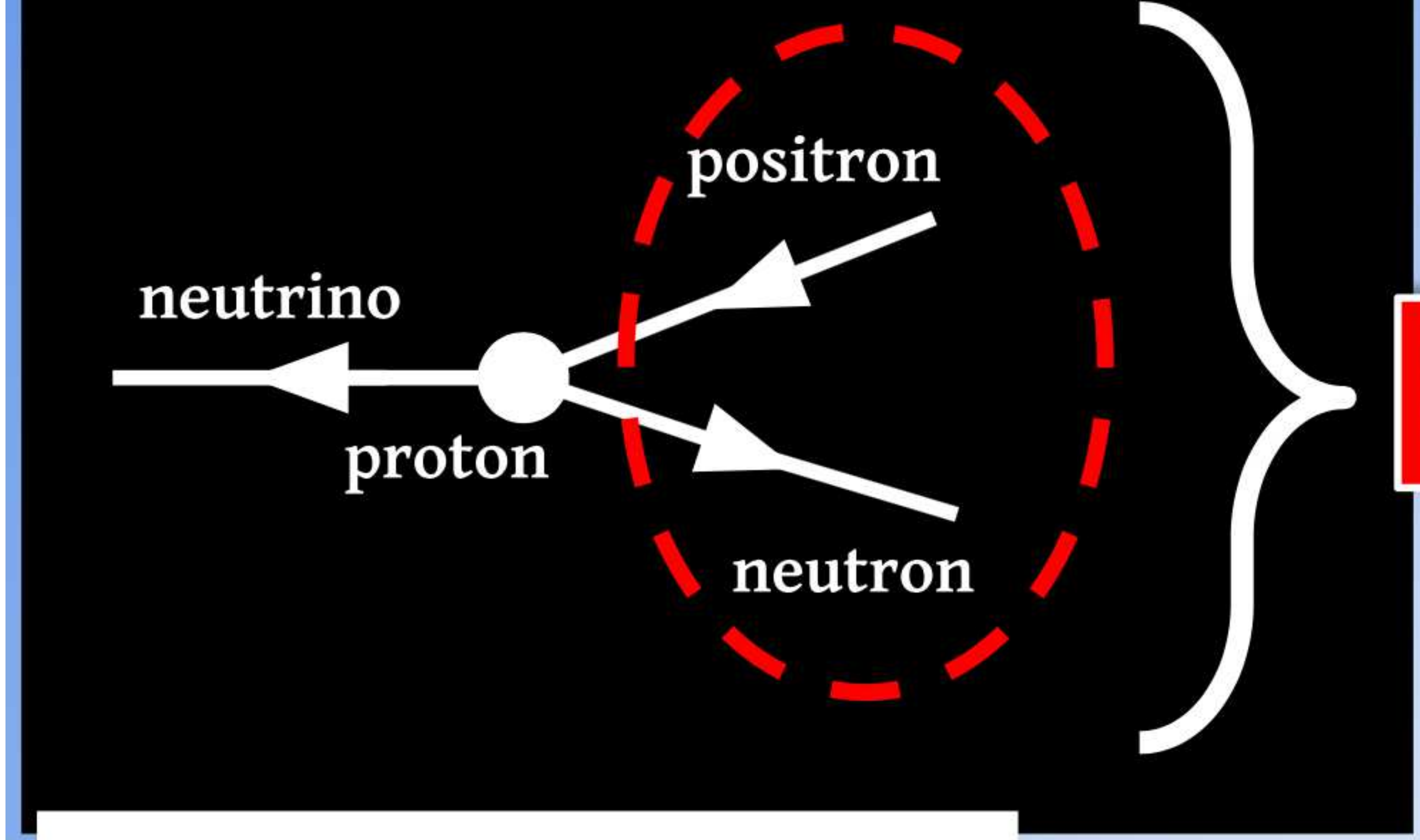
looking inside the neutron

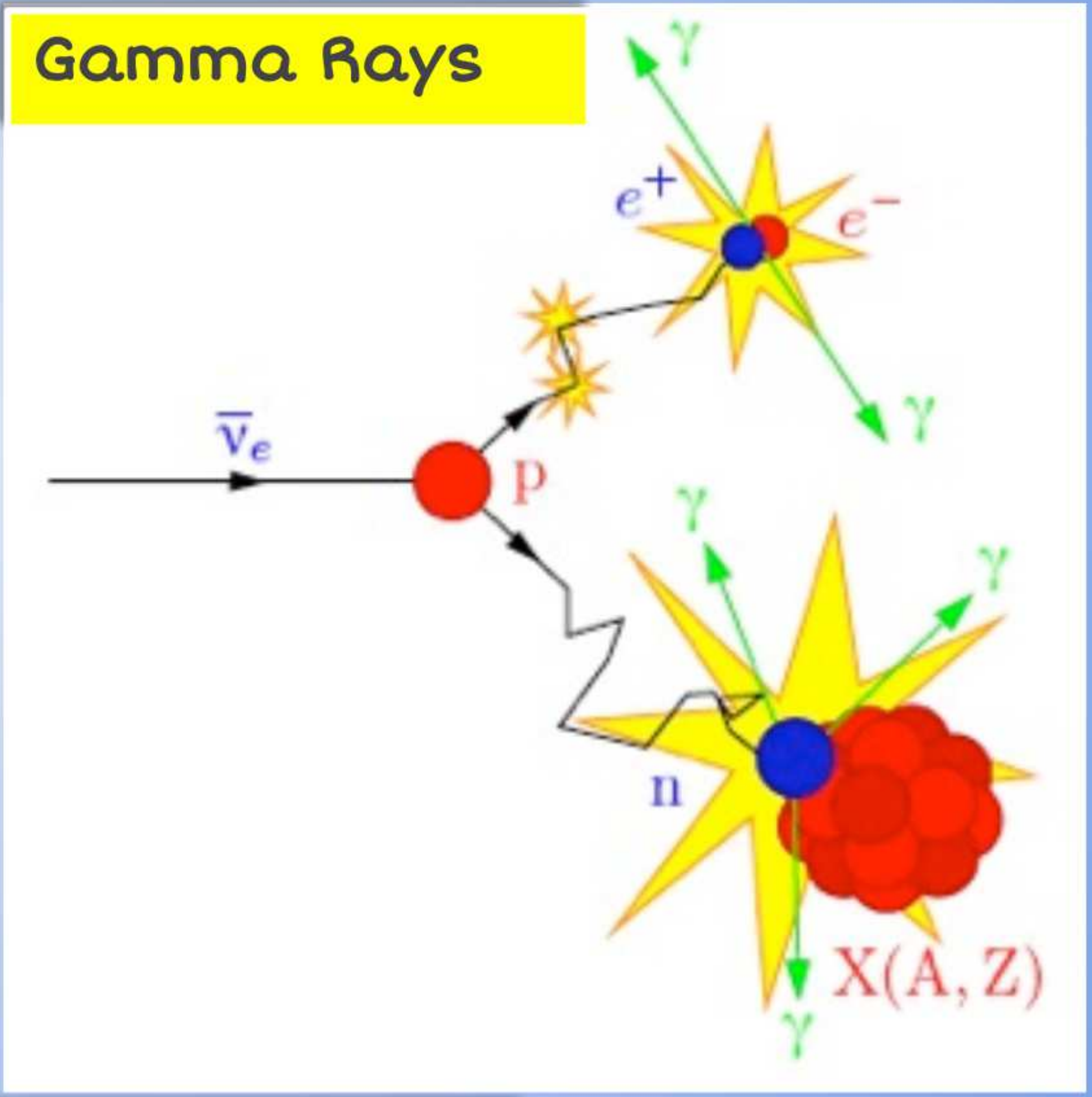


an atomic nucleus can capture a neutron → strong force binds the neutron in the nucleus to create a heavier particle → the heavier particle is unstable → emits gamma rays to become stable



signature of the inverse beta decay

Gamma Rays



The HULK is unstable.
Bruce Banner is stable.

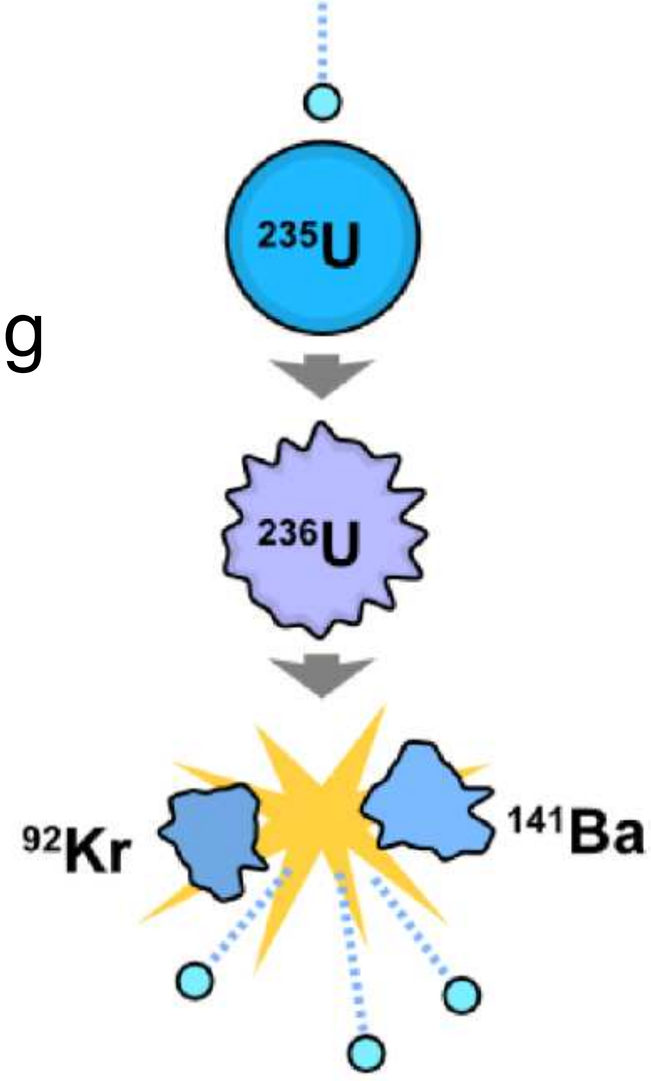
Reactor neutrinos

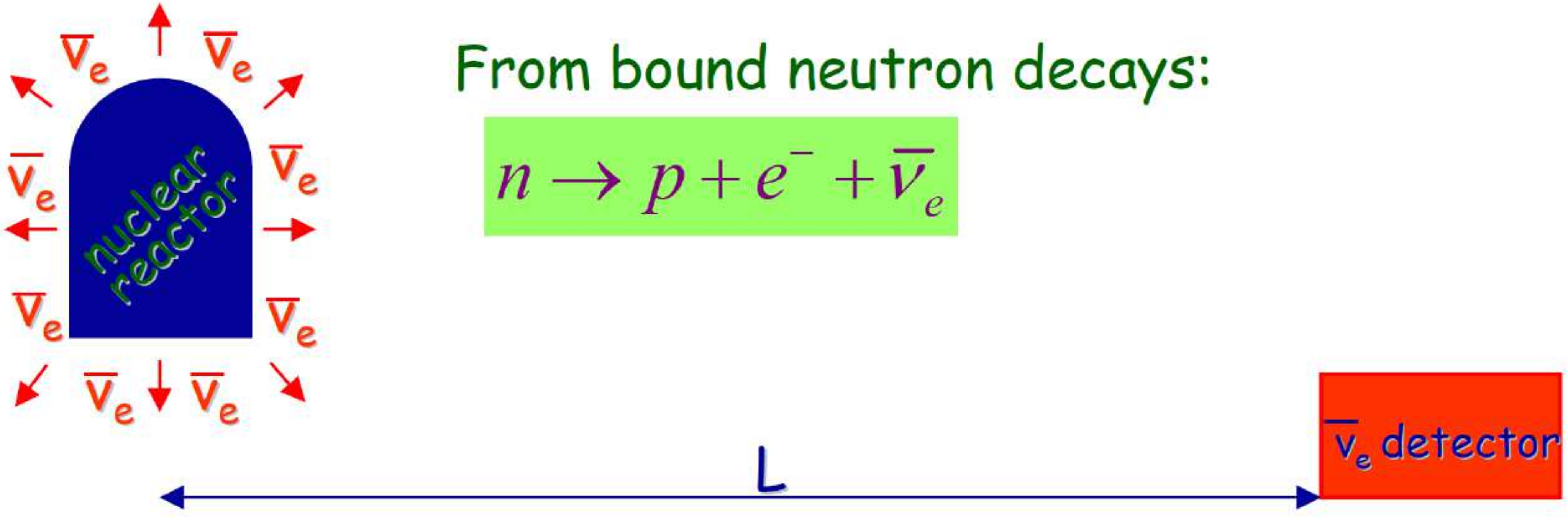
- Nuclear fission creates artificial radioactivity: bombarding heavy elements with slow neutrons

- Neutrons are unstable: $n \rightarrow p + e^- + \bar{\nu}_e$

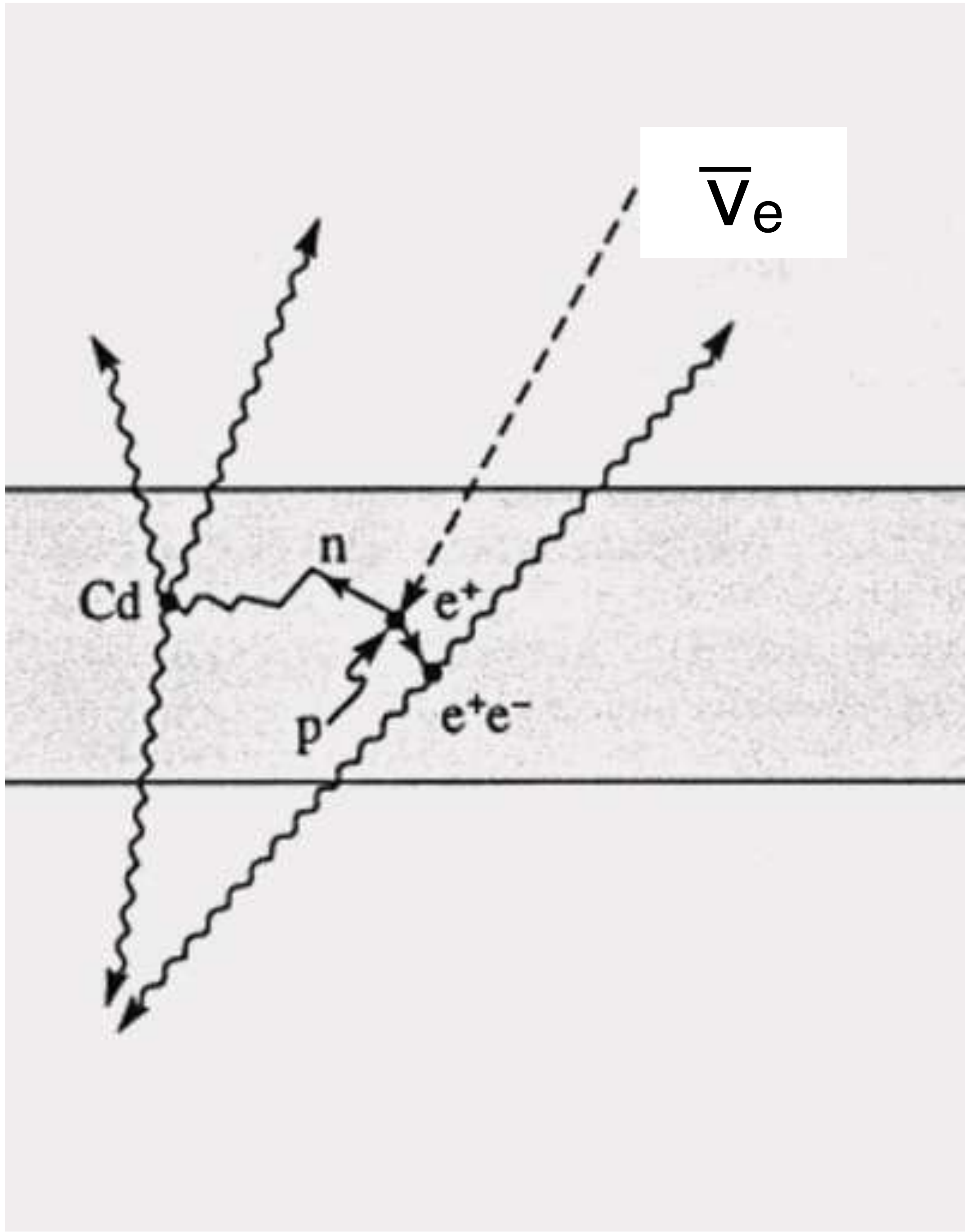
- The electron antineutrino can be detected as:

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





Poltergeist project

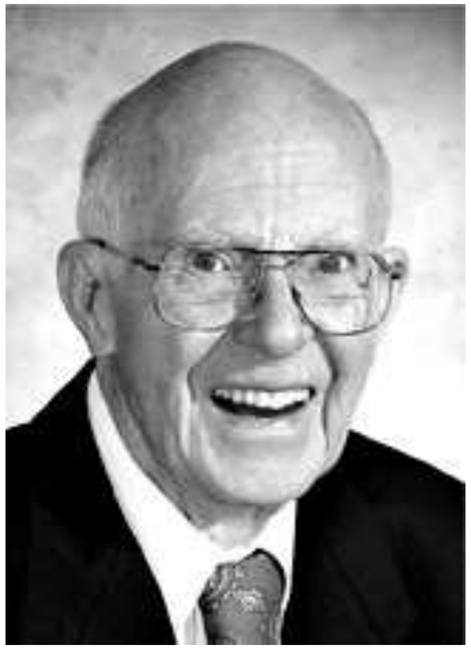


- (1956) A team lead by Clyde Cowan and Frederick Reines designed an experiment to detect neutrinos from a reactor.
- Observed 0.56 counts per hour.

Homestake experiment

- (1961) Ray Davis confirmed the detection of solar neutrinos.
- Neutrino interactions convert Cl-37 into radioactive Ar-37.

It was expected 1 neutrino per day.



Ray Davis

Homestake experiment

- (1961) Ray Davis confirmed the detection of solar neutrinos.
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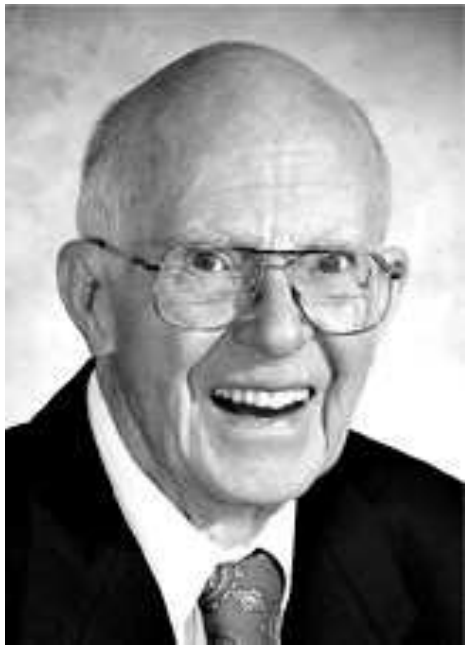
It was expected 1 neutrino per day. However, they only saw 1 neutrino every fourth days.



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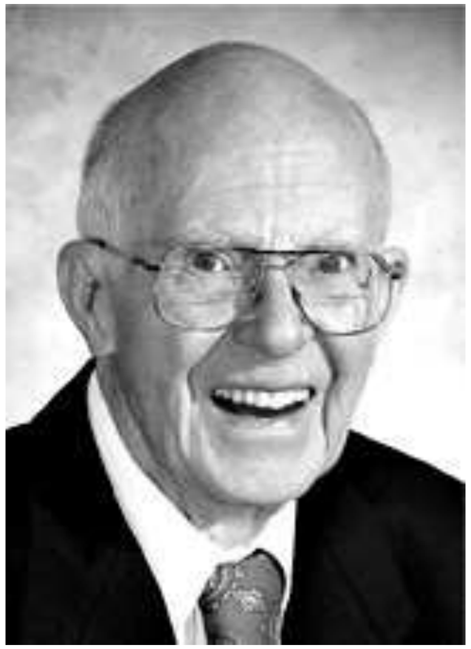

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Our understanding of how our detector behaves is wrong

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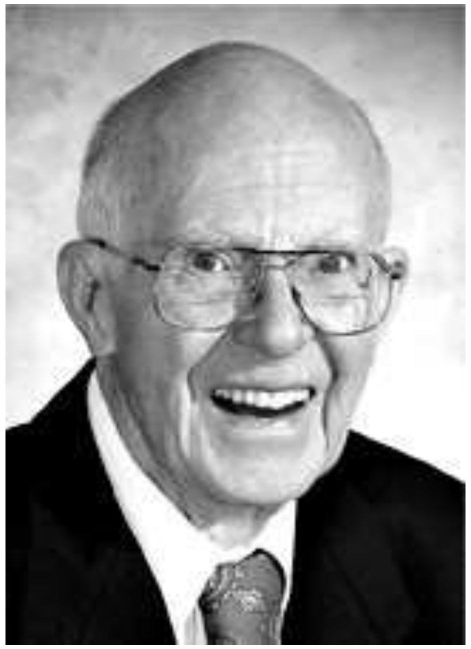

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Is the Solar model wrong?

