Why are Neutrinos important for Physics beyond the Standard Model

Mu-Chun Chen, University of California at Irvine

Neutrino University, Fermilab, July 5, 2018

The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

Super-Kamiokande Collaboration

Photo: K. MacFarlane. Queen's University /SNOLAB

Arthur B. McDonald

Sudbury Neutrino Observatory Collaboration

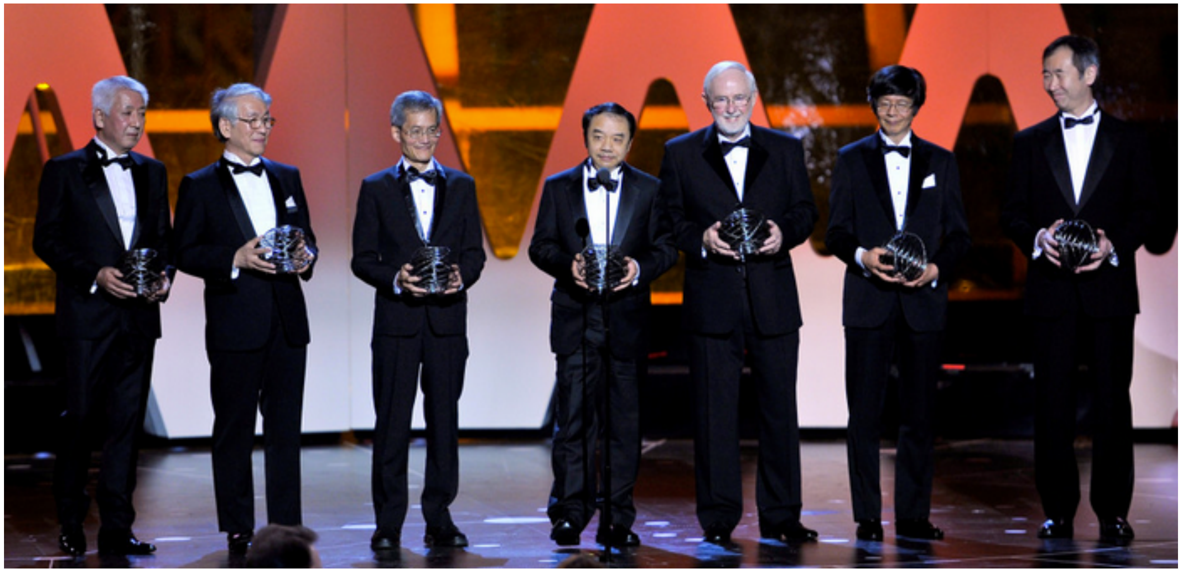
Neutrino Oscillations

⇩

Neutrinos have Mass

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

2016 Breakthrough Prize in Fundamental Physics



Daya Bay
KamLand
K2K+T2K
SNO
Super-K

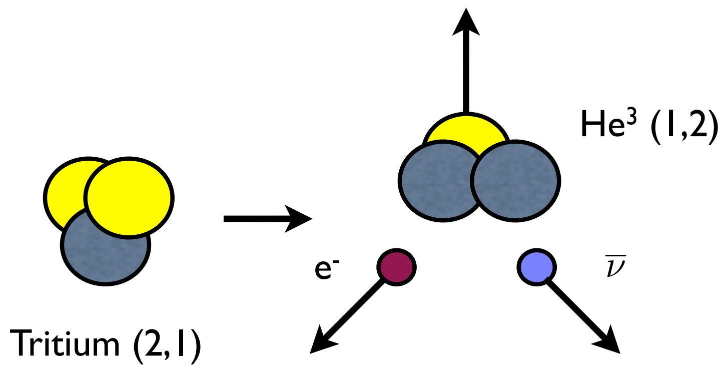
… recognizes major insights into the deepest questions of the Universe:

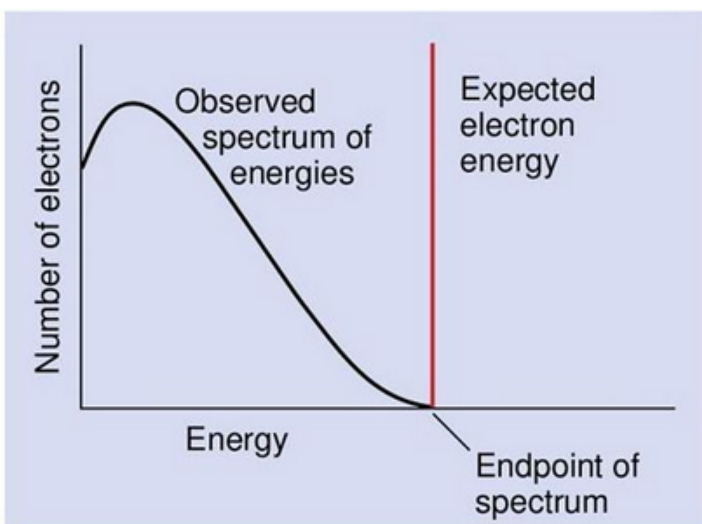
"for the fundamental discovery and exploration of neutrino oscillations, revealing a new frontier beyond, and possibly far beyond, the standard model of particle physics."

Neutrino: Solution to the "Energy Crisis"!