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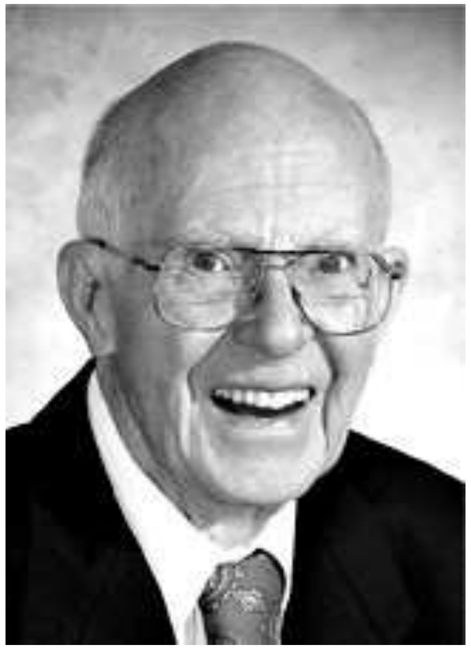
- (1961) Ray Davis confirmed the detection of solar neutrinos.
- Neutrino interactions convert Cl-37 into radioactive Ar-37.



Ray Davis

It was expected 1 neutrino per day. However, they only saw 1 neutrino every fourth days.

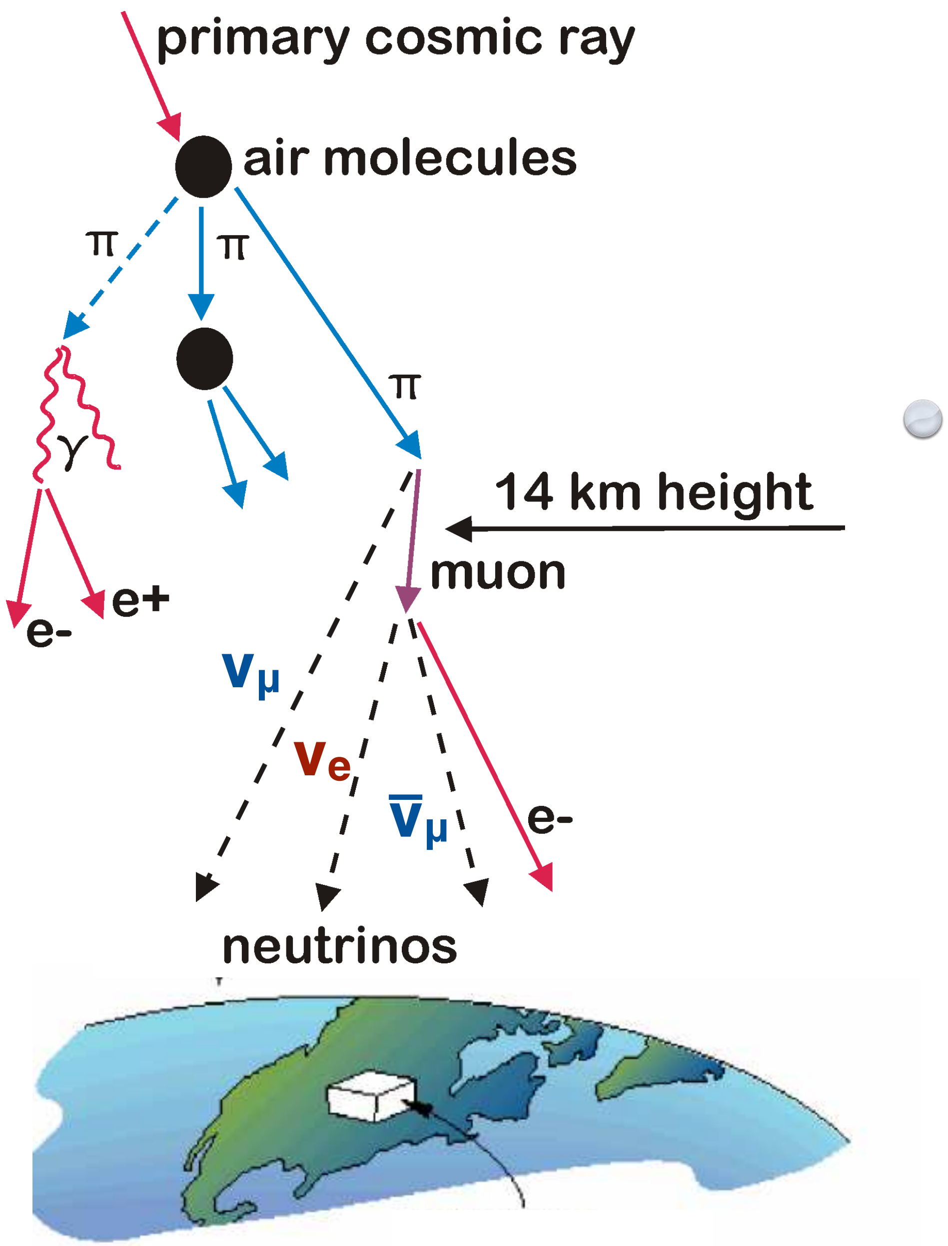
Our understanding of how our detector behaves is wrong

Is the Solar model wrong?

Our understanding on how neutrinos behave is wrong?

Atmospheric neutrinos

- Cosmic rays (mostly) interact in the upper atmosphere creating a hadronic showers (mostly pions).

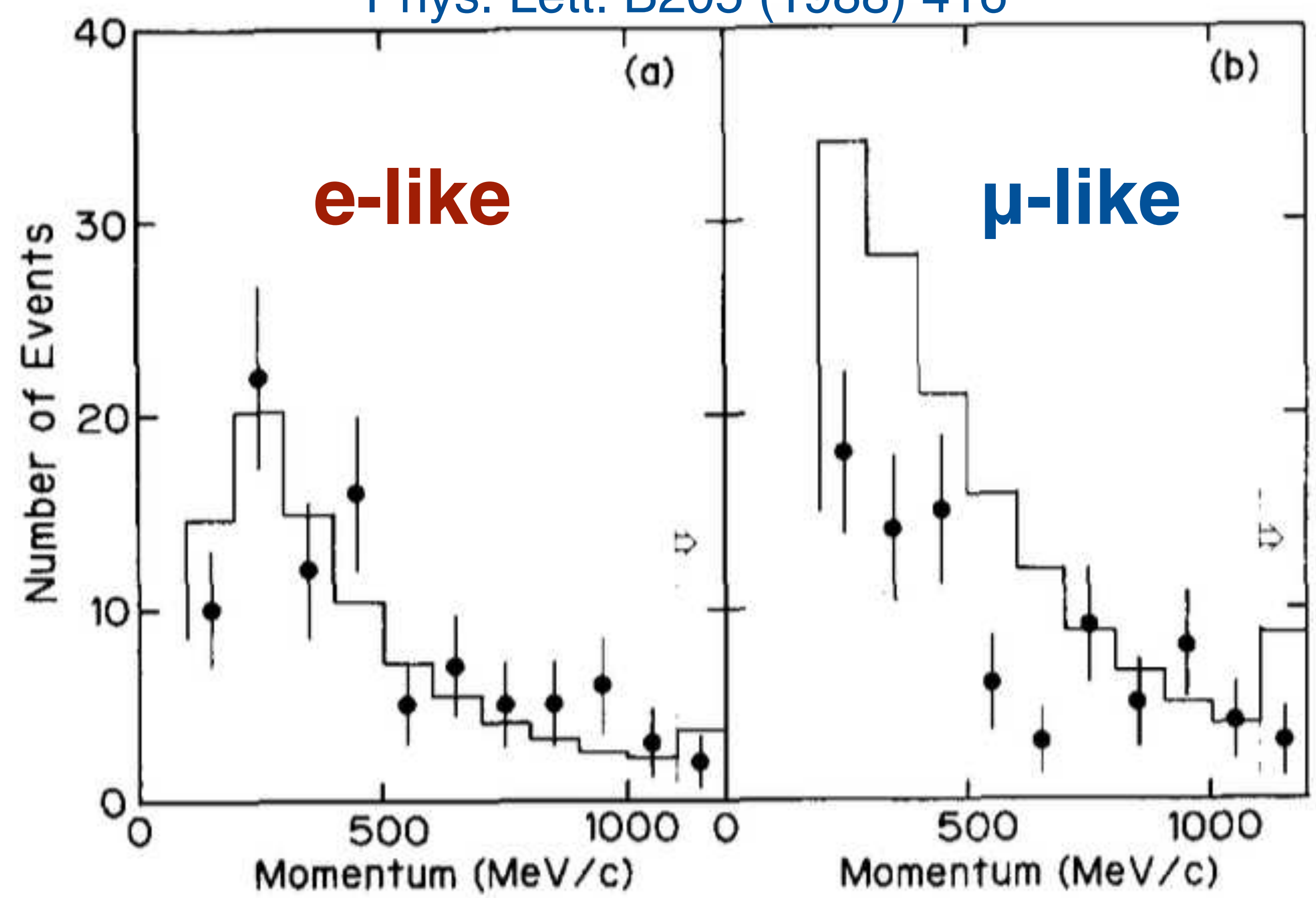


- Roughly 2:1 muon neutrinos to electron neutrinos expected:

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

- Events found in Kamiokande (~3kton WC) 1988

Phys. Lett. B205 (1988) 416



Nobel Prize in 2015 for Discovering Neutrino Oscillations

Takaaki Kajita

Super - Kamiokande

Arthur B. McDonald

SNO

Neutrino Oscillations

Create in one flavor, but detect in another flavor

Create in one flavor, but detect in another flavor

Created or detected

States associated to the corresponding lepton

ν_e

ν_μ

ν_τ

Create in one flavor, but detect in another flavor

Created or detected	***Traveling***
ν_e	ν_1
ν_μ	ν_2
ν_τ	ν_3

States associated to the corresponding lepton (created or detected)

States with well determined mass (traveling)

Create in one flavor, but detect in another flavor

Created or detected | ***Traveling***

States associated to the corresponding lepton

ν_e ↔ ν_1

ν_μ ↔ ν_2

ν_τ ↔ ν_3

States with well determined mass

They do not match

Create in one flavor, but detect in another flavor

$$\nu_e = \nu_1 + \nu_2 + \nu_3$$

$$\nu_\mu = \nu_1 + \nu_2 + \nu_3$$

$$\nu_\tau = \nu_1 + \nu_2 + \nu_3$$

https://www.youtube.com/watch?v=7fgKBJDMO54

Create in one flavor, but detect in another flavor

$$\nu_e = \rightarrow\nu_1 + \rightarrow\nu_2 + \uparrow\nu_3$$

$$\nu_\mu = \nwarrow\nu_1 + \nearrow\nu_2 + \rightarrow\nu_3$$

Create in one flavor, but detect in another flavor

$$\nu_e = \nu_1 + \nu_2 + \nu_3$$

$$\nu_1 + \nu_2 + \nu_3$$

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Create in one flavor, but detect in another flavor

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$$\searrow\nu_1 + \swarrow\nu_2 + \searrow\nu_3$$

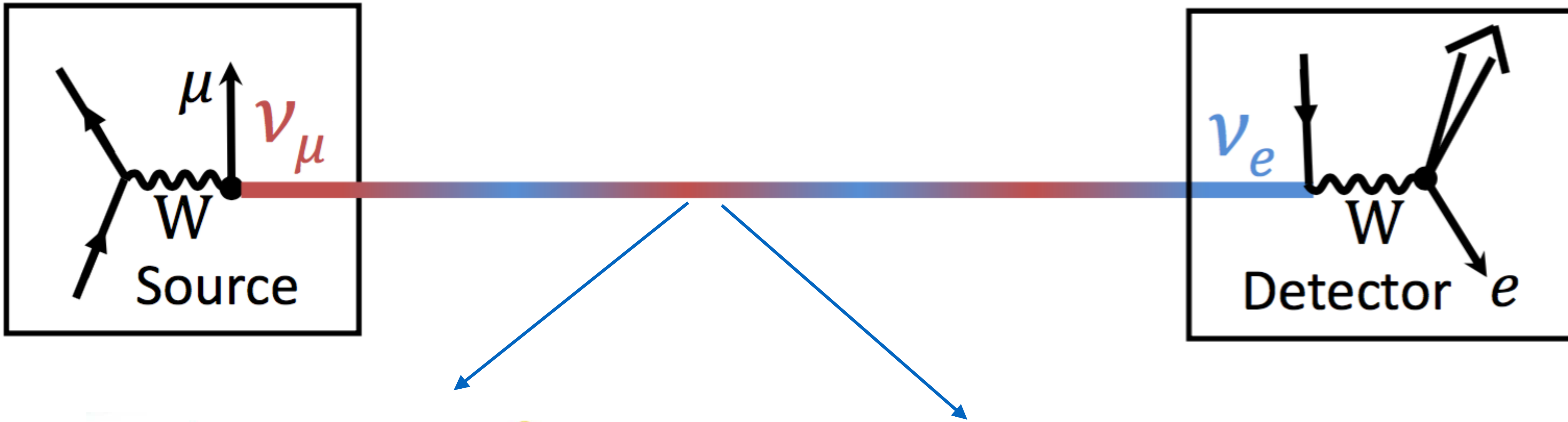
$$\nu_\mu = \nwarrow\nu_1 + \nearrow\nu_2 + \rightarrow\nu_3$$

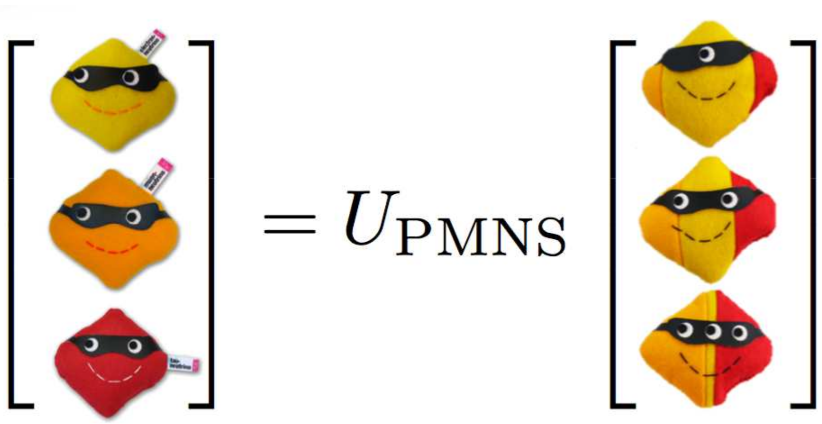
Create in one flavor, but detect in another flavor

$$\nu_e = \rightarrow \nu_1 + \rightarrow \nu_2 + \uparrow \nu_3$$

$$\nu_\mu = \nwarrow \nu_1 + \nearrow \nu_2 + \rightarrow \nu_3$$

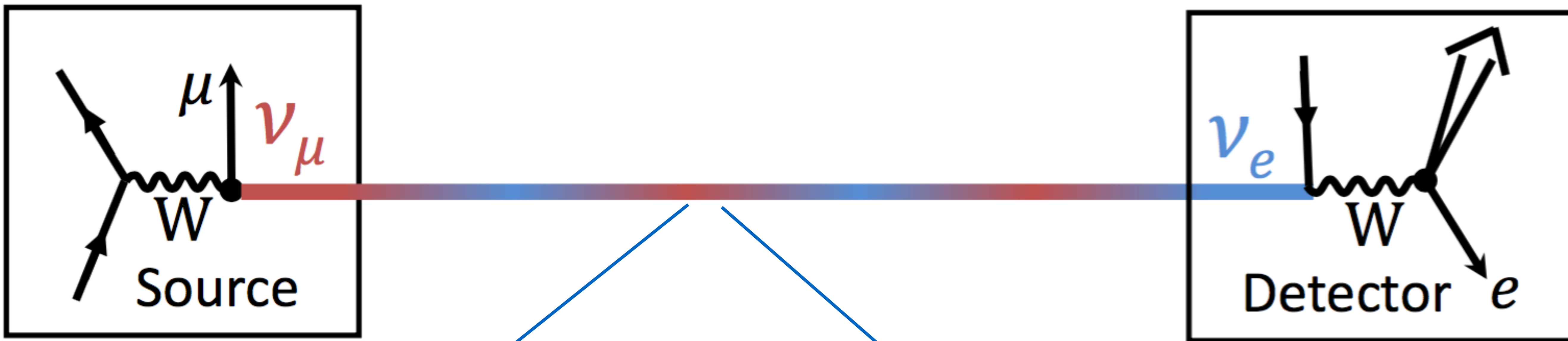
Create in one flavor, but detect in another flavor

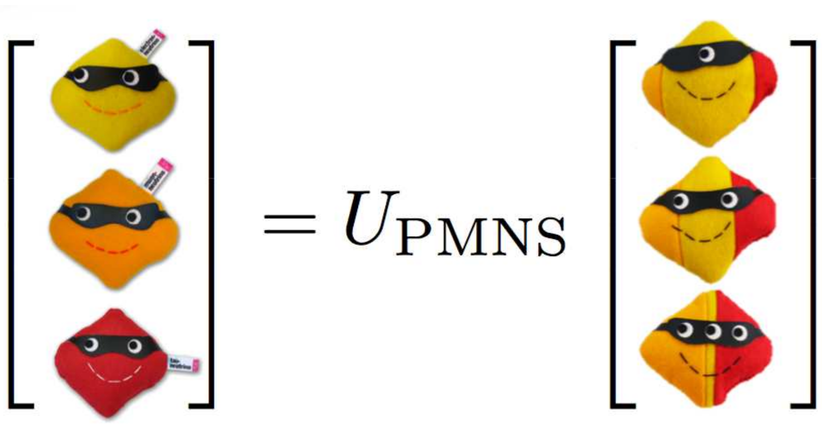




$\phi(p,E,r,t)$

Create in one flavor, but detect in another flavor





φ(p,E,r,t)

$$P_{\alpha\to\beta} = \left|\langle \nu_\beta(t)|\nu_\alpha\rangle\right|^2$$

α, β: e, μ, τ

If we have only 2 neutrinos…

Each flavor is a superposition of different masses:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

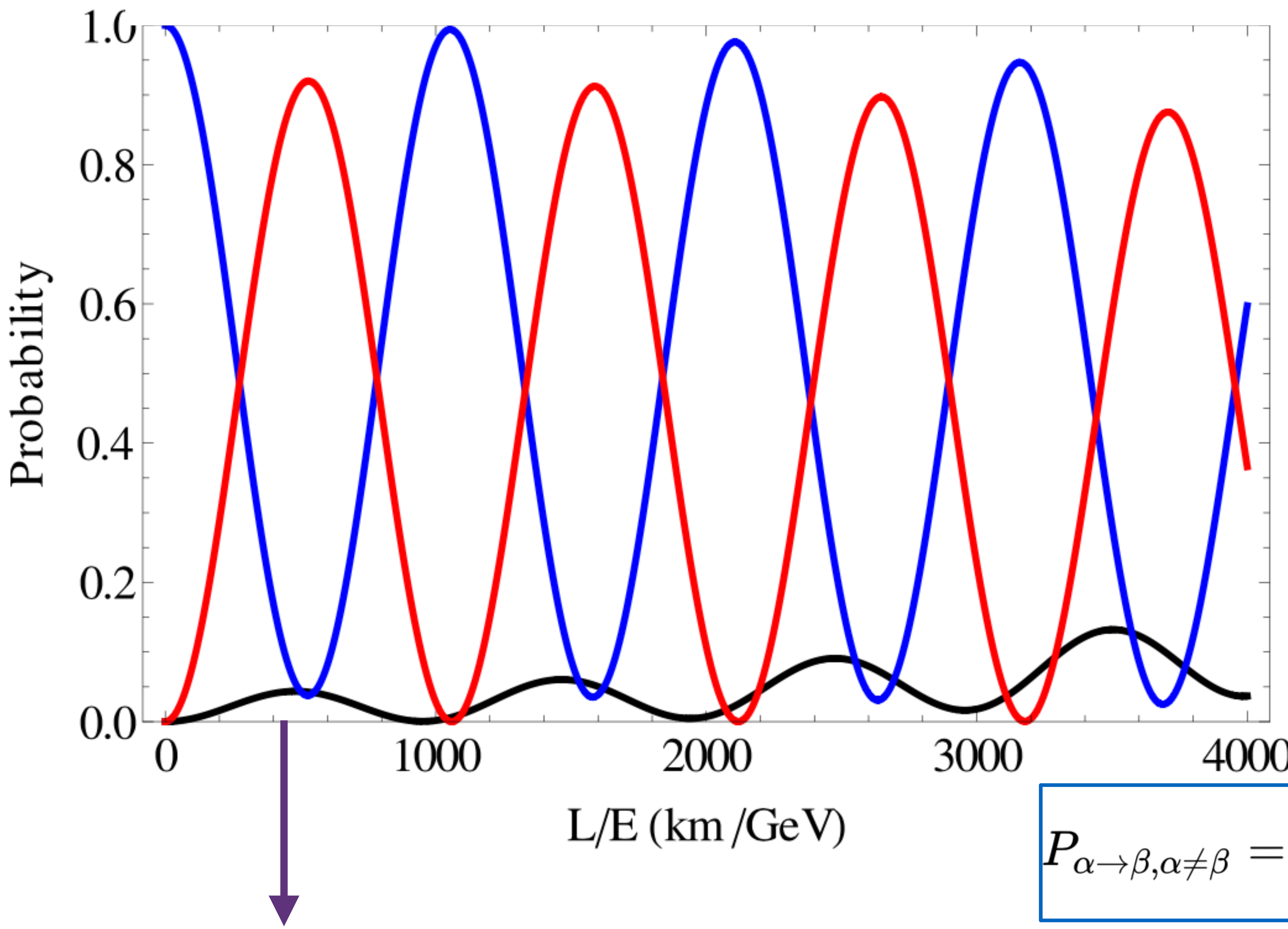
"Mixing Matrix"

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

α, β: e, μ, τ

$\Delta m^2 = m_i^2 - m_j^2$

Oscillation probability for an initial ν_μ



Blue: ν_μ

Black: ν_τ

Red : ν_e

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

For NOvA, L = 810 km and E ~ 2GeV, **L/E ~ 405 km/GeV**

https://en.wikipedia.org/wiki/Neutrino_oscillation

Neutrino Puzzle

There are 3 mayor symmetries that are expected to hold :

CHARGE	TIME	PARITY
$q \longrightarrow \bar{q}$	$t \longrightarrow -t$	$(x,y,z) \longrightarrow (-x,-y,-z)$

Wu experiment

- (1956) Use Co-60: radioactive, decay under **beta decay**, under nearly absolute zero

$$^{60}_{27}\mathrm{Co} \longrightarrow {}^{60}_{28}\mathrm{Ni} + e^{-} + \bar{\nu}_e$$

Wu experiment

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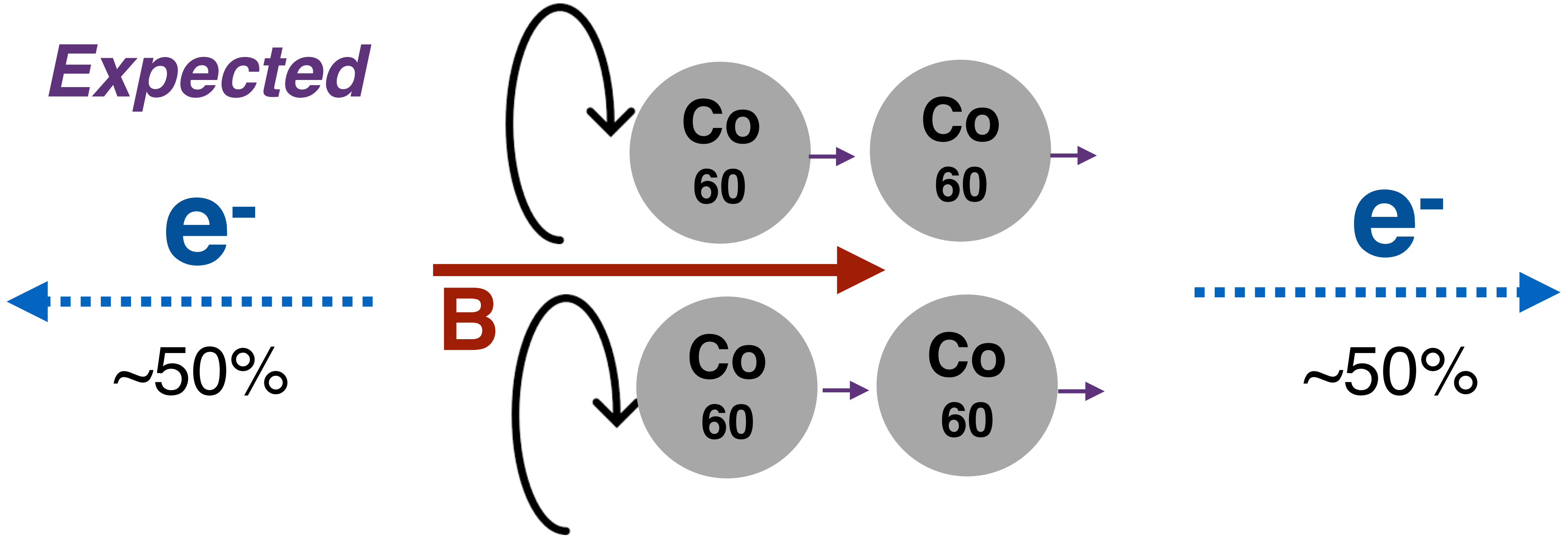
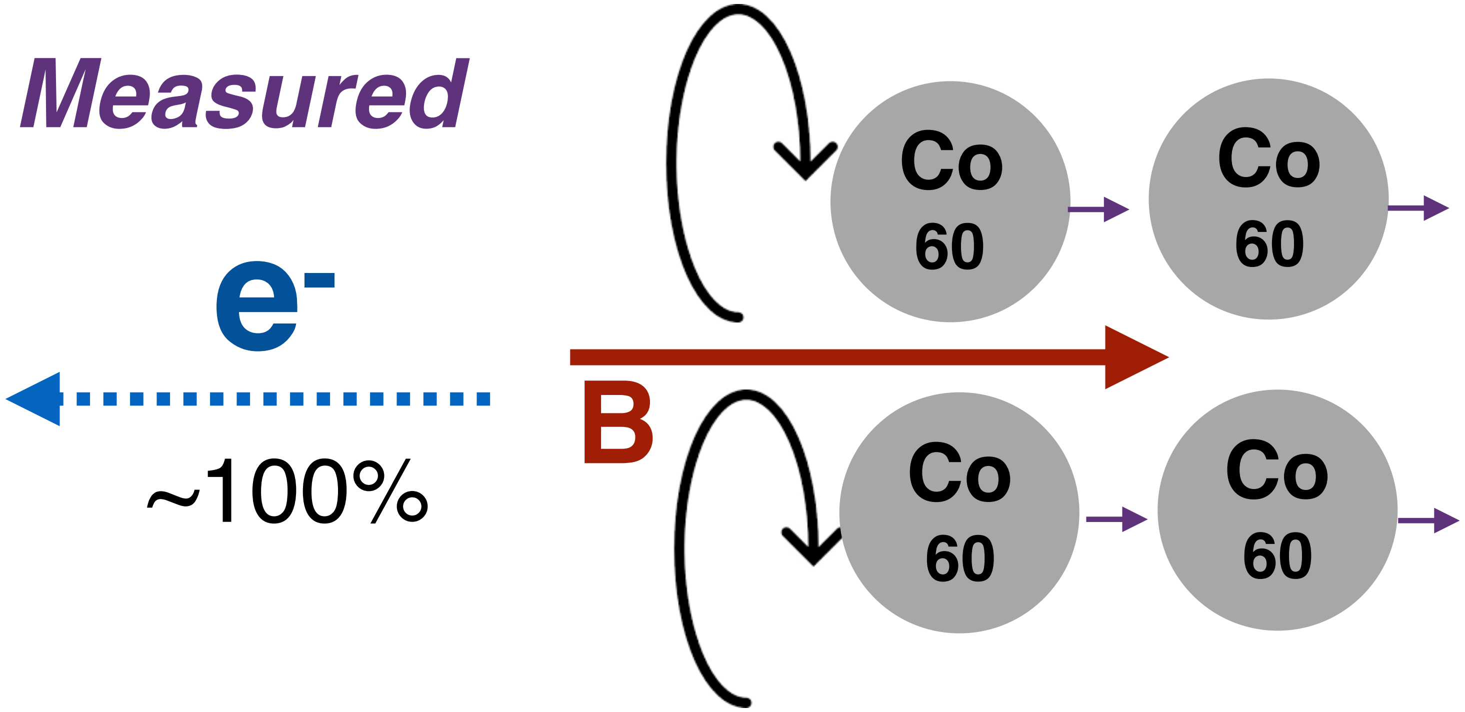


Wu experiment

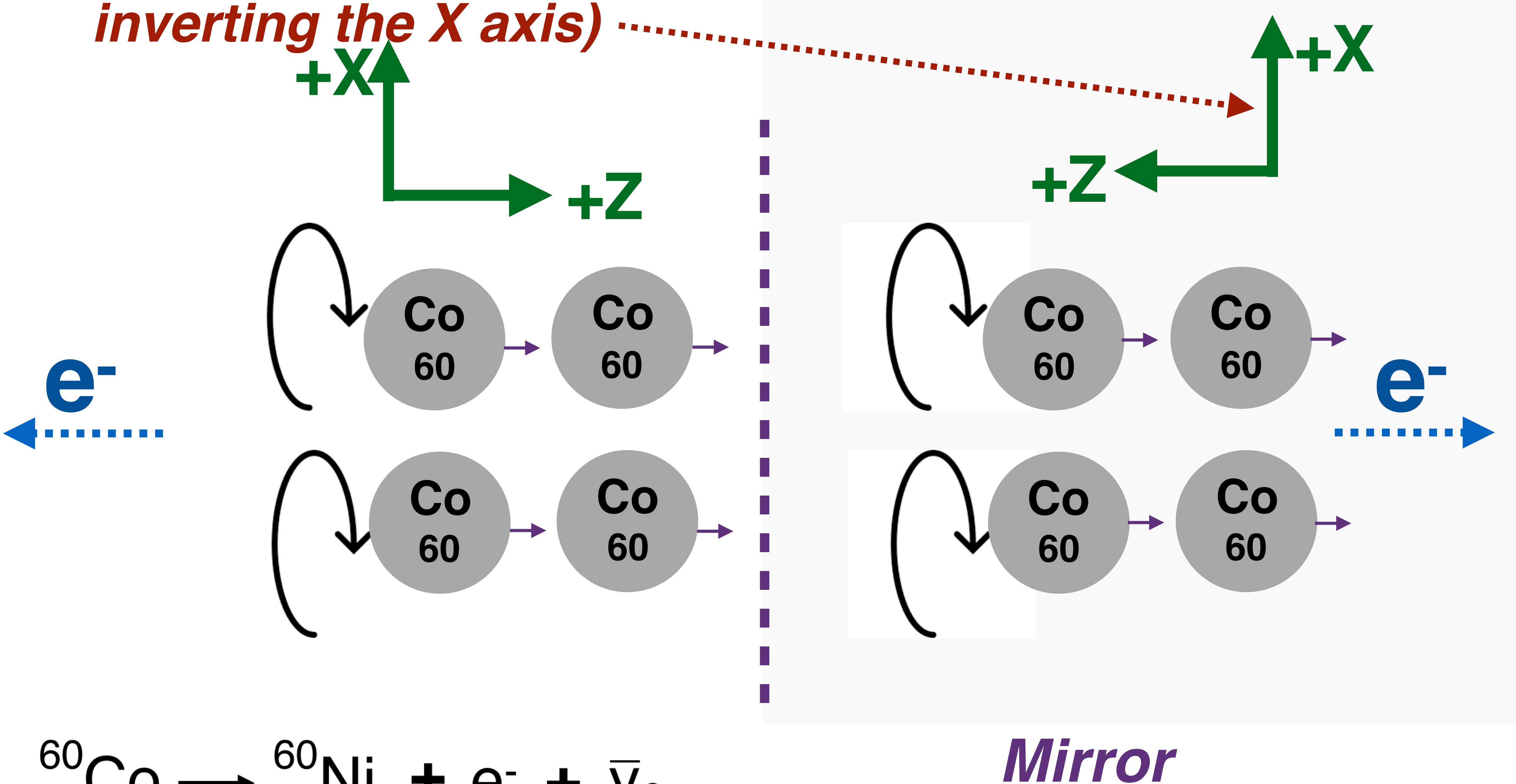
- (1956) Use Co-60: radioactive, decay under beta decay, under nearly absolute zero

$$^{60}_{27}\mathrm{Co} \longrightarrow {}^{60}_{28}\mathrm{Ni} + e^{-} + \bar{\nu}_e$$



Consequence: Parity violation

Do not read too much in this analogy… we are not inverting the X axis)



$$^{60}_{27}Co \longrightarrow \, ^{60}_{28}Ni + e^- + \bar{\nu}_e$$

https://www.youtube.com/watch?time_continue=503&v=yArprk0q9eE

Consequence: Parity violation

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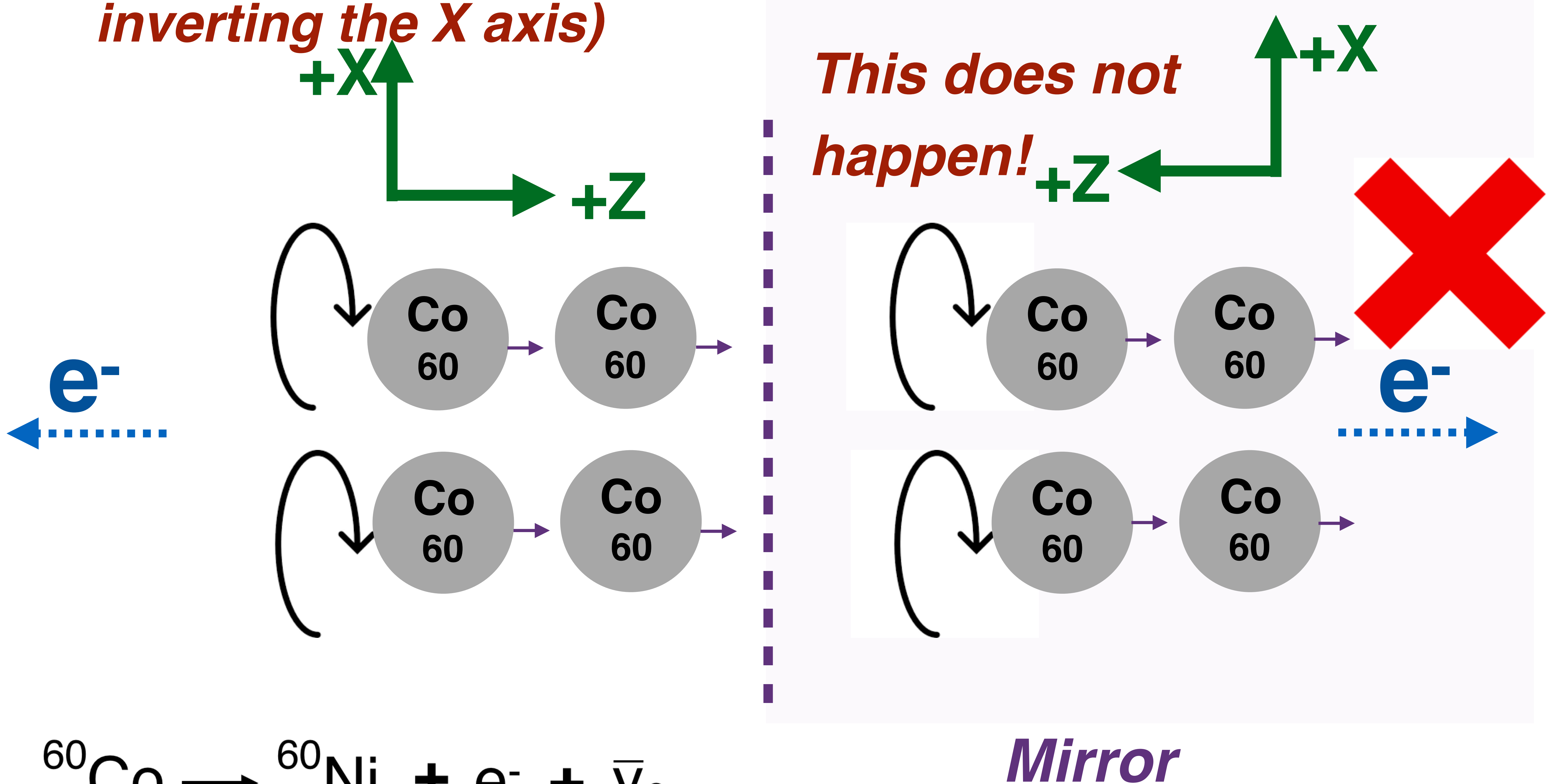