Dec. 1930: invented by Pauli to explain missing energy spectrum in beta decay

$$(N, Z) \to (N-1, Z+1) + e^- + \overline{\nu}$$

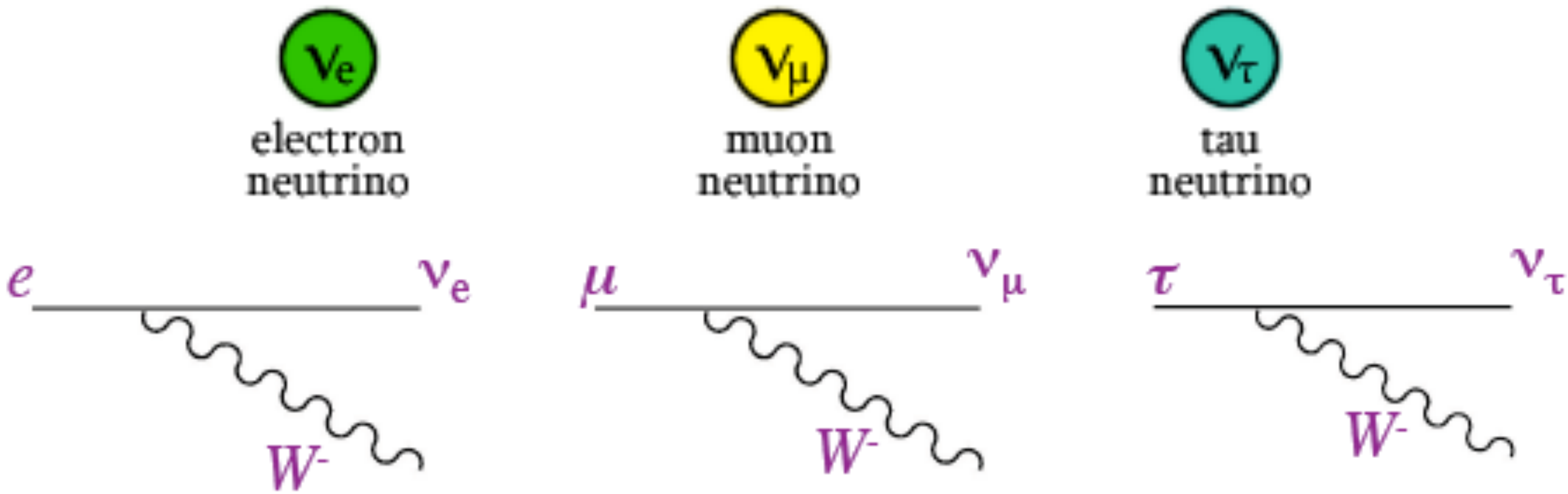


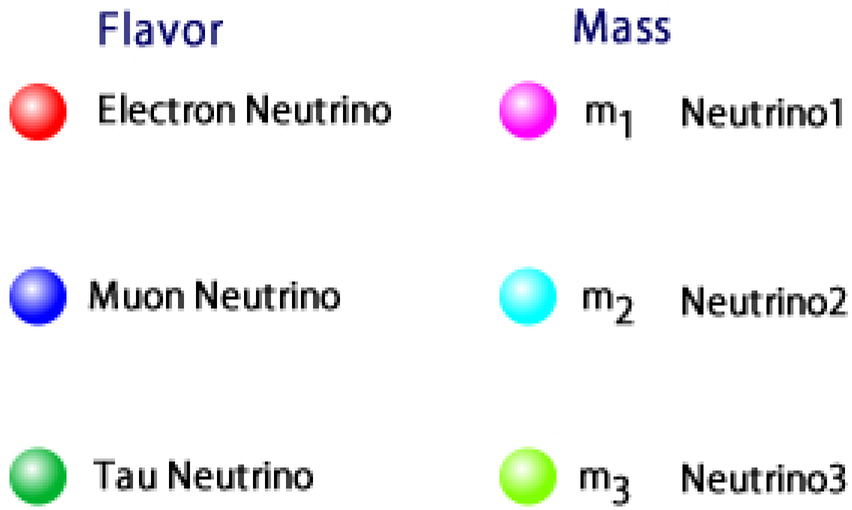


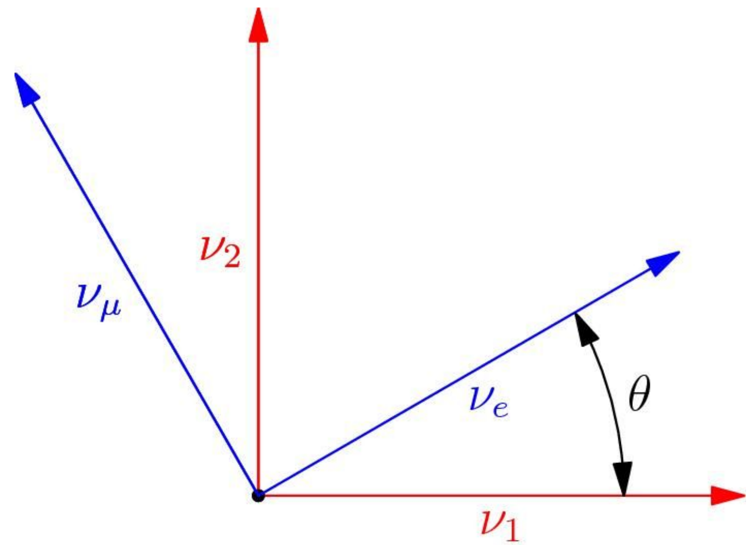
Recall Lectures by Boris Kayser & Stephen Parke