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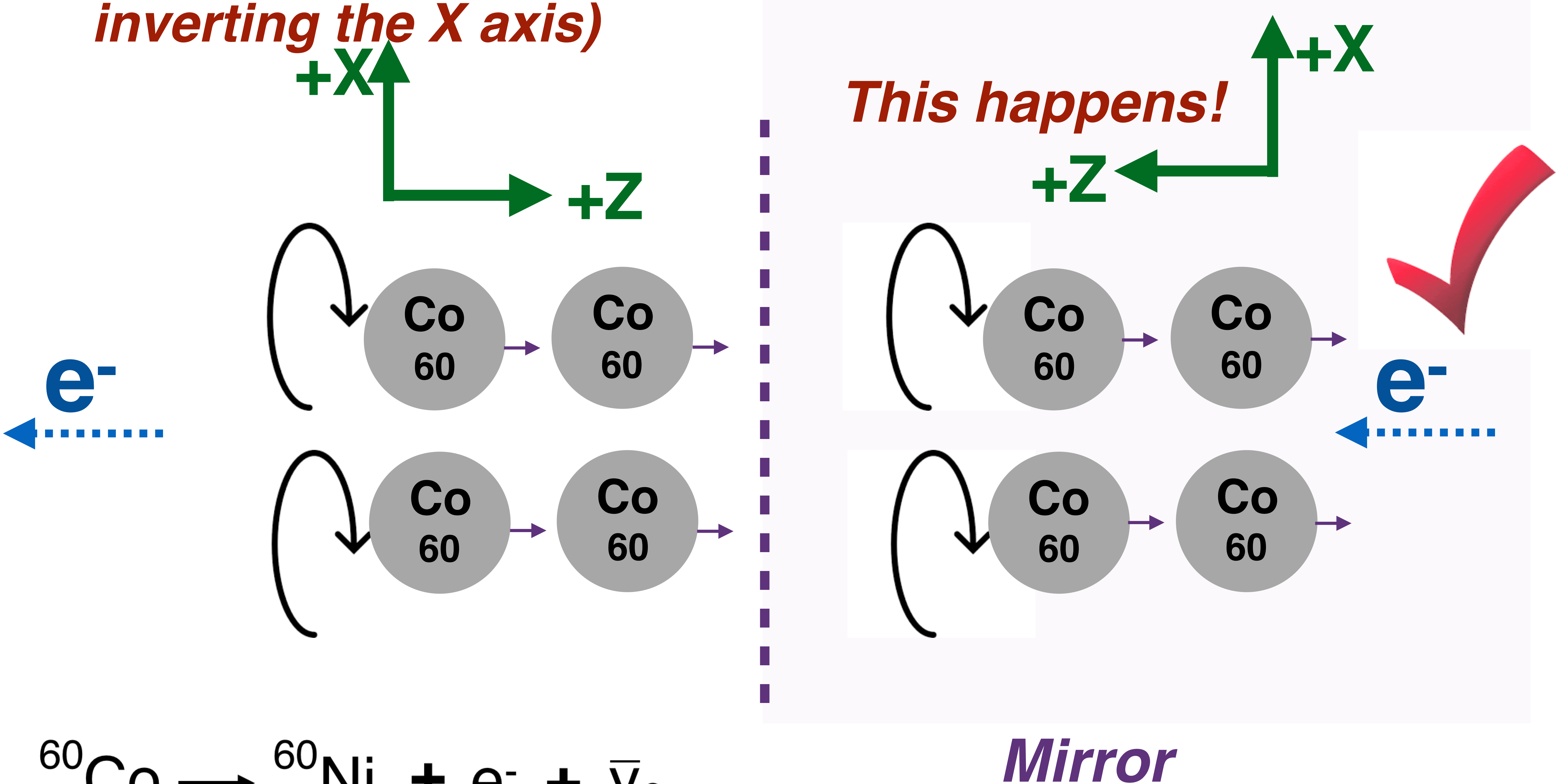
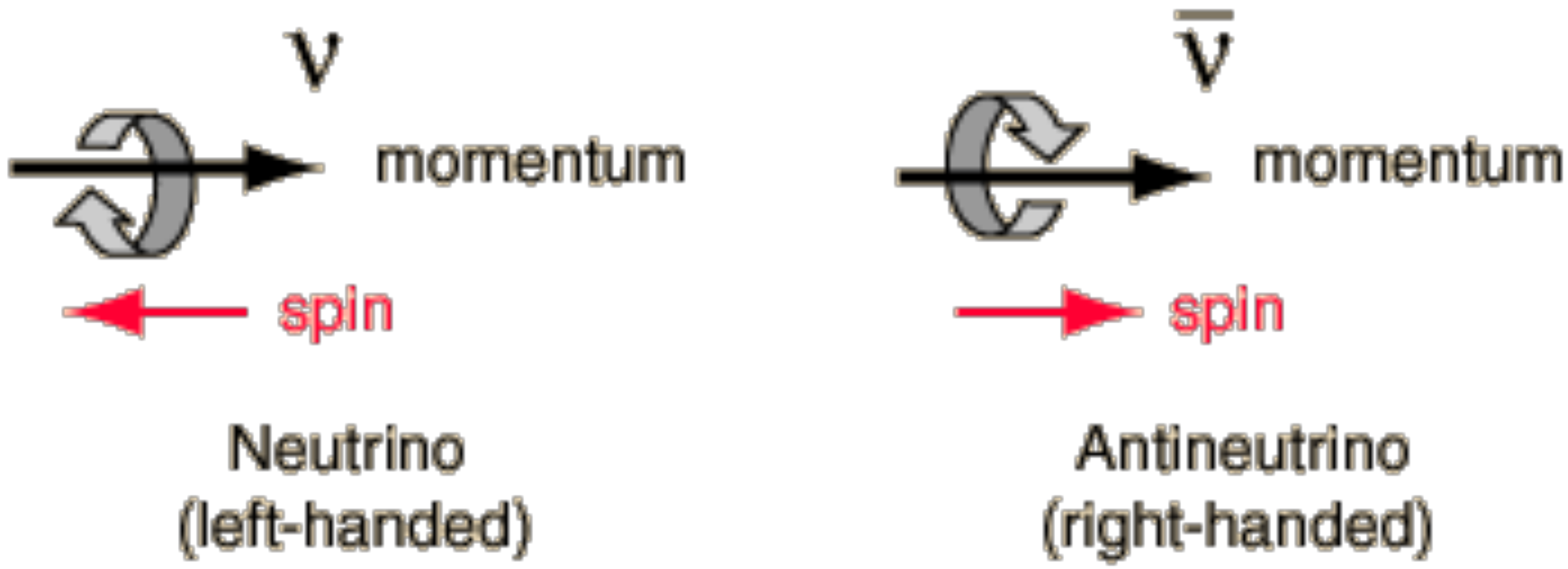


$$^{60}_{27}Co \longrightarrow\ ^{60}_{28}Ni + e^- + \bar{\nu}_e$$

Parity is maximally violated in weak interactions.

Soon was determined that neutrinos are left handed



ν_L $\qquad$ ν_R

$$q \longrightarrow \bar{q}$$

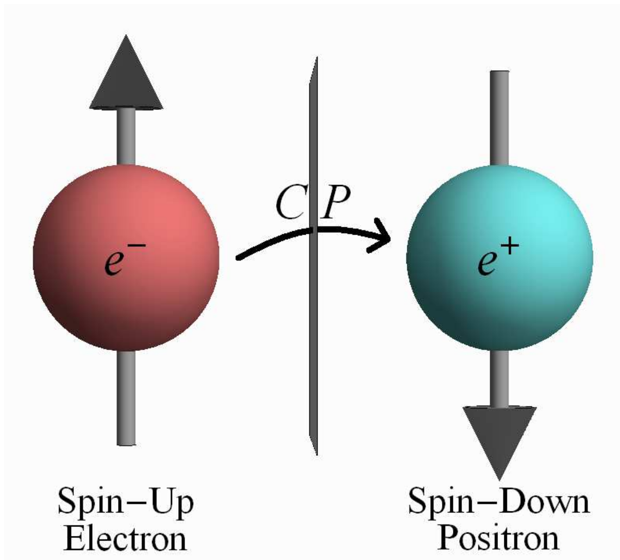
Is charge conserved in neutrinos?

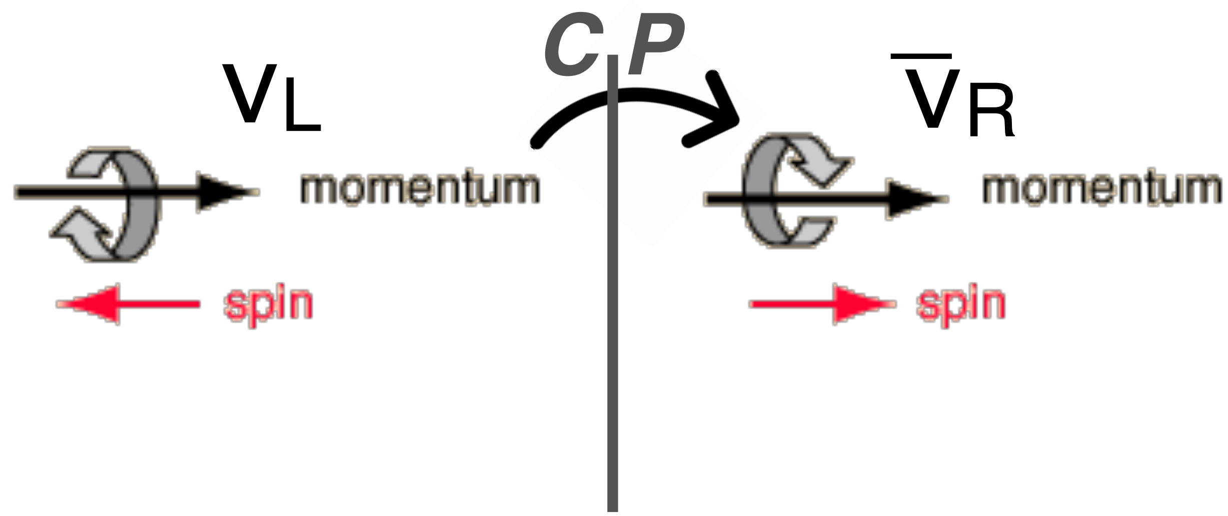
$$\nu_L \longrightarrow \bar{\nu}_L$$

Has never been seen!

Charge - parity symmetry?

- Perhaps neither P nor C are fundamental symmetries of the universe only part of a **larger symmetry: CP**





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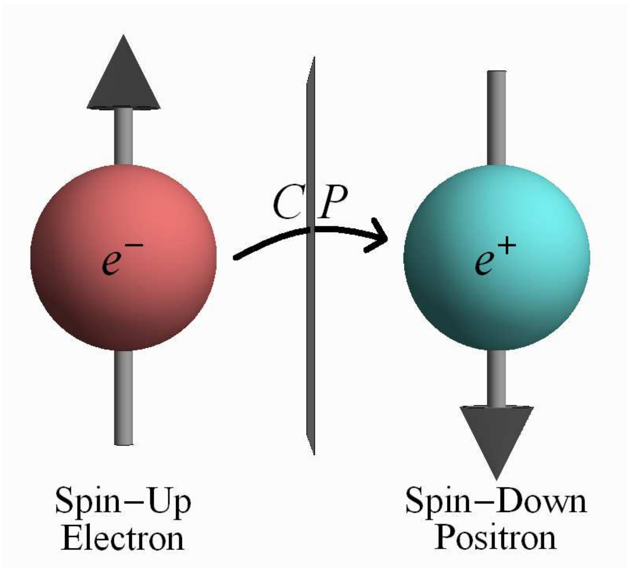

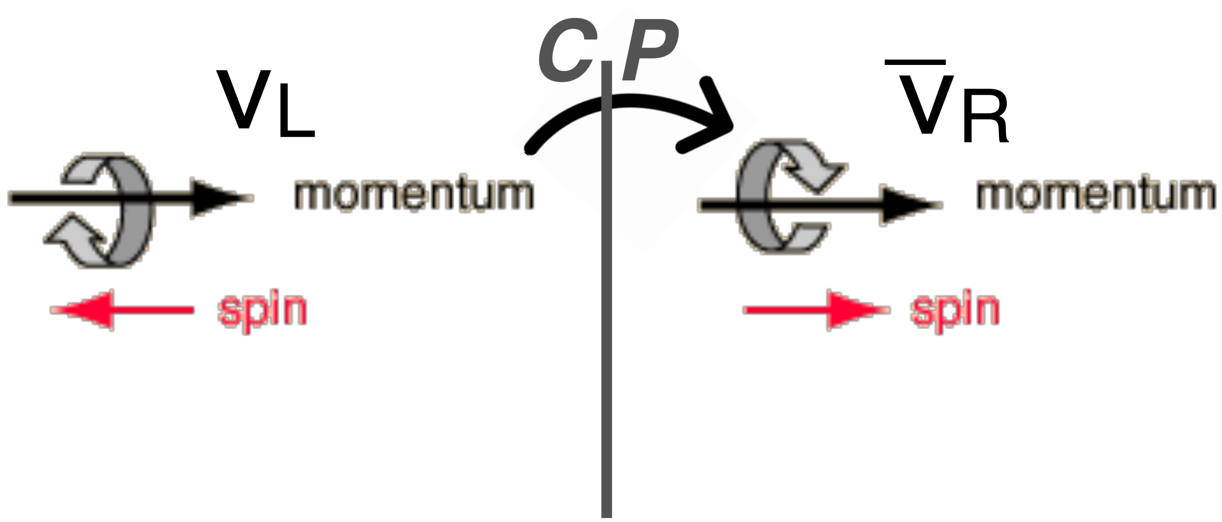

Nope!!

CP is violated too (there are clearly evidence since 1964: (neutral kaon transformation)…

Charge - parity symmetry?

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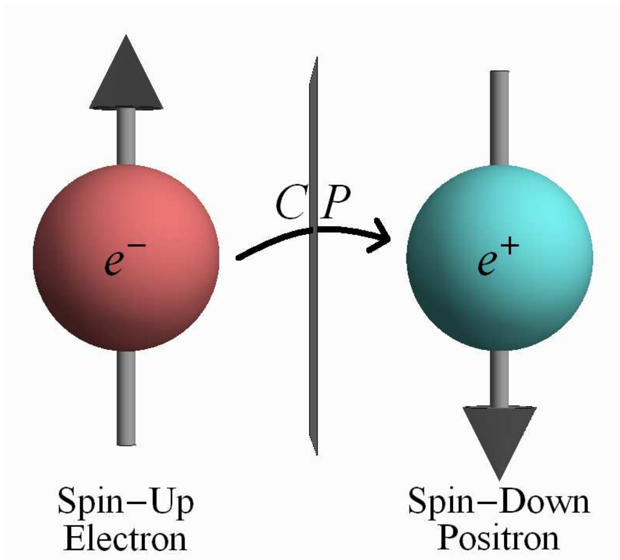
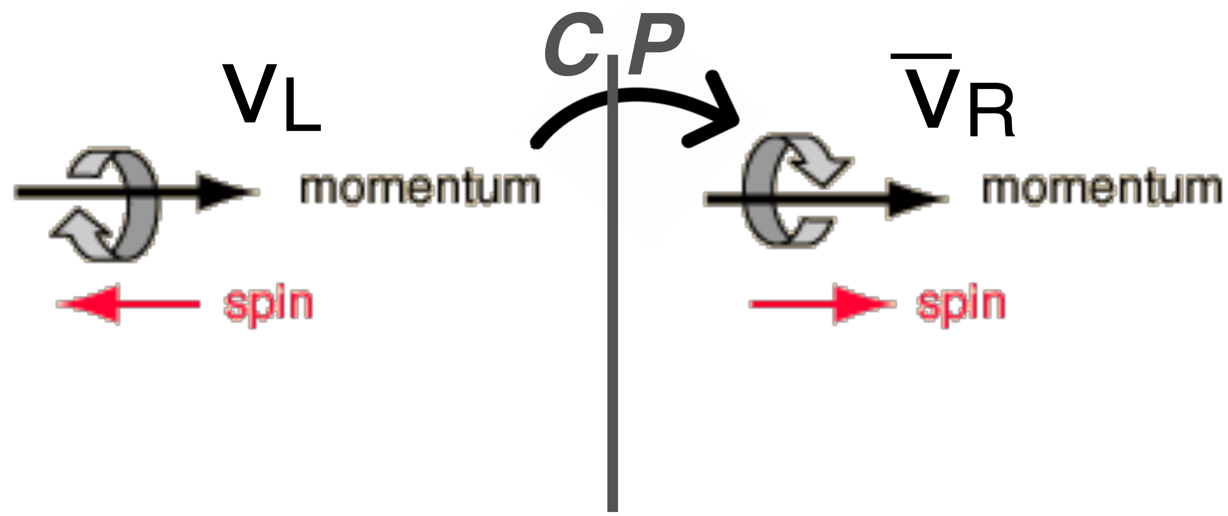


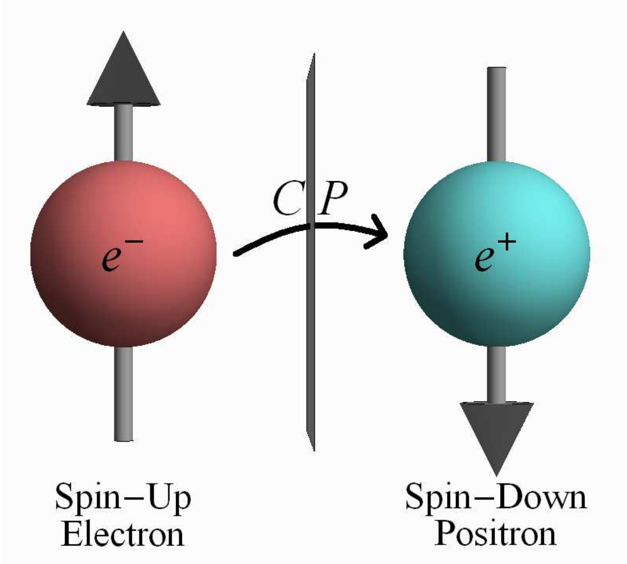


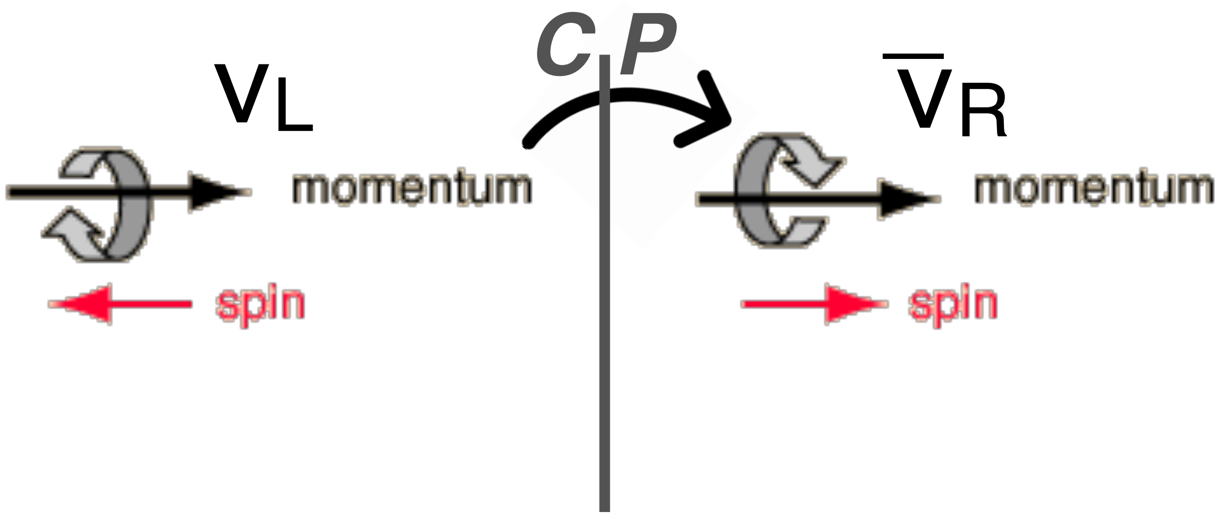
CP is violated too (there are clearly evidence since 1964: (neutral kaon transformation)…

Matter and antimatter behaves differently due to the weak interaction… could this solved the matter - antimatter asymmetry in the universe?

Charge - parity symmetry?

- Perhaps neither P nor C are fundamental symmetries of the universe only part of a **larger symmetry: CP**





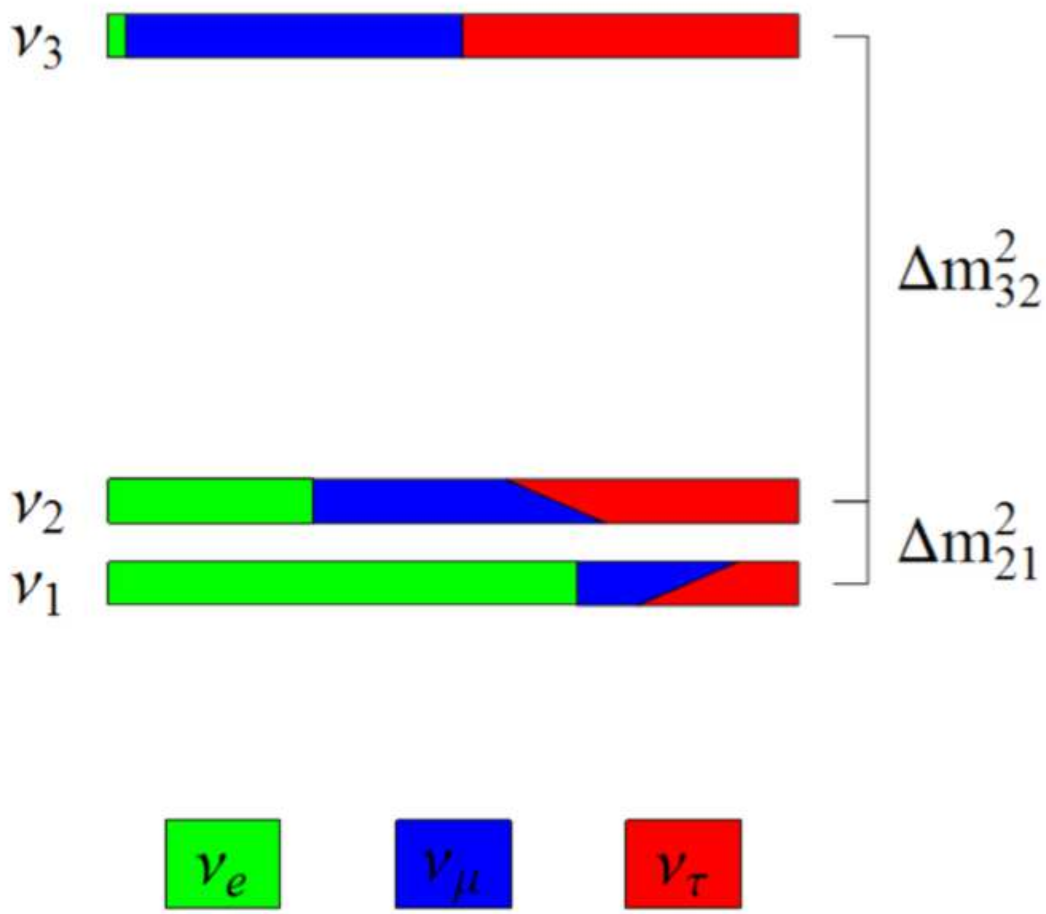
CP is violated too (there are clearly evidence since 1964: (neutral kaon transformation)…

Can neutrinos provide an access to check CP violation?

Current knowledge of the oscillation parameters

Measured from Sun, atmosphere, reactor and accelerators"

Normal hierarchy



$\sim 0(10^{-3} eV^2)$

$\sim 0(10^{-5} eV^2)$

We do not know if

NH: $m_3 > m_1, m_2$ ….

or

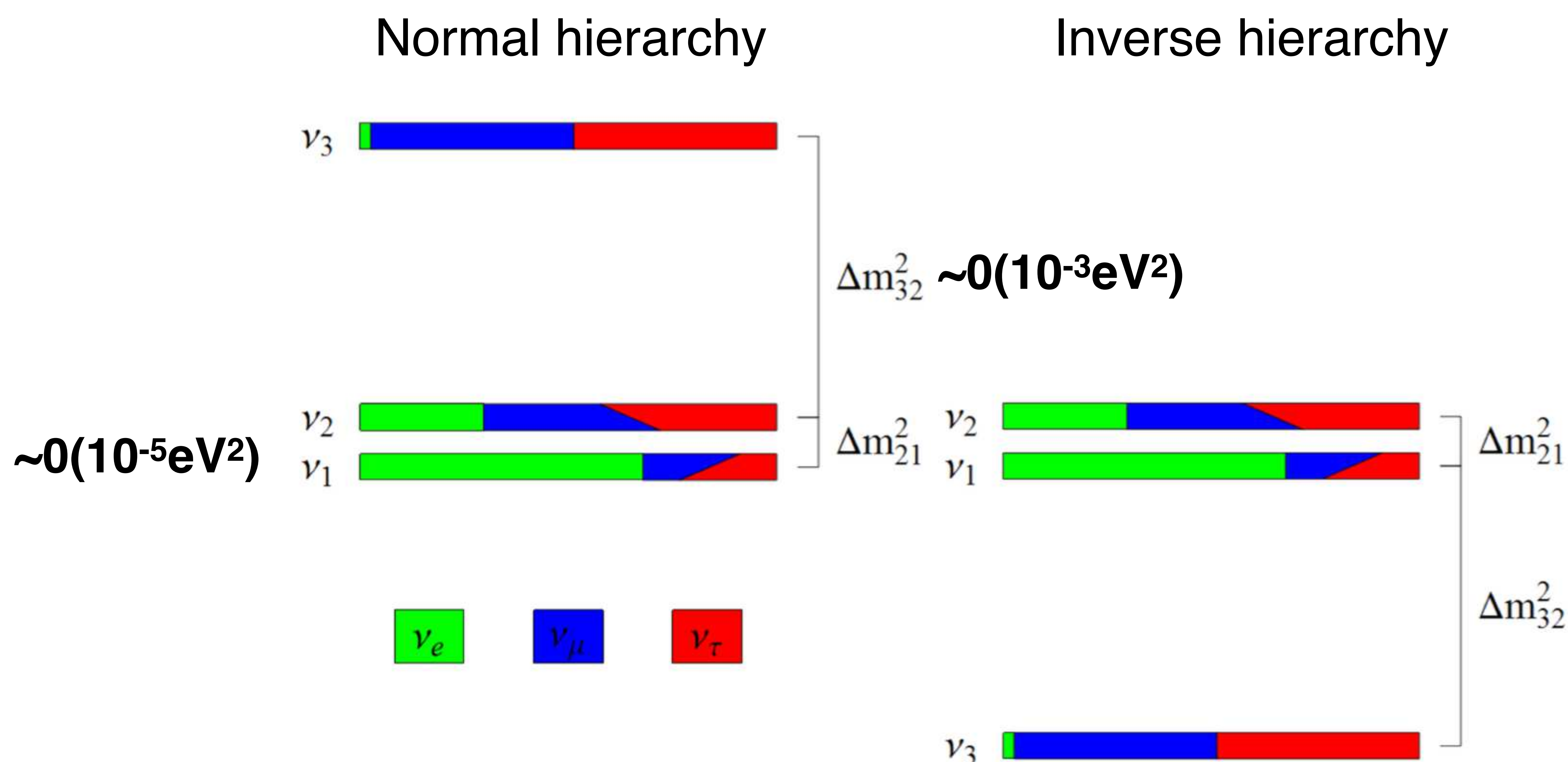
IH: $m_3 < m_1, m_2$

We know that $m_2 > m_1$, see:

https://en.wikipedia.org/wiki/Mikheyev–Smirnov–Wolfenstein_effect

Current knowledge of the oscillation parameters

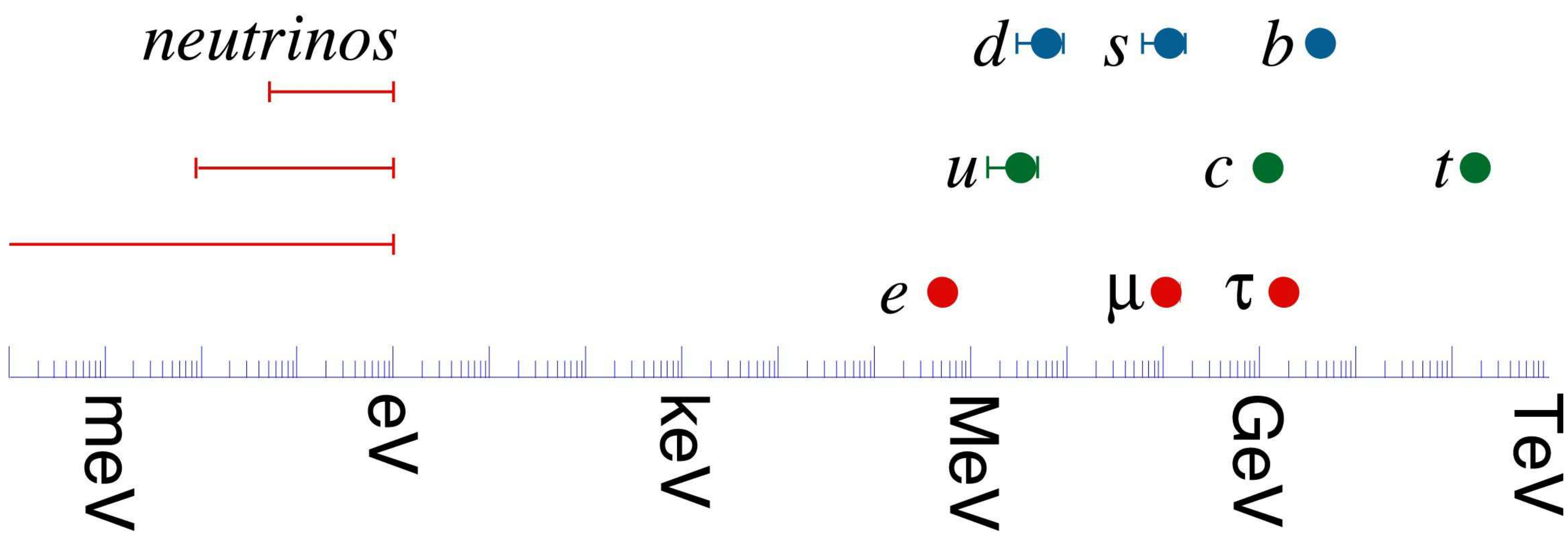
Measured from Sun, atmosphere, reactor and accelerators



We know that $m_2 > m_1$, see:

https://en.wikipedia.org/wiki/Mikheyev–Smirnov–Wolfenstein_effect

Neutrinos masses are oddly small



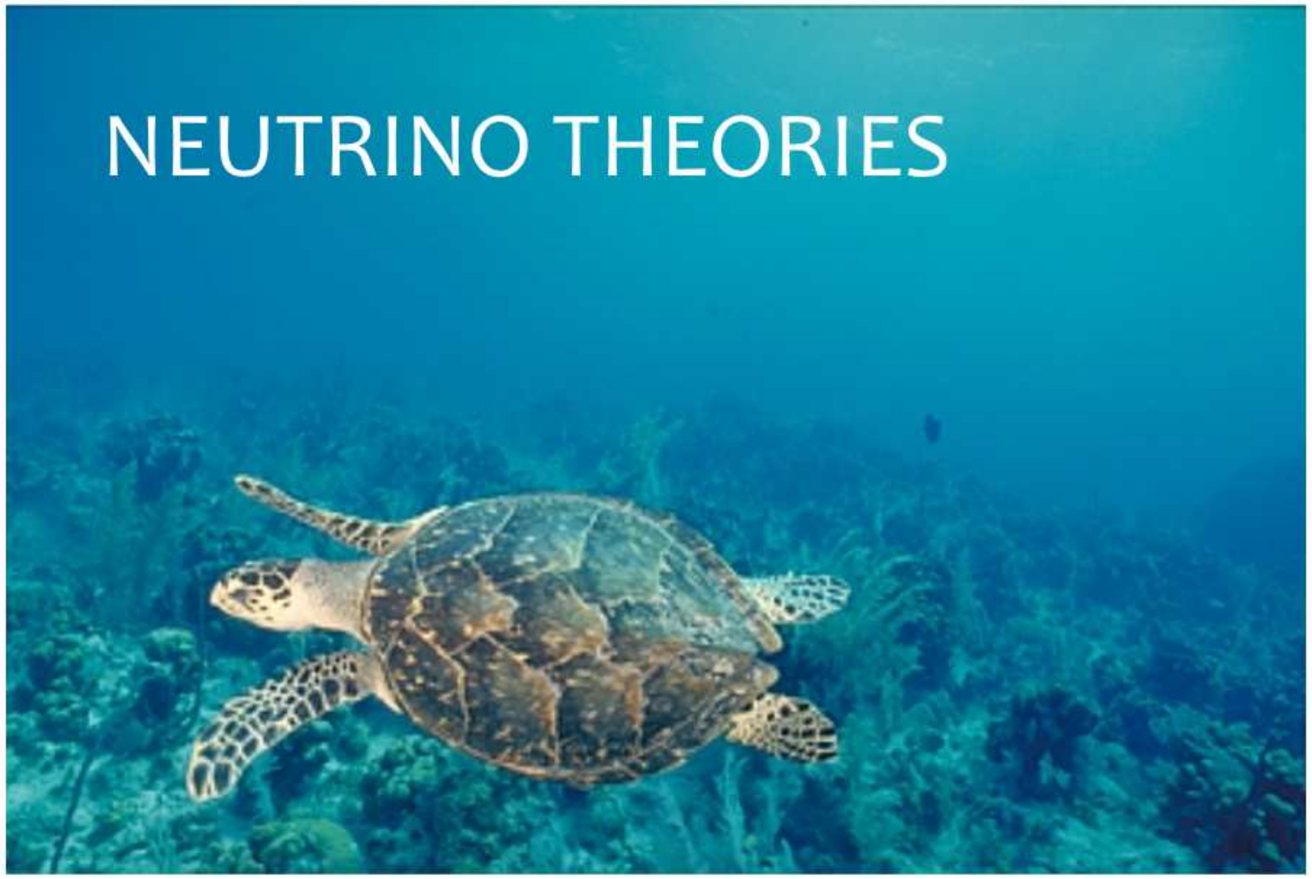
The basic Standard Model predicts that they ought to be massless

But neutrinos have mass… six orders of magnitude smaller than the other elementary particles.

Do neutrinos acquire mass in the same way as the other particles?

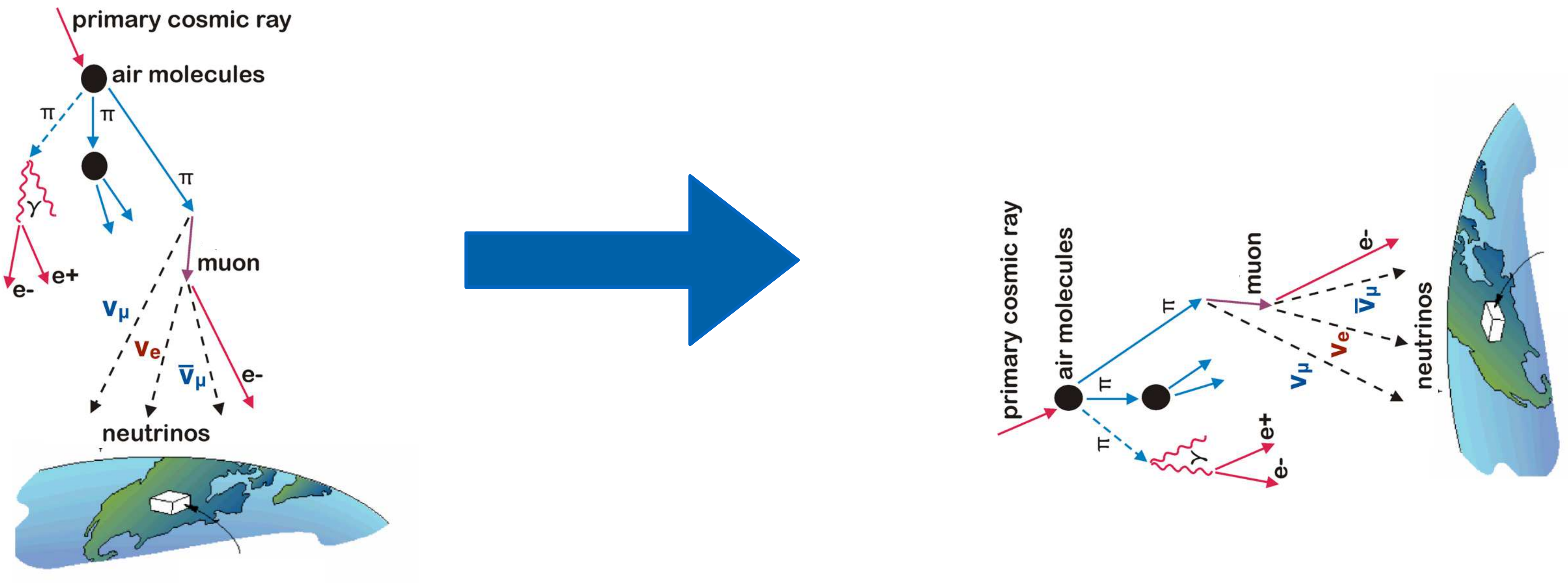
Solving neutrino mysteries: Neutrinos from accelerators


NEUTRINO EXPERIMENTS


NEUTRINO THEORIES

https://www.smbc-comics.com/comic/2010-08-29

Basic idea: we use the same principle of the atmospheric neutrinos



By 1960s….

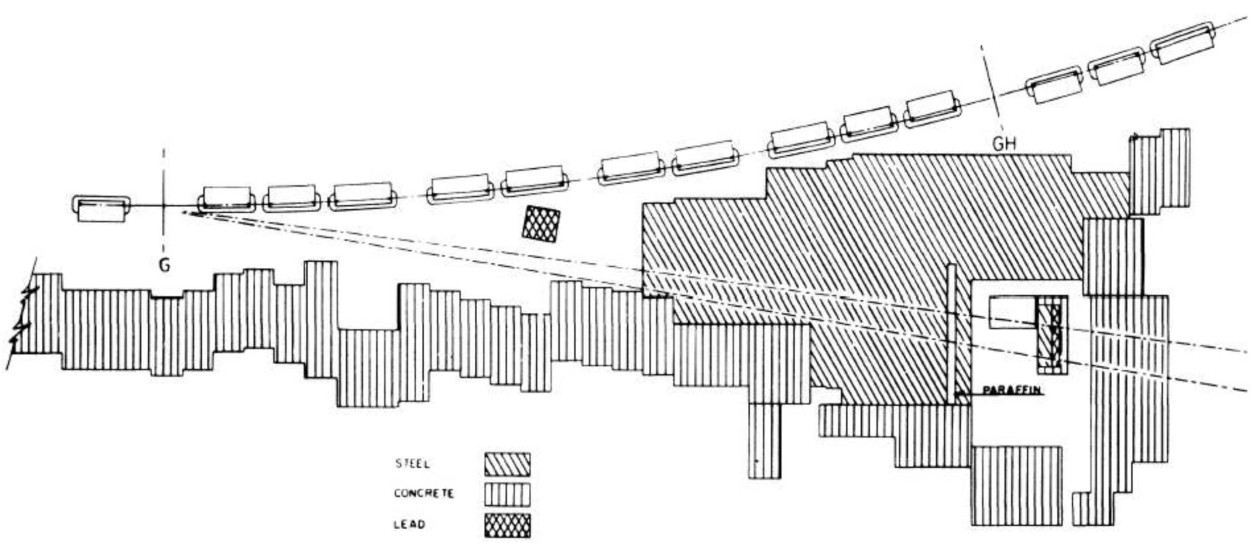
- The Standard Model was under construction… many remaining unsolved problems in the electroweak sector….

For instance, ***are ν*** *(emitted in β decays)* ***and ν*** *(emitted in π -> μ)* ***identical particles?***

Is it possible to use high energy ν's to study weak interactions?

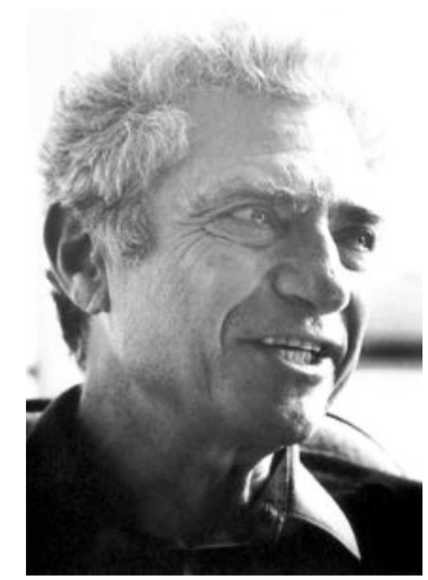
- The concept of the **neutrino beam from accelerators** was proposed independently by Pontecorvo and Schwartz to answer the question…

Yes! we get 1 ν per hour.