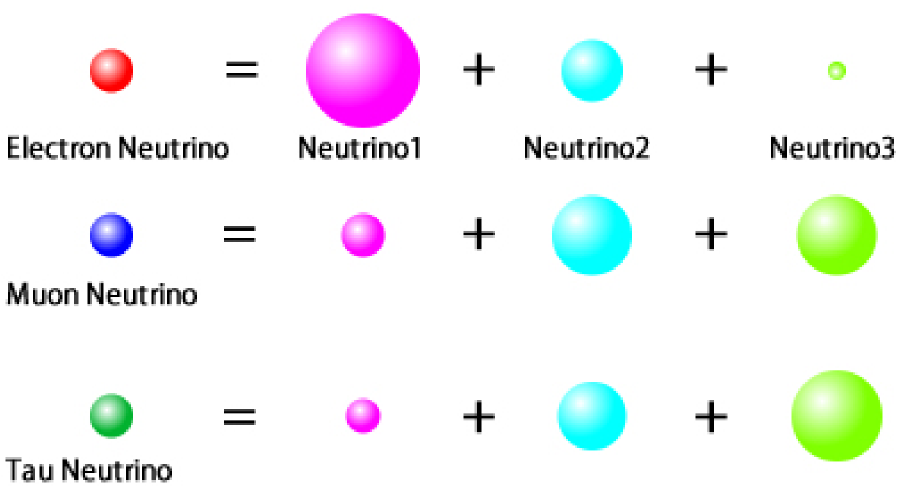
Three Neutrino Flavors

Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences



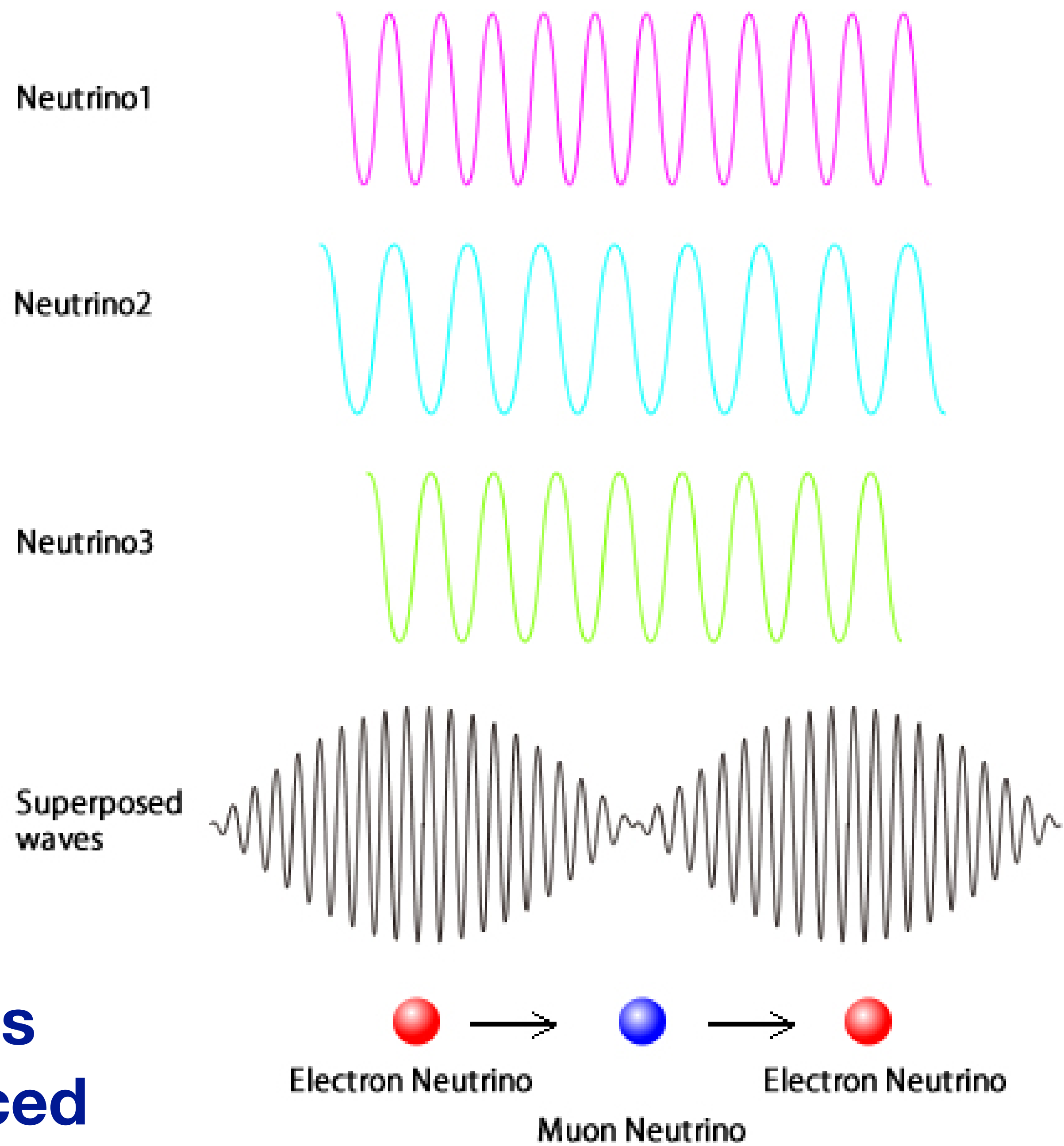






[Picture credit: Symmetry Magazine]