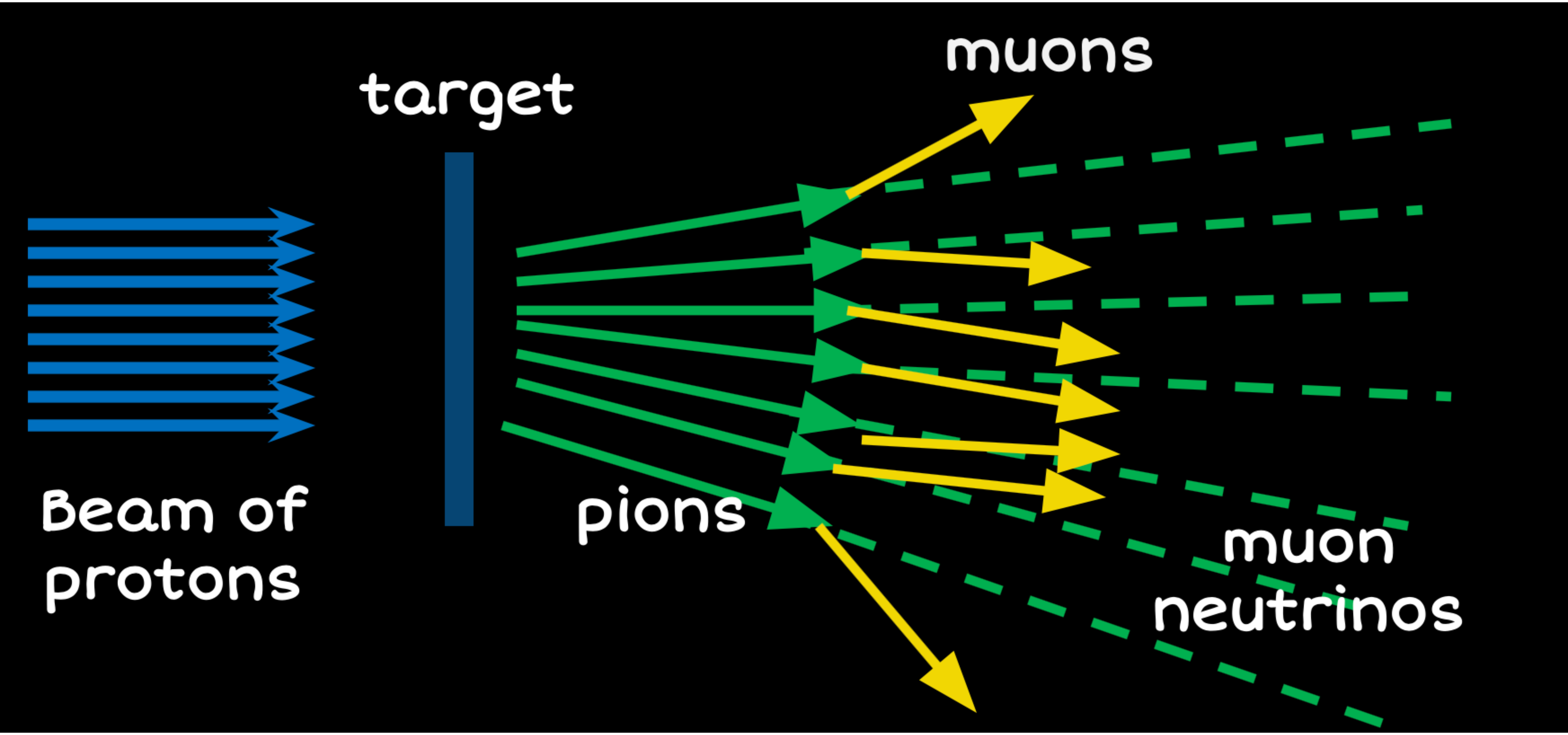
LEDERMAN

SCHWARTZ

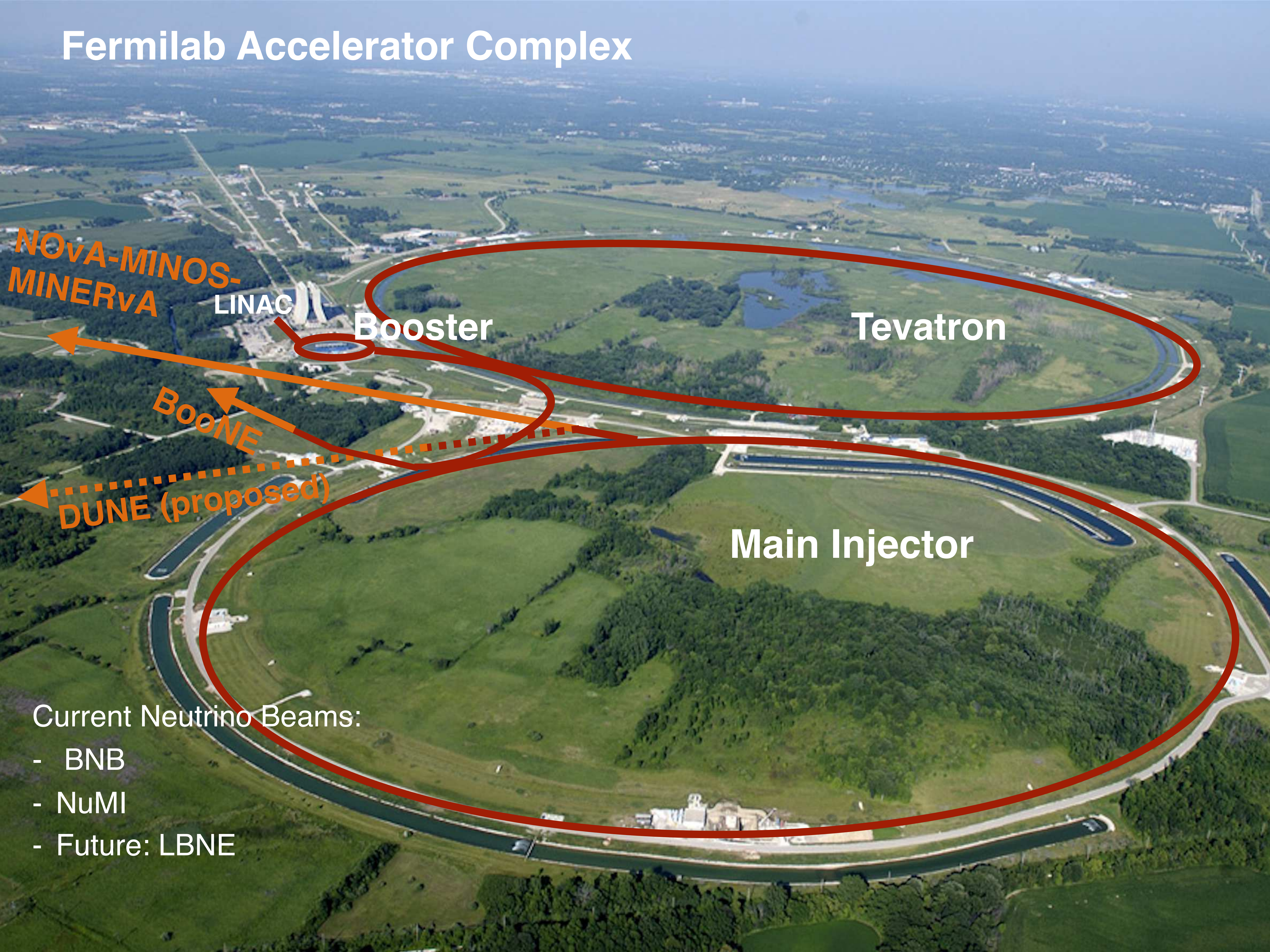


STEINBERGER

How to make a neutrino beam



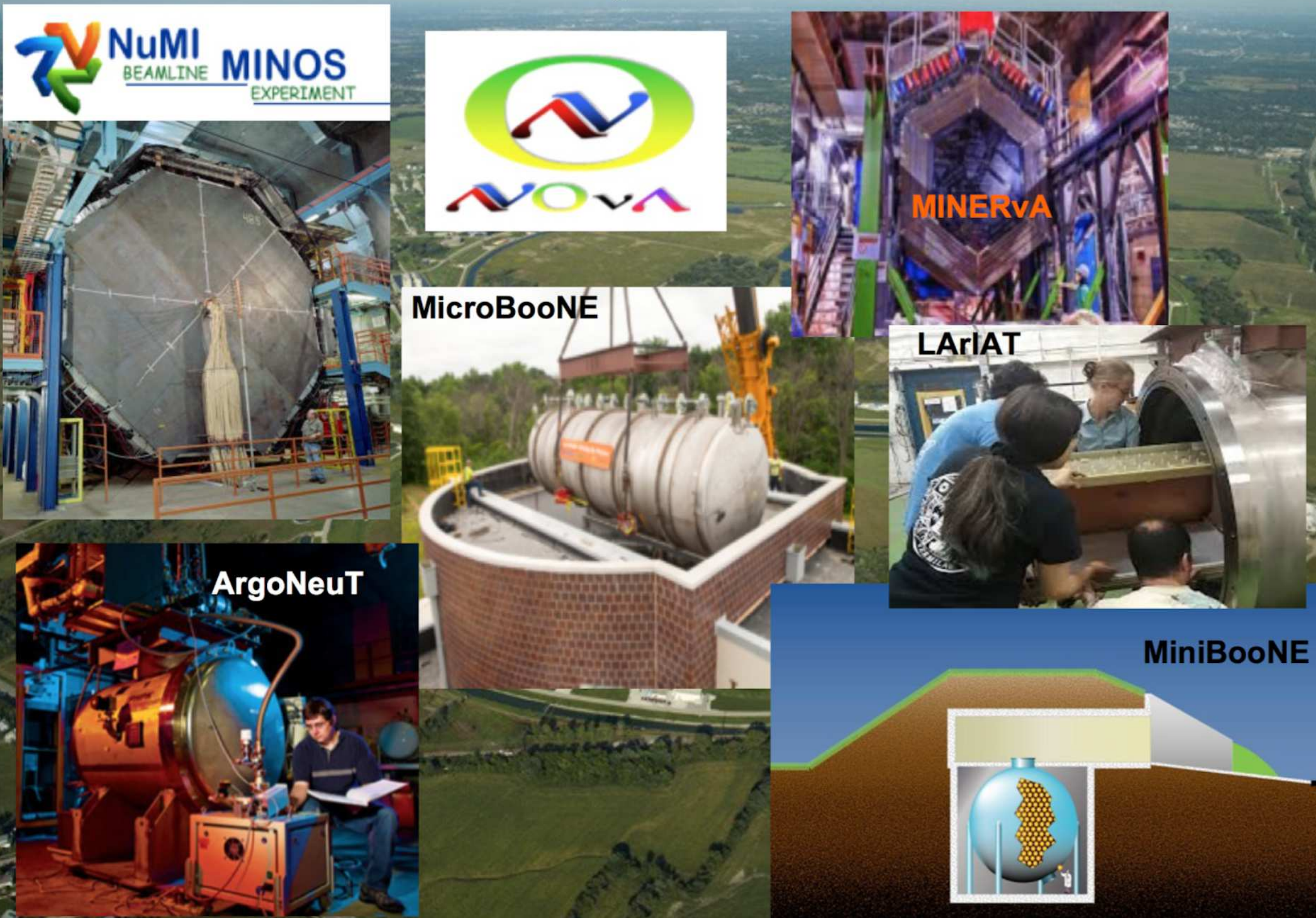
Fermilab Accelerator Complex



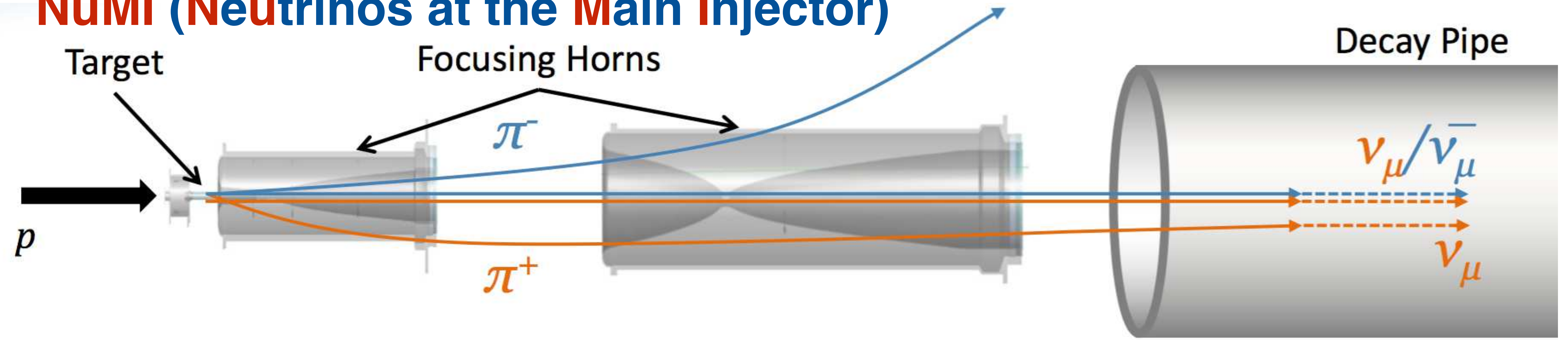
Current Neutrino Beams:

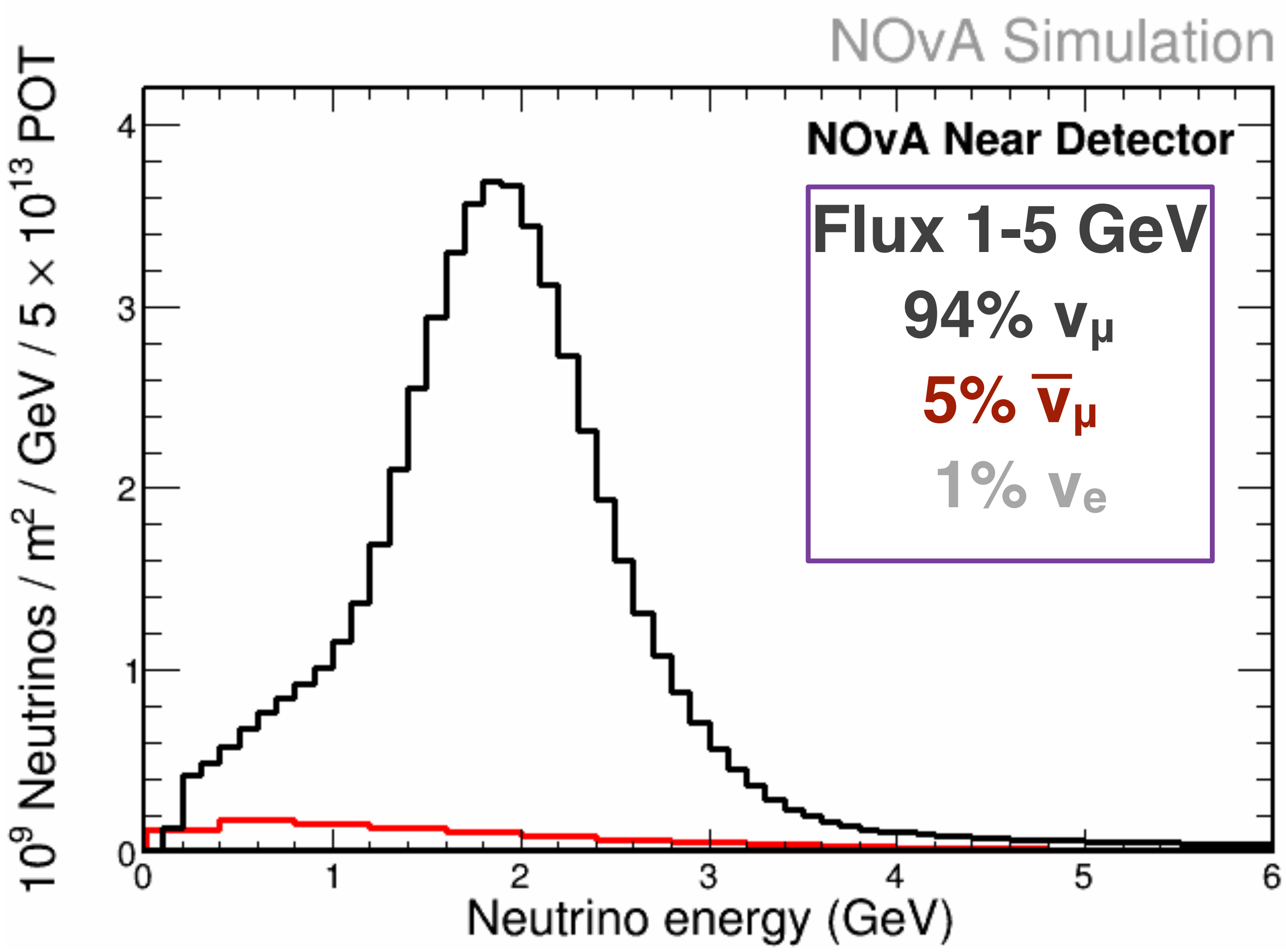
- BNB
- NuMI
- Future: LBNE

Several Neutrino experiments at Fermilab...



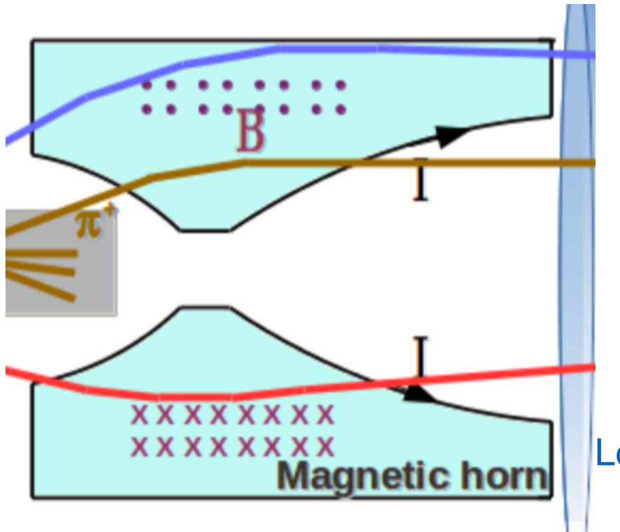
NuMI (Neutrinos at the Main Injector)





Neutrinos mostly coming from:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$



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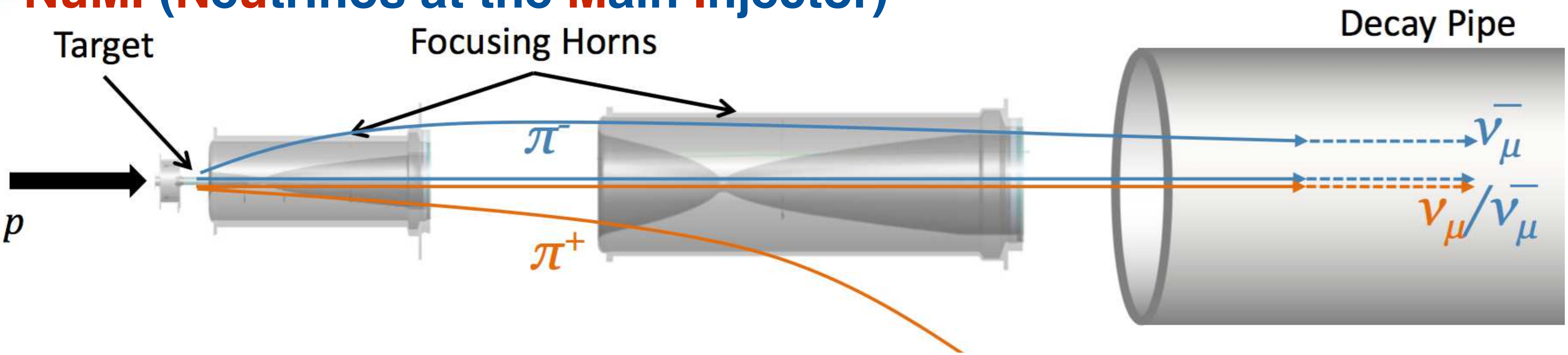
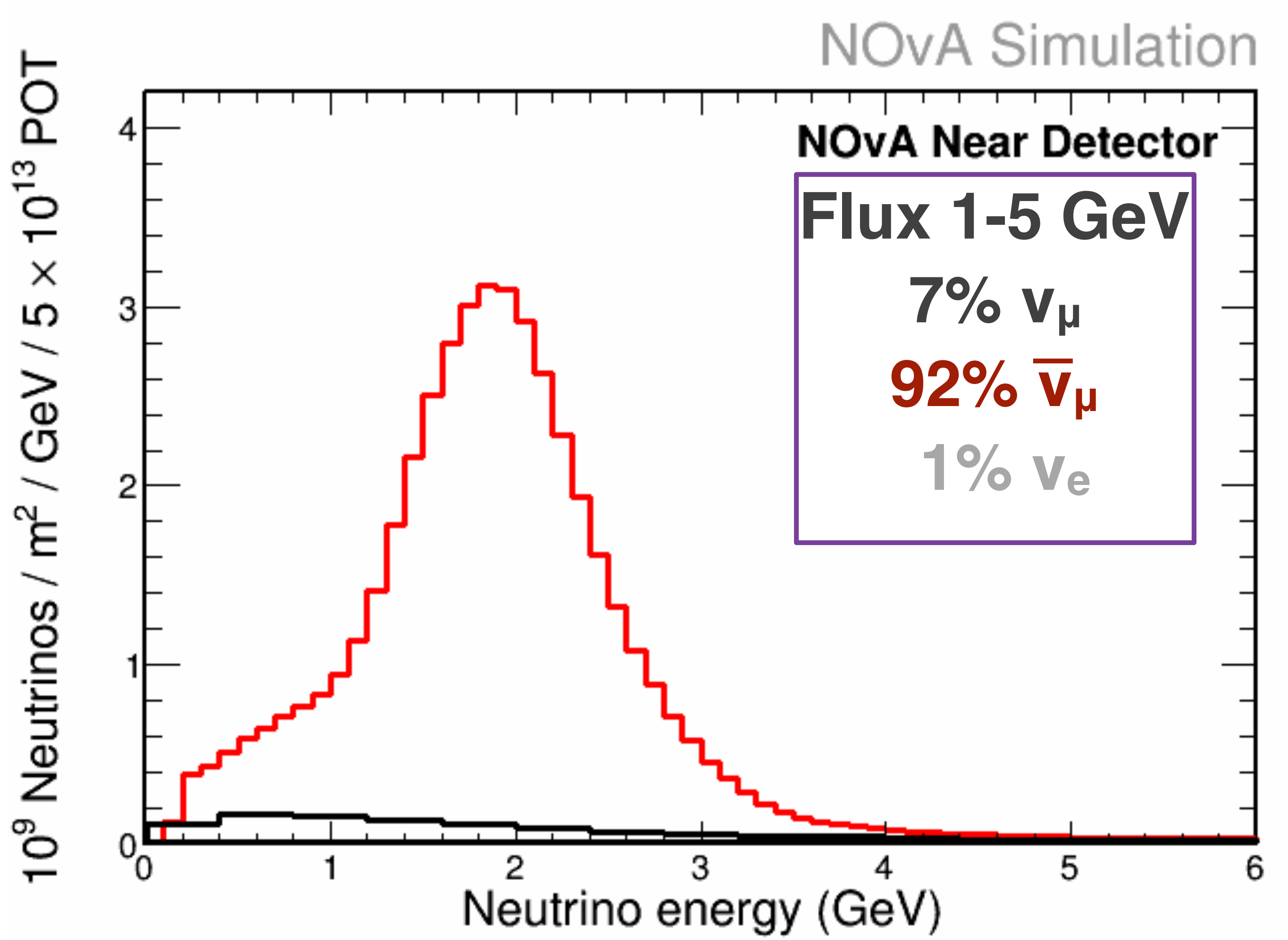


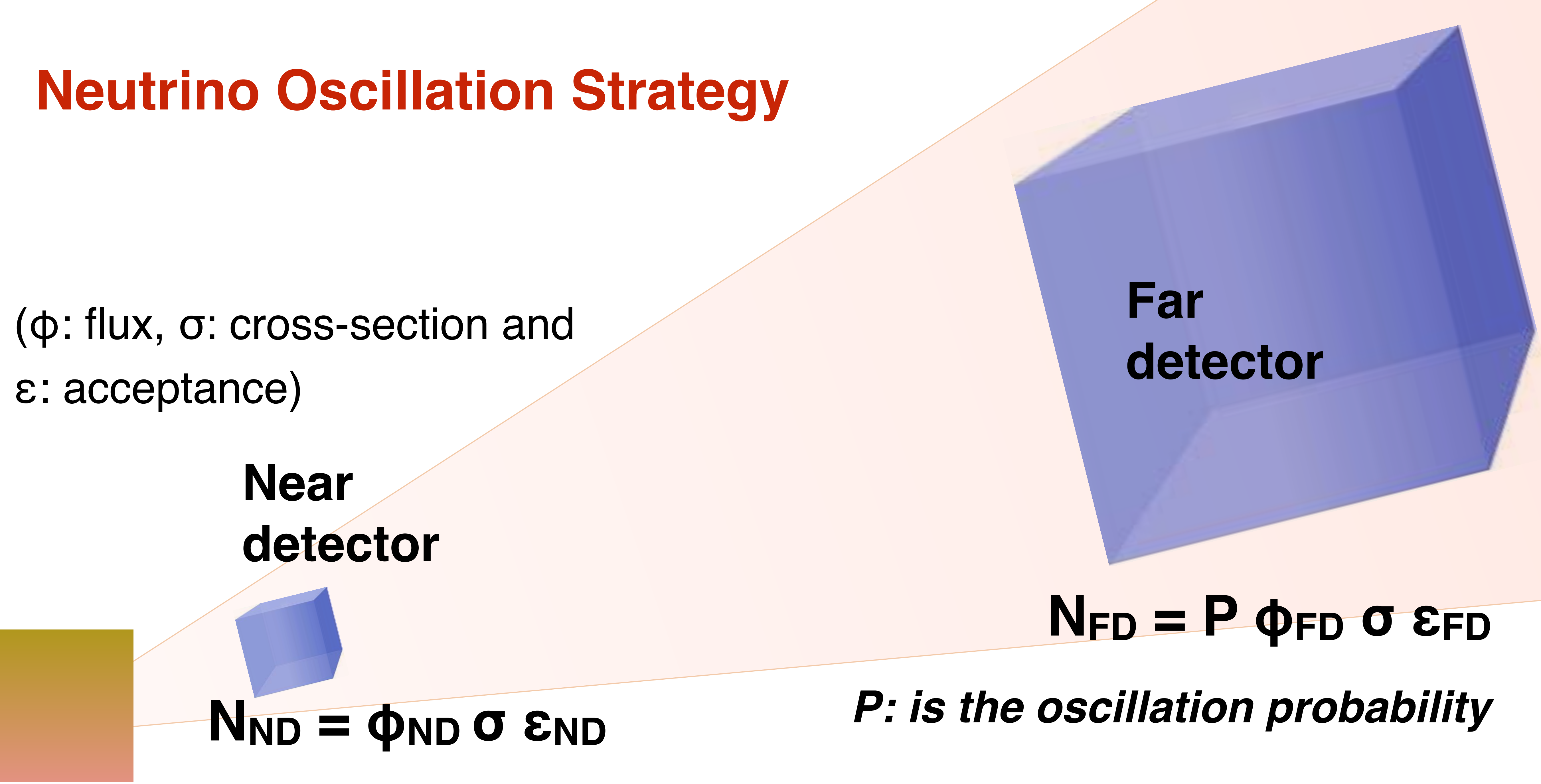
Antineutrinos mostly coming from:

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$



Neutrino Oscillation Strategy

(ϕ: flux, σ: cross-section and
ε: acceptance)



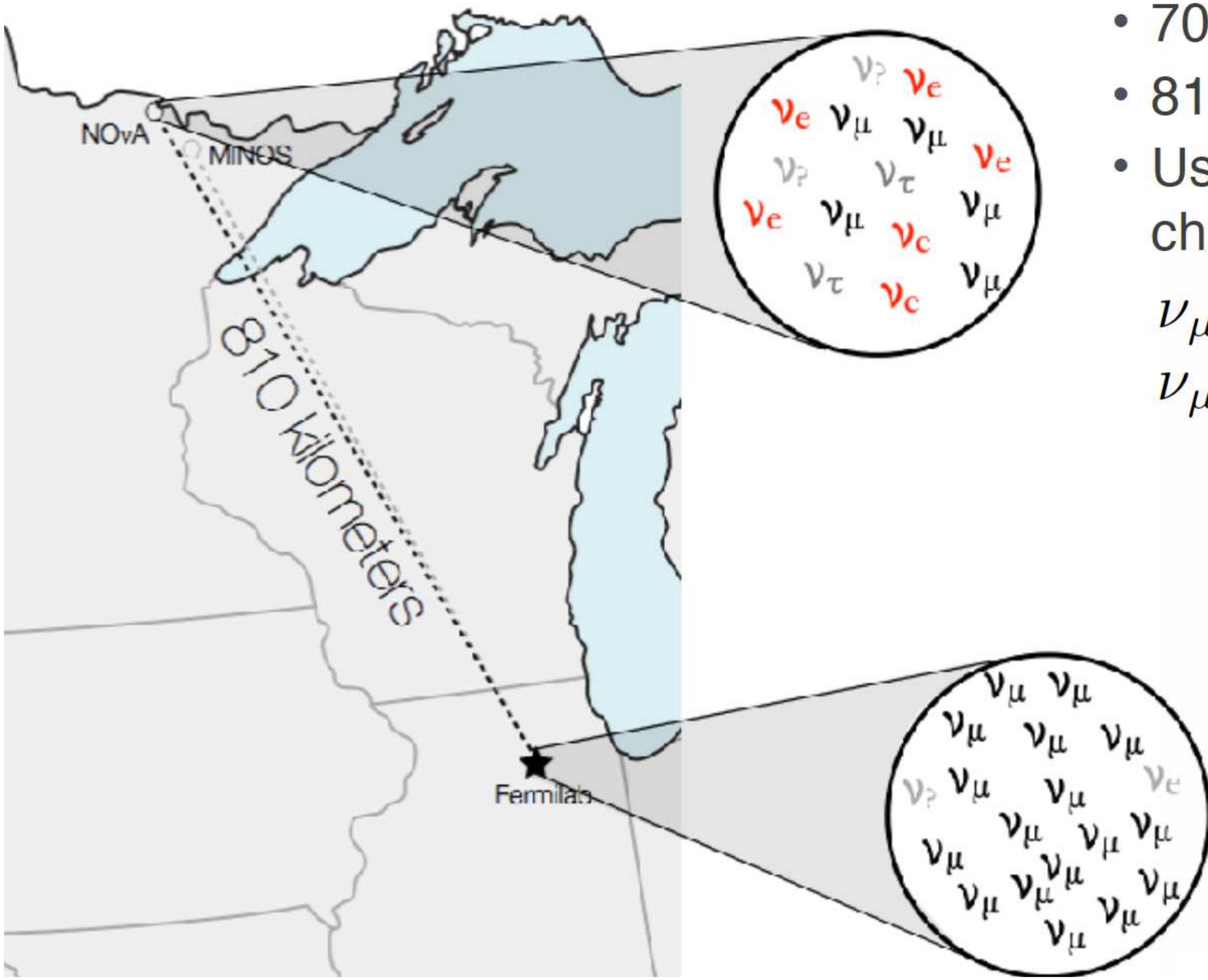
$$N_{ND} = \phi_{ND}\ \sigma\ \varepsilon_{ND}$$

$$N_{FD} = P\ \phi_{FD}\ \sigma\ \varepsilon_{FD}$$

P: is the oscillation probability

*Compare what we expected without oscillation repeat to what we see: the **discrepancy comes from the neutrino oscillation***

The NOvA Experiment

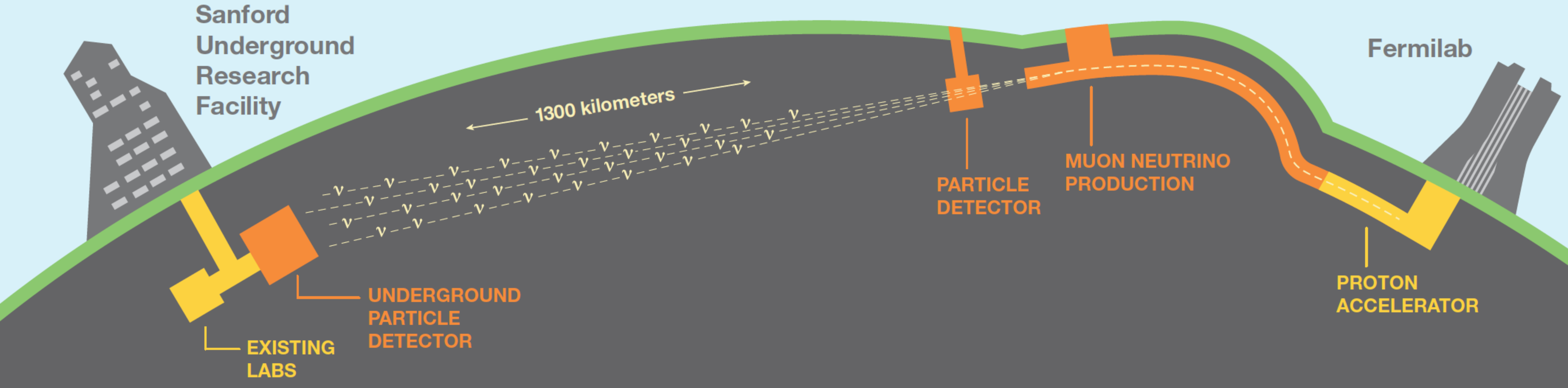


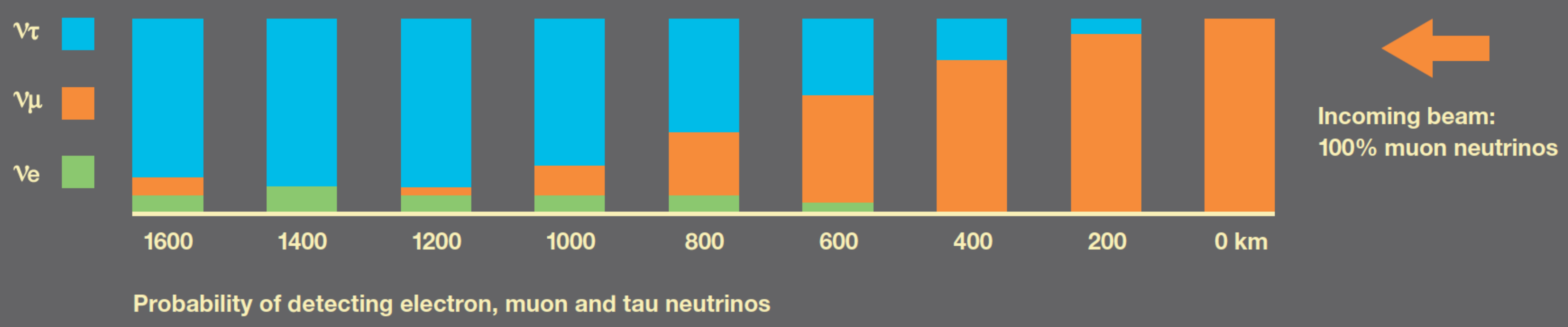
- Observe neutrinos from NuMI neutrino beam line at Fermilab
- Two functionally identical detectors, 14 milliradians off-axis from beam center
- 700 kW beam
- 810 km baseline
- Uses four primary oscillation channels:

$$\nu_\mu \to \nu_\mu \qquad \overline{\nu}_\mu \to \overline{\nu}_\mu$$
$$\nu_\mu \to \nu_e \qquad \overline{\nu}_\mu \to \overline{\nu}_e$$

- The NOvA detectors are:
  - Large, 14 kTon at the Far Detector
  - Consist of plastic cells filled with liquid scintillator
  - Arranged in alternating directions for 3D reconstruction
- The far detector is on the surface while the near detector is 300 ft underground.

Deep Underground Neutrino Experiment





Additional materials and links

- Neutrino Oscllations. From minutephysics (video). https://www.youtube.com/watch?v=7fgKBJDMO54

- Neutrino Hunters. Ray Jayawardhana (book).

- How heavy is a neutrino. Fermilab Symmetry (article). You can find more neutrino articles in the link.

  https://www.symmetrymagazine.org/article/how-heavy-is-a-neutrino

- Neutrino (Frank Close, book).

- Neutrinos (Fermilab, video) https://www.youtube.com/watch?v=RGv-pcKRf6Q&t=23s

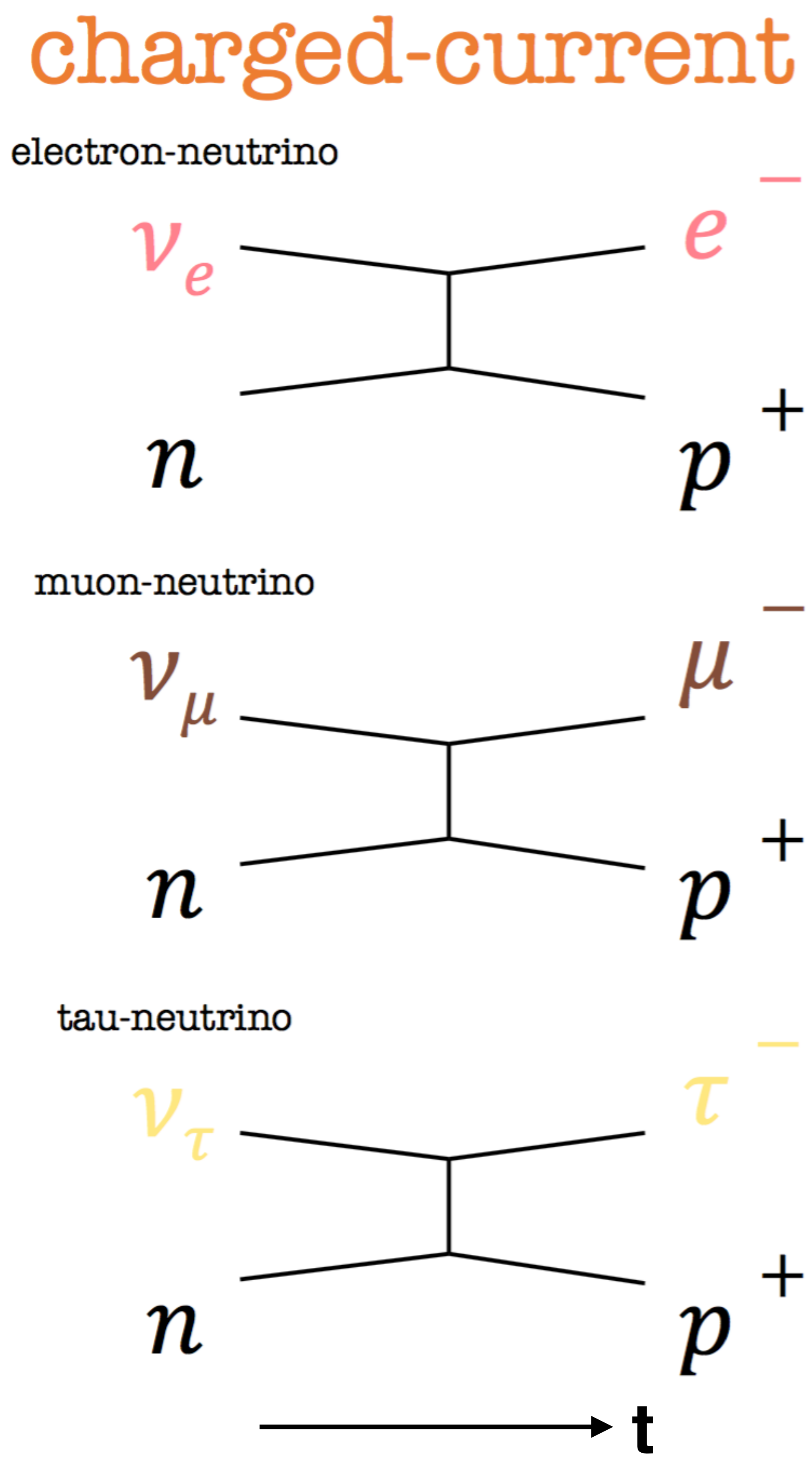
Backup

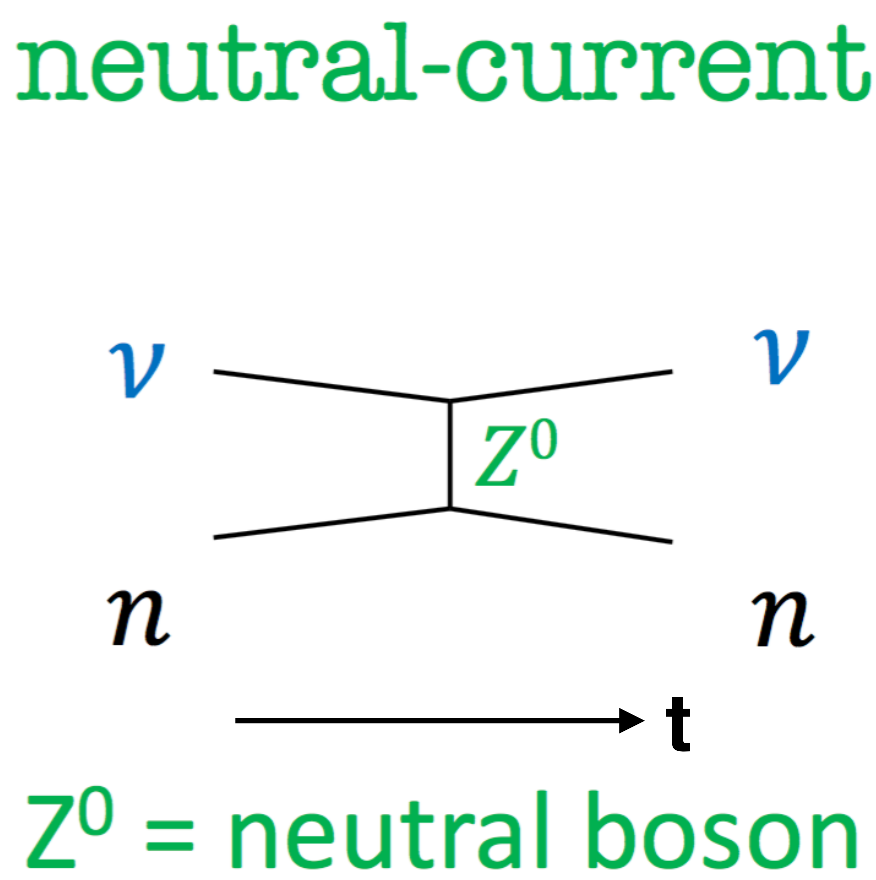
The complete view with 3 flavor oscillation

$$= R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12})$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