Macroscopic Quantum Mechanics at Work

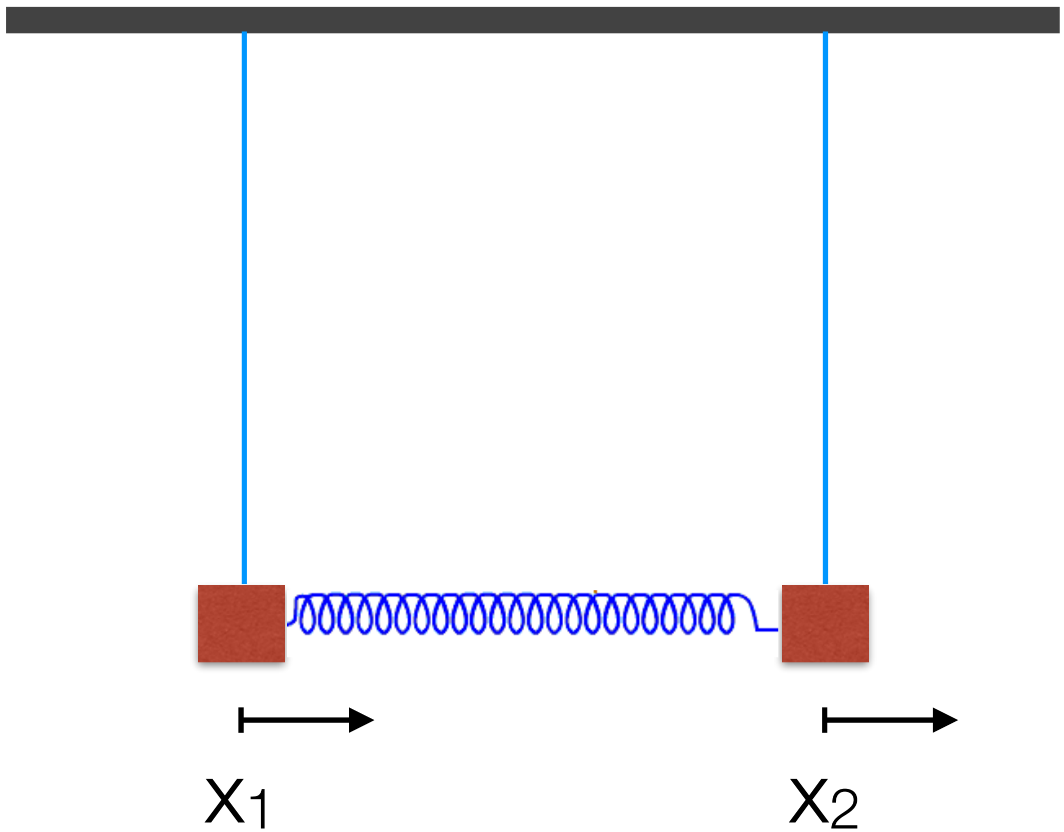


states propagate

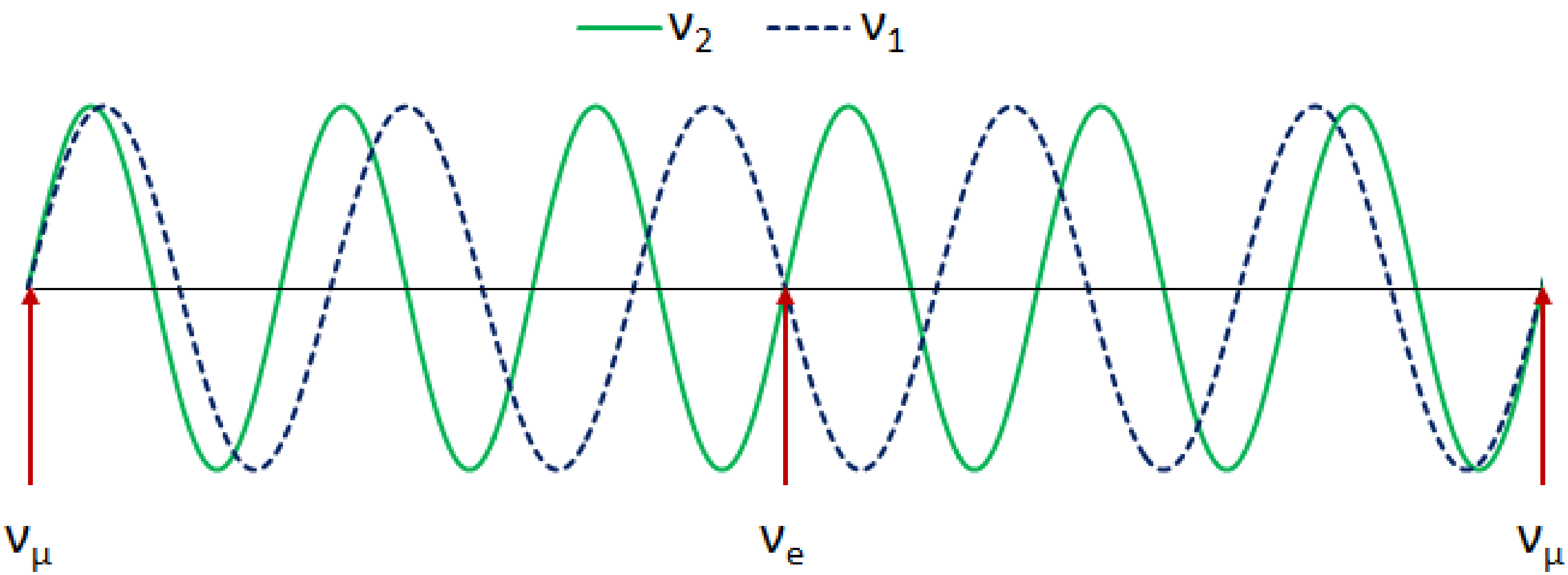
states produced

states detected

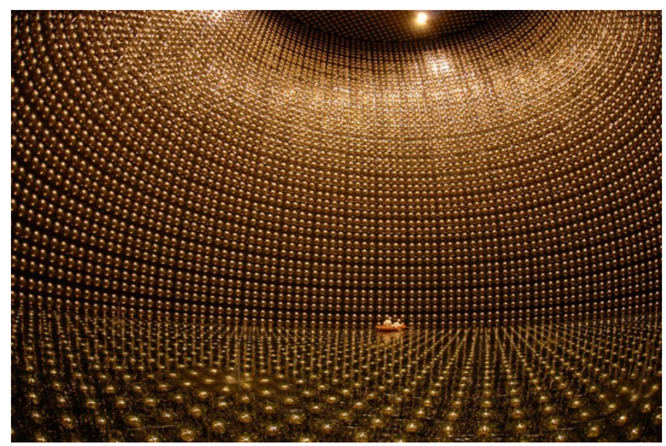
Normal Modes of Coupled Pendulums



Macroscopic Quantum Mechanics at Work



neutrino source: (the Sun, nuclear reactors, accelerators)



neutrino detector

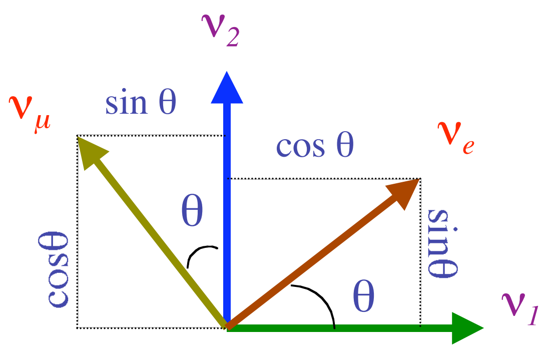
Neutrino Oscillation: Macroscopic Quantum Mechanics

- **production**: neutrinos of a definite flavor produced by weak interaction
- **propagation**: neutrinos evolve according to their masses
- **detection**: neutrinos of a different flavor composition detected

Oscillation Mechanism

- Simplified two-flavor analysis:

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



$$|\nu_e\rangle = |\nu_1\rangle \cos\theta + |\nu_2\rangle \sin\theta$$

$$|\nu_\mu\rangle = |\nu_2\rangle \cos\theta - |\nu_1\rangle \sin\theta$$

- In vacuum: $|\nu_\mu\rangle$ evolves in time

$$|\nu_\mu(t)\rangle = |\nu_2\rangle e^{-im_2^2 t/4p} \cos\theta - |\nu_1\rangle e^{-im_1^2 t/4p} \sin\theta$$

- transition probability from ν_μ to ν_e

$$P(\nu_\mu \to \nu_e) = \langle \nu_e | \nu_\mu(t) \rangle$$
$$= \sin^2 2\theta \, \sin^2(\pi L/\lambda)$$

- Survival probability for ν_μ

$$P(\nu_\mu \to \nu_\mu)$$
$$= 1 - \sin^2 2\theta \, \sin^2(\pi L/\lambda)$$

- Oscillation length

$$\lambda = \frac{2.5 E_\nu}{\Delta m^2}$$

Δm^2 must be non-zero to have neutrino oscillation!!

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

Recall Lecture by Boris Kayser

$$P\left[\nu_\mu \to \nu_e\right] = \sin^2 2\theta \sin^2\left[1.27\Delta m_{32}^2 \left(\frac{(\mathrm{eV})^2}{c^2}\right)\frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right]$$

θ = Mixing angle

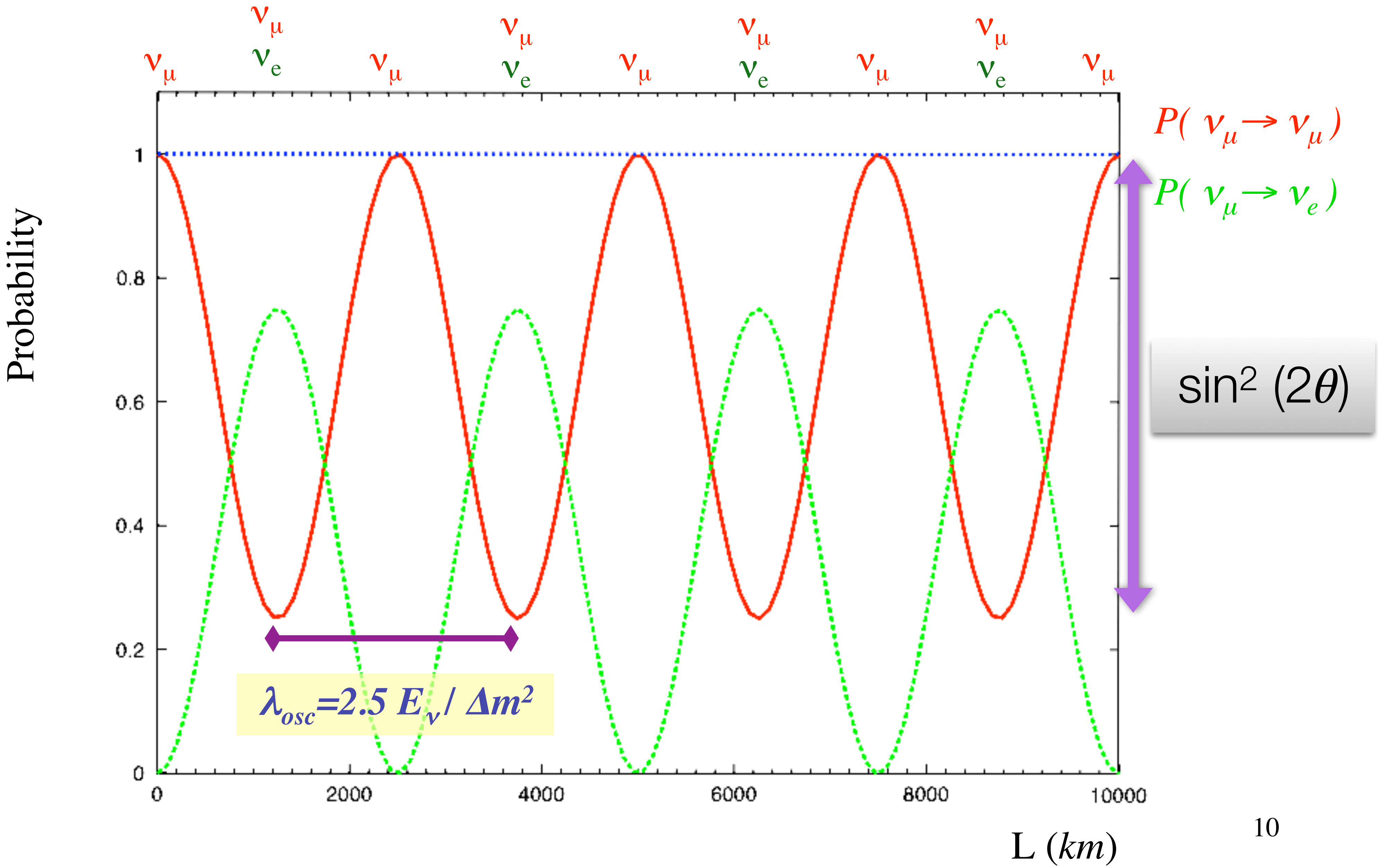
c = Speed of light

L = Travel distance

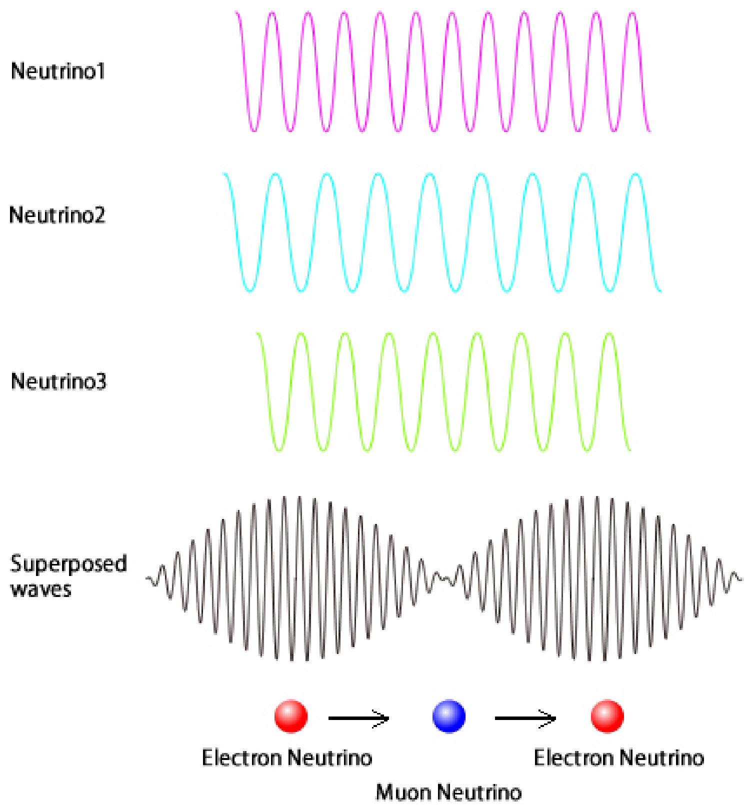
E = Energy

$$1\mathrm{GeV} = 10^9\,\mathrm{eV}$$

Vacuum oscillation: E_ν=1 GeV, $\Delta m^2=10^{-3}$ eV^2, $\theta = \pi/6$



Neutrino Oscillation ⇒ Neutrinos must have masses



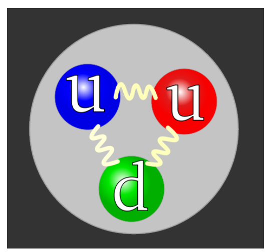
[Picture credit: Symmetry Magazine]

Standard Model of Particle Physics

- Gauge Theory based on the group $SU(3)_c \times SU(2)_L \times U(1)_Y$
- Matter Content:
  - 3 generations of quarks and leptons
  - Force carriers:

$SU(3)_c$: strong force

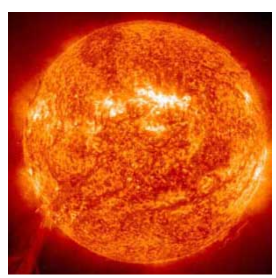
→ gluons



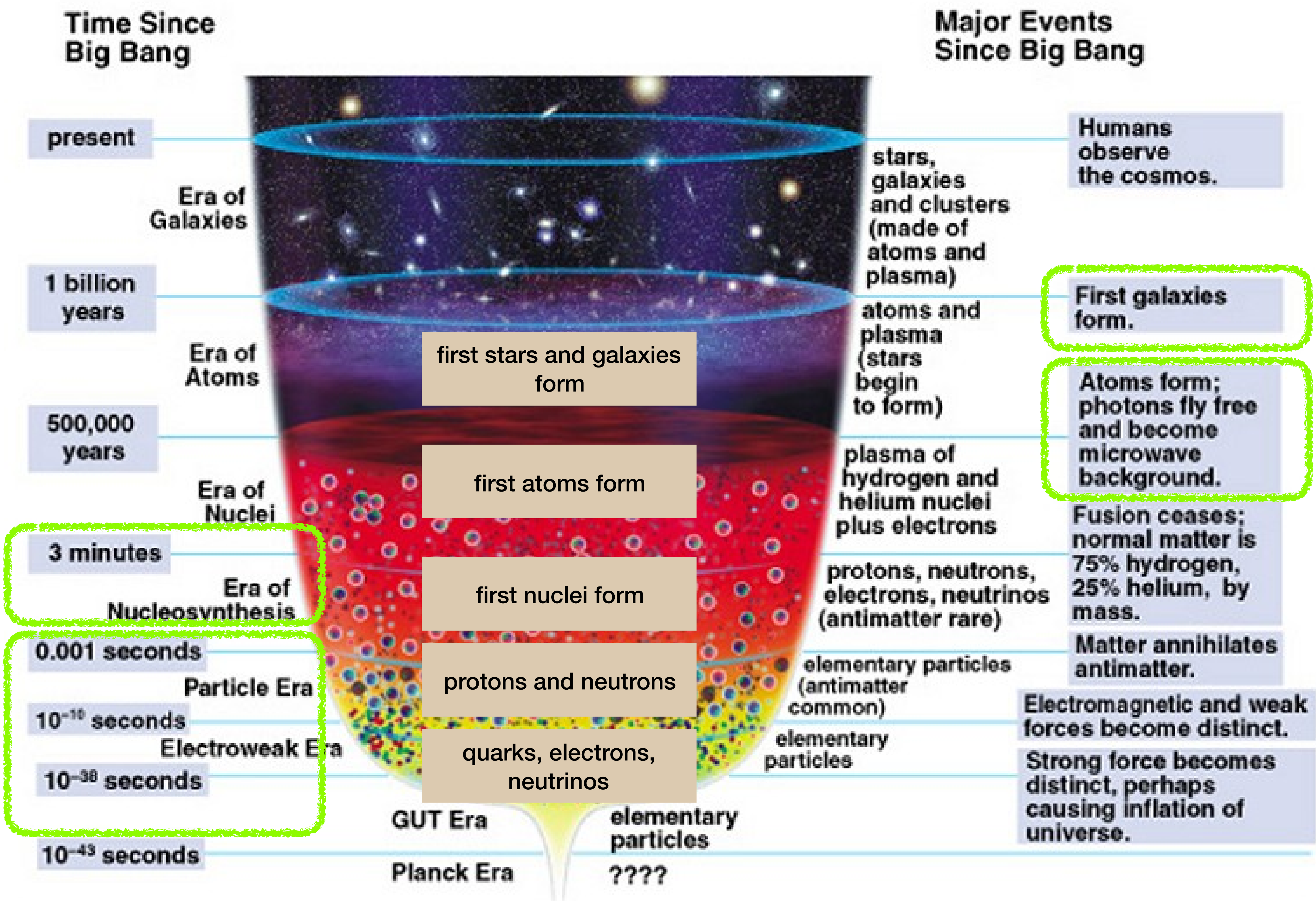
$SU(2)_L \times U(1)_Y \Rightarrow$

EM & weak interactions

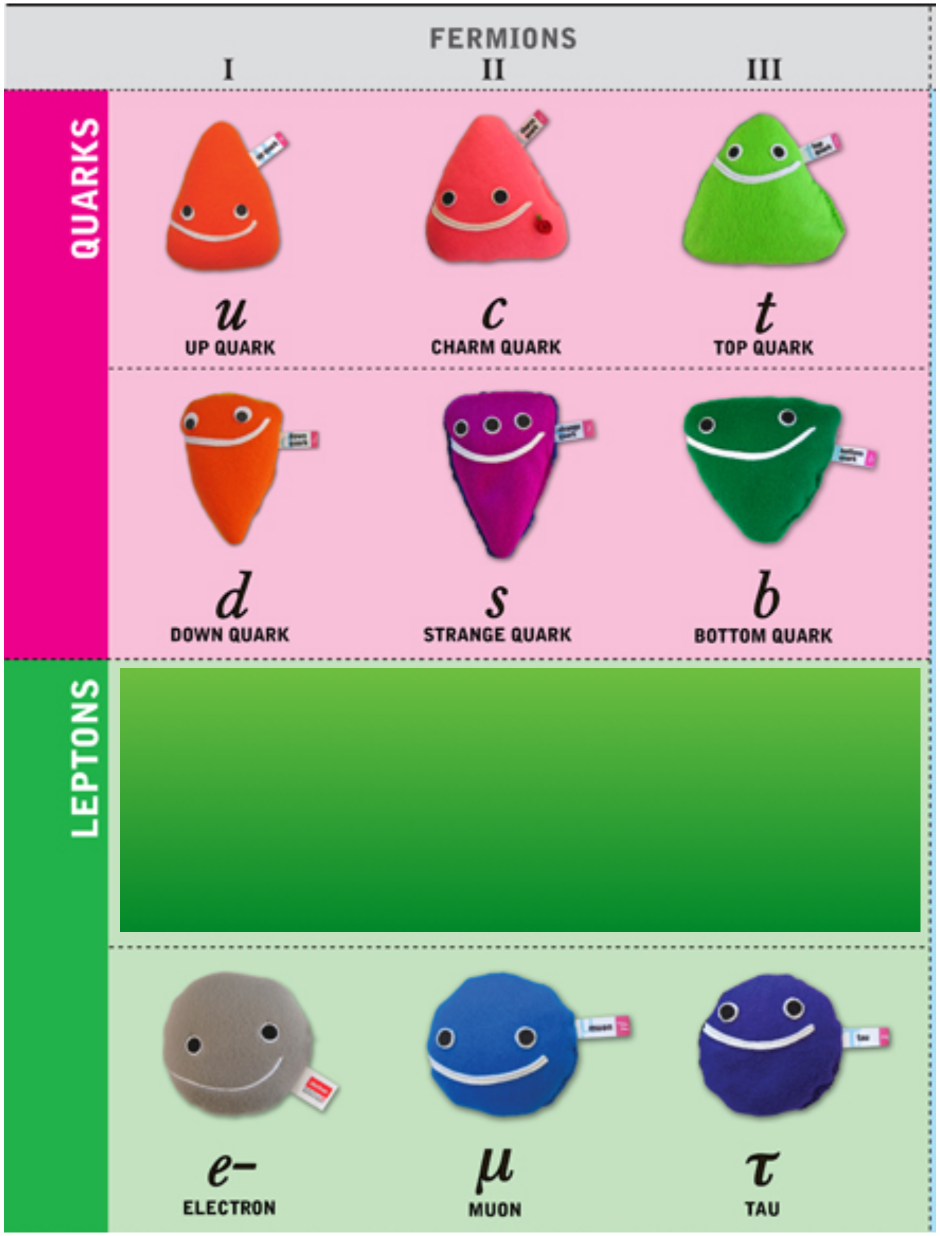
→ W, Z, photon

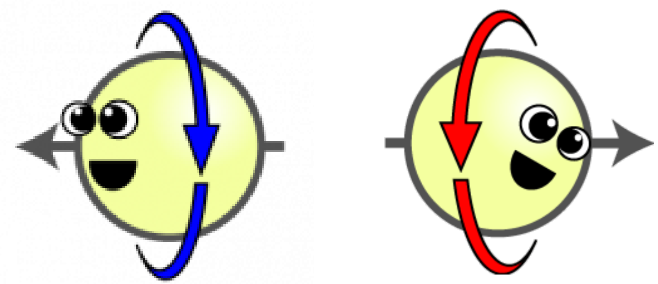


[Picture credit: http://particlezoo.net]


Time Since Big Bang
Major Events Since Big Bang
present
Humans observe the cosmos.
Era of Galaxies
stars, galaxies and clusters (made of atoms and plasma)
1 billion years
First galaxies form.
atoms and plasma (stars begin to form)
Era of Atoms
first stars and galaxies form
500,000 years
Atoms form; photons fly free and become microwave background.
first atoms form
plasma of hydrogen and helium nuclei plus electrons
Era of Nuclei
Fusion ceases; normal matter is 75% hydrogen, 25% helium, by mass.
3 minutes
Era of Nucleosynthesis
first nuclei form
protons, neutrons, electrons, neutrinos (antimatter rare)
0.001 seconds
Matter annihilates antimatter.
Particle Era
protons and neutrons
elementary particles (antimatter common)
10^-10 seconds
Electromagnetic and weak forces become distinct.
Electroweak Era
quarks, electrons, neutrinos
elementary particles
10^-38 seconds
Strong force becomes distinct, perhaps causing inflation of universe.
GUT Era
elementary particles
10^-43 seconds
Planck Era
????

Standard Model of Particle Physics





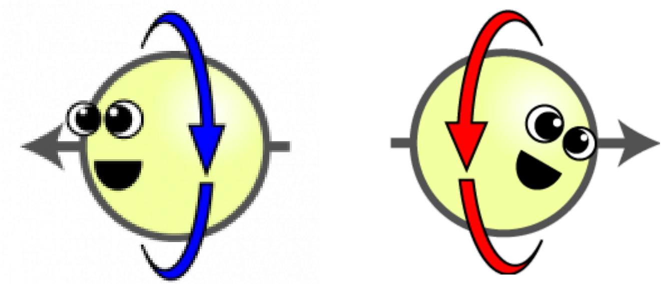
all particles have both left-handed and right-handed partners

Standard Model of Particle Physics

Helicity of Neutrinos*

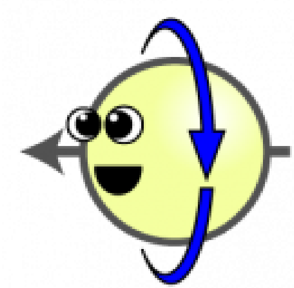
M. Goldhaber, L. Grodzins, and A. W. Sunyar
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] 0−, we find that the neutrino is "left-handed," i.e., $\sigma_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).



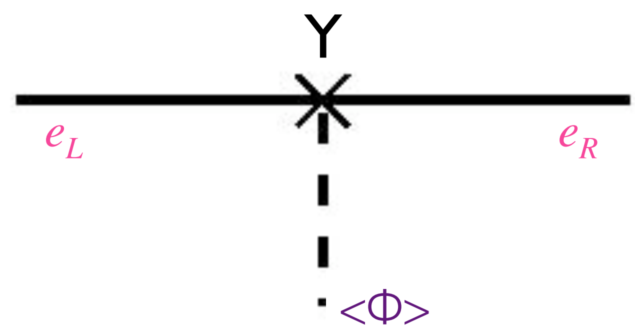
all particles have both left-handed and right-handed partners, except for neutrinos

only LH neutrinos have been observed

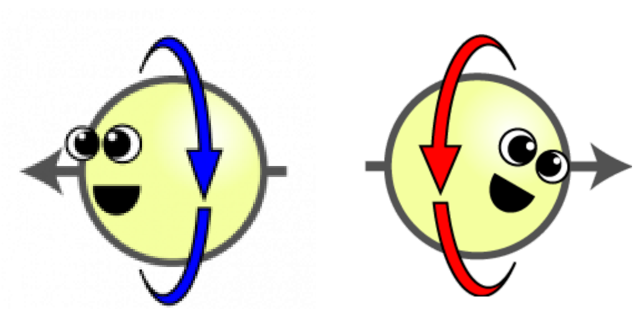