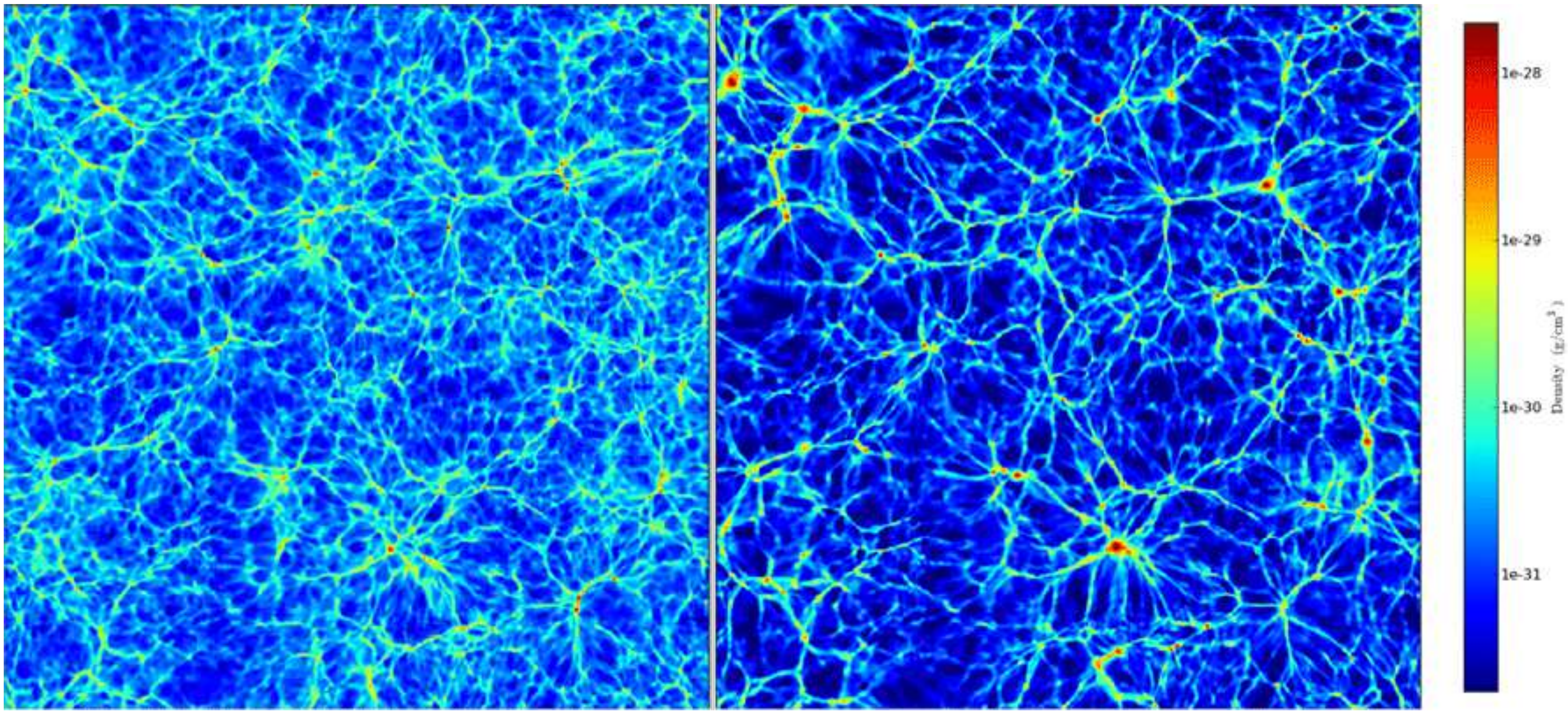
Neutrino and weak interactions





An upper limit on the sum of the three neutrino masses is estimated at < 0.3 eV

Density distribution in the Universe



Massive Neutrinos **Massless Neutrinos**

https://physics.aps.org/articles/v3/57

This was determined by exploring the effect of the neutrino mass on the structure formation in the early universe

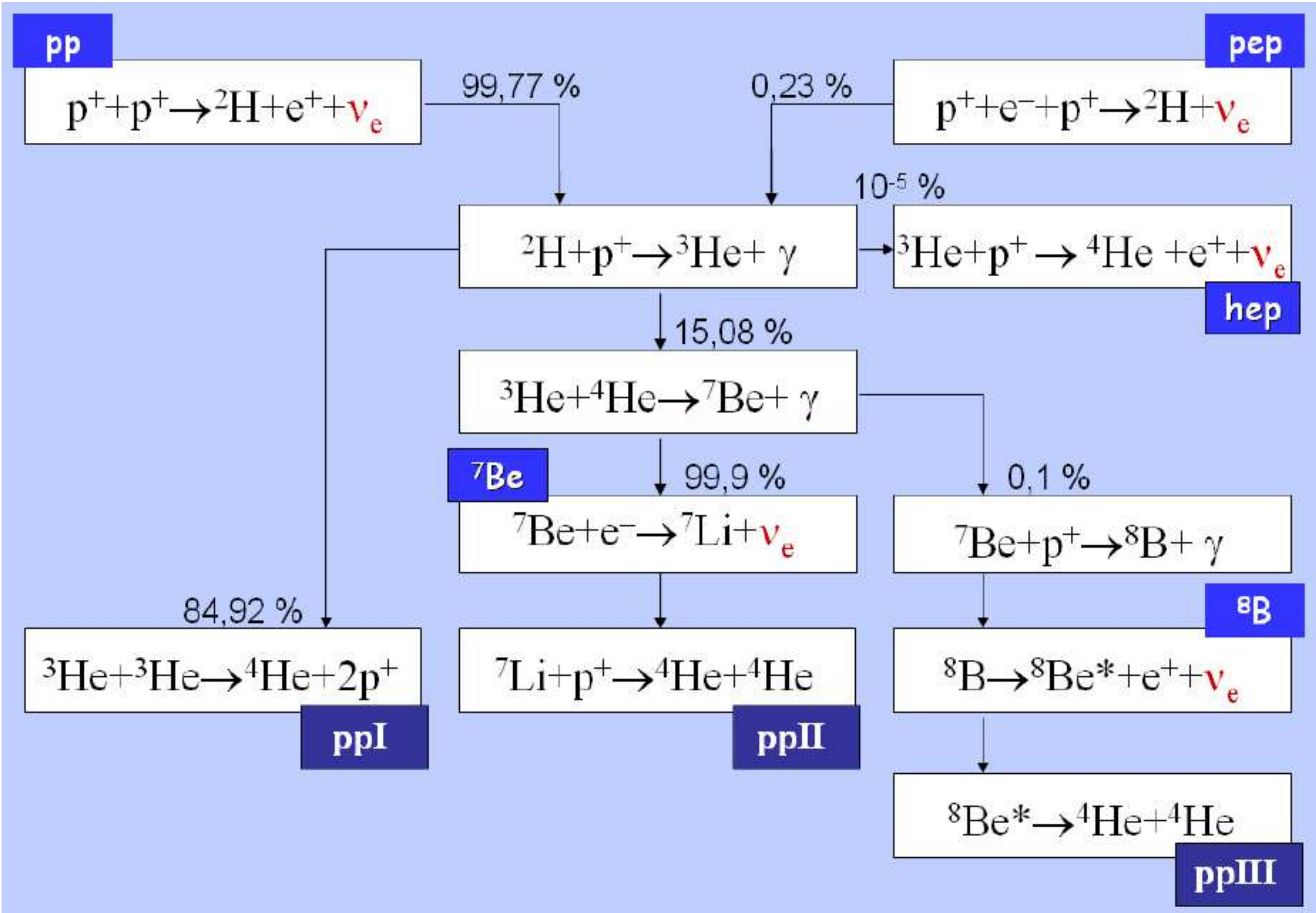
Do we have everything?

Not yet!

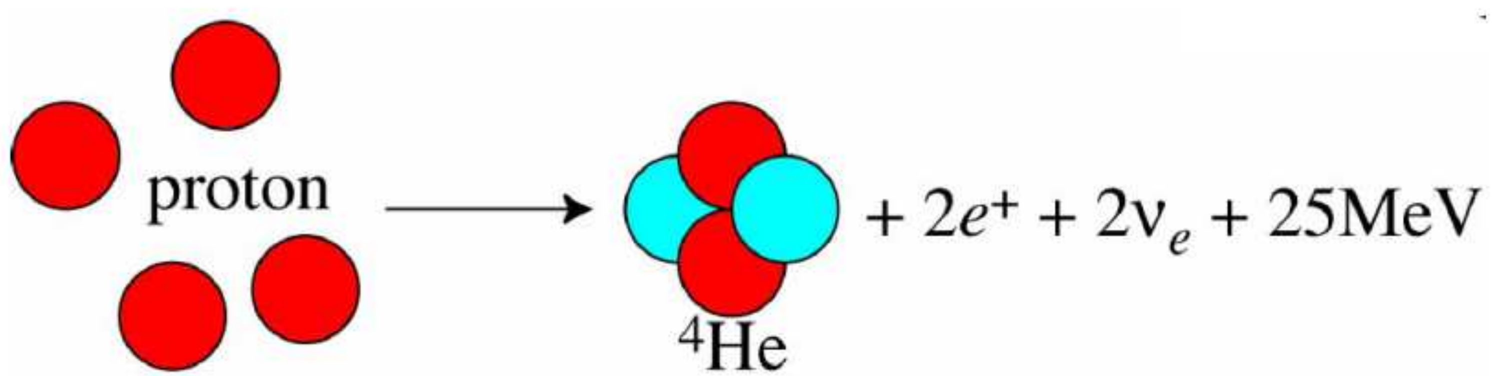
	What is the absolute neutrino mass?	Are neutrinos Dirac or Majorana particles?	What is the neutrino mass ordering?	Is there CP violation in the neutrino sector?	Are there more than 3 neutrino flavors?	Is our picture of neutrinos correct?
β decay	✓					✓
$0\nu\beta\beta$ decay	✓	✓				✓
astrophysics and cosmology	✓		(✓)		✓	✓
Atmospheric oscillations			(✓)	(✓)	✓	✓
Reactor oscillations			(✓)		✓	✓
Accelerator oscillations			✓	✓	✓	✓

(credit: S. Zeller)

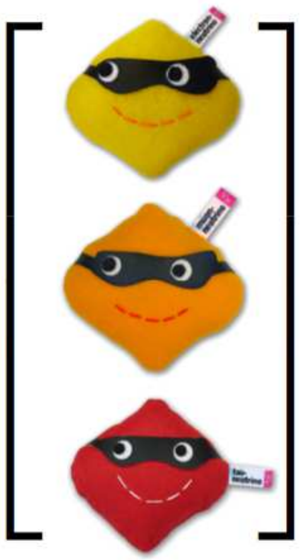
Neutrinos from the Sun



- For instance:

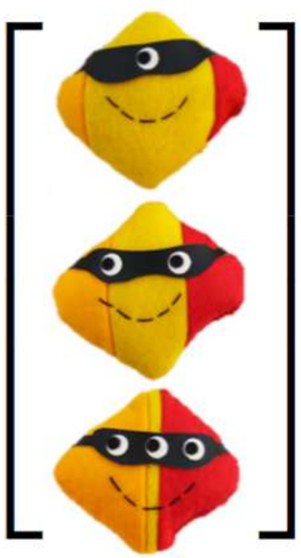


The complete view with 3 flavor oscillation



PMNS

$$= \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$



The complete view with 3 flavor oscillation

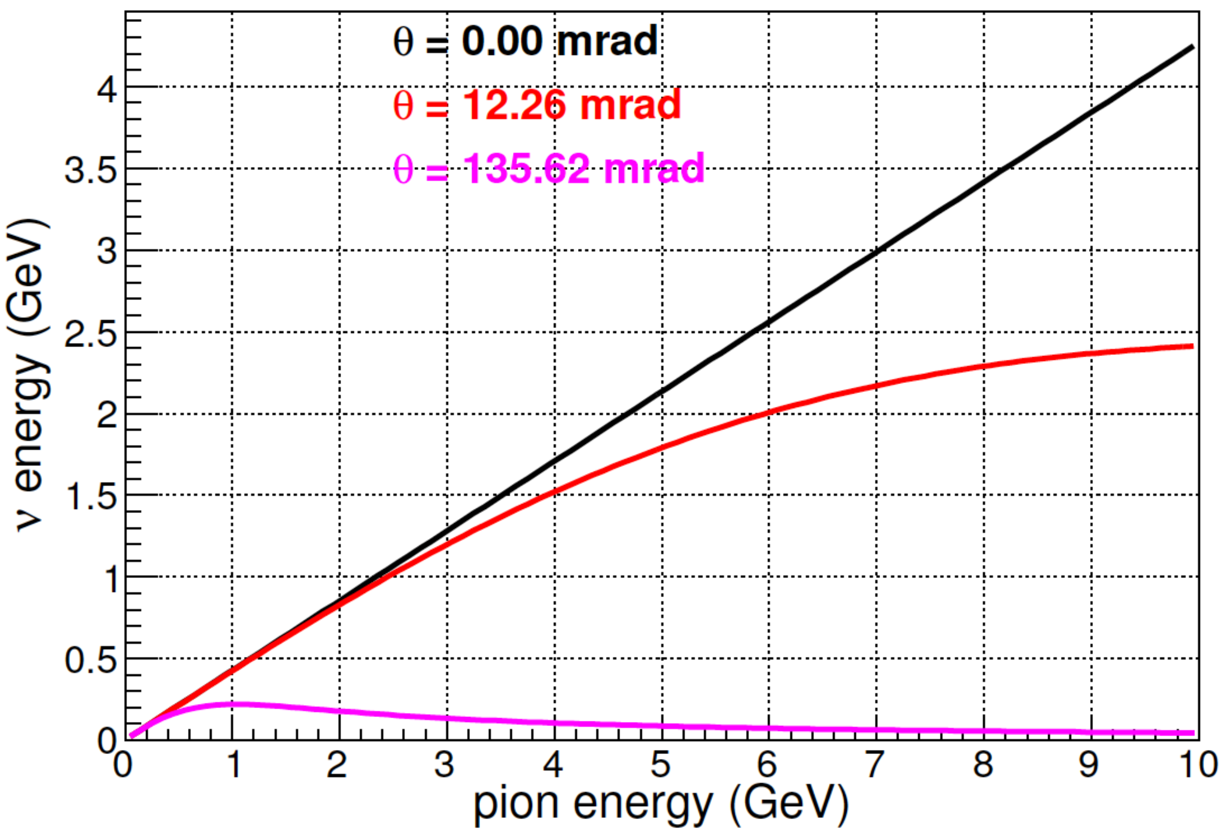
$$= R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12})$$

How to Make a Conventional Neutrino Beam

Neutrino decay:

- Main decay to neutrino mode for neutrino beam:

Decay	Chanel	Branching ratio (%)
1	$\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$	99.9877
2	$\pi^{\pm} \to e^{\pm} + \nu_{e}(\bar{\nu}_{e})$	0.0123
3	$K^{\pm} \to \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$	63.55
4	$K^{\pm} \to \pi^{0} + e^{\pm} + \nu_{e}(\bar{\nu}_{e})$	5.07
5	$K^{\pm} \to \pi^{0} + \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$	3.353
6	$K_L^0 \to \pi^{\pm} + e^{\mp} + \nu_{e}$	40.55
7	$K_L^0 \to \pi^{\pm} + \mu^{\mp} + \nu_{\mu}$	27.04
8	$\mu^{\pm} \to e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$	100.0



- From 2 pion body decay:

$$E_{\nu} \approx \frac{(1 - \frac{m_{\mu}^2}{M^2}) E_{\pi(K)}}{1 + \gamma^2 \tan^2\theta_{\nu}}$$

- dP/dΩ ??

How to study oscillation

$$P(\nu_\mu \to \nu_e) \approx \left| \sqrt{P_{\rm atm}} e^{-e(\Delta_{32}+\delta_{CP})} + \sqrt{P_{\rm sol}} \right|^2$$

$$\approx P_{\rm atm} + P_{\rm sol} + 2\sqrt{P_{\rm atm} P_{\rm sol}} \left(\cos\Delta_{32}\cos\delta_{CP} \mp \sin\Delta_{32}\sin\delta_{CP}\right)$$

$$\sqrt{P_{\rm atm}} = \sin(\theta_{23})\sin(2\theta_{13})\frac{\sin(\Delta_{31}-aL)}{\Delta_{31}-aL}\Delta_{31}$$

$\nu_\mu \to \nu_e$ depends on:

- *CP* phase: $\delta_{\rm CP}$
- Mass hierarchy and matter effects
- Atmospheric parameters: $\sin^2(\theta_{23})$, Δm^2_{32}
- The smallest mixing angle: θ_{13}
- Solar parameters: $\sin^2(\theta_{12})$, Δm^2_{12}

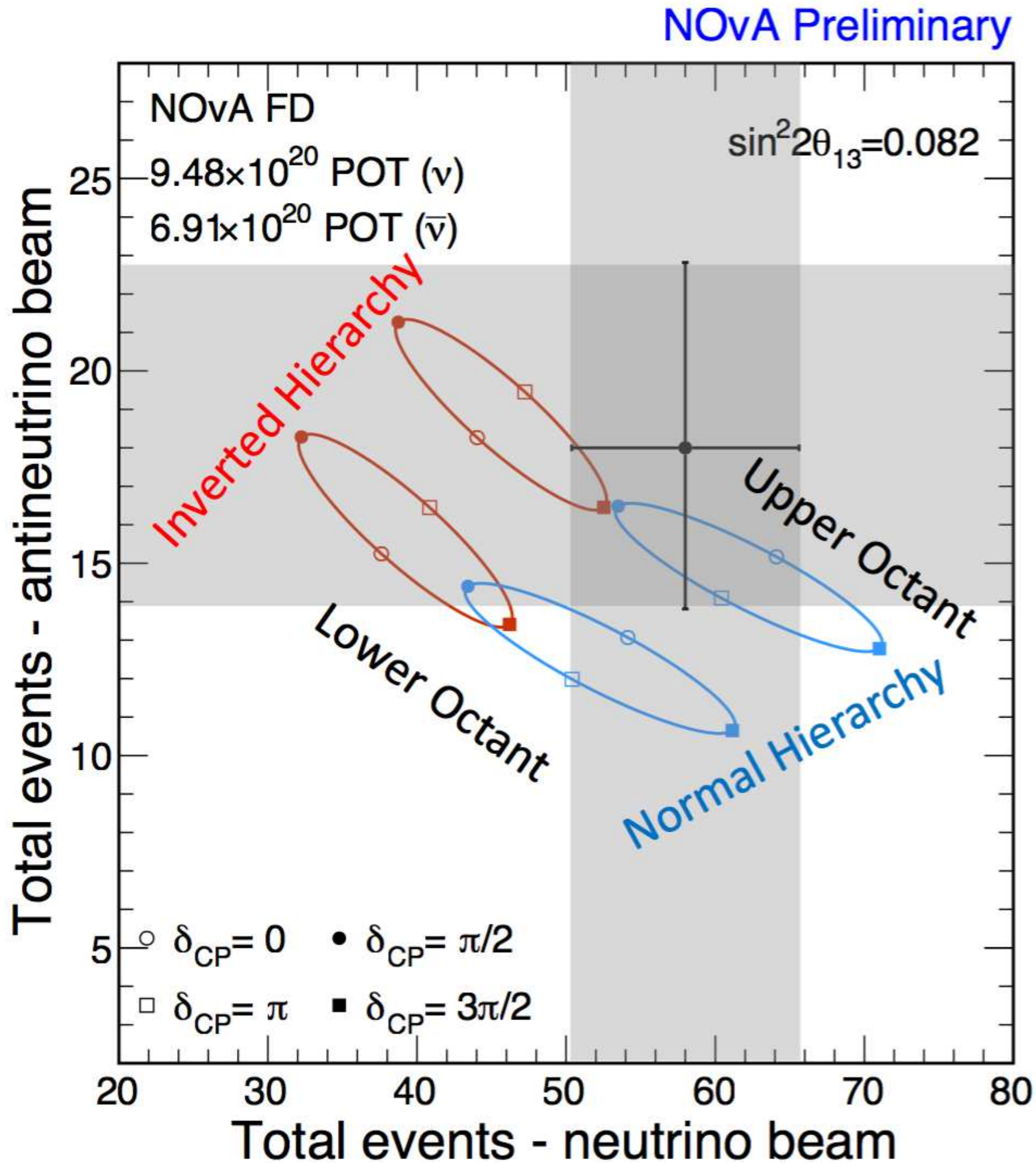
Open Questions (CP phase; mass hierarchy and matter effects)

Disappearance Constraints (atmospheric parameters; smallest mixing angle; solar parameters)

NOvA: $\nu_\mu \to \nu_\mu$

Reactor: $\nu_e \to \nu_e$

Solar: $\nu_e \to \nu_e$



NOvA Preliminary
NOvA FD
9.48×10^20 POT (ν)
6.91×10^20 POT (ν̄)
sin²2θ13=0.082
Inverted Hierarchy
Upper Octant
Lower Octant
Normal Hierarchy
δCP= 0
δCP= π/2
δCP= π
δCP= 3π/2
Total events - antineutrino beam
Total events - neutrino beam
25
20
15
10
5
20
30
40
50
60
70
80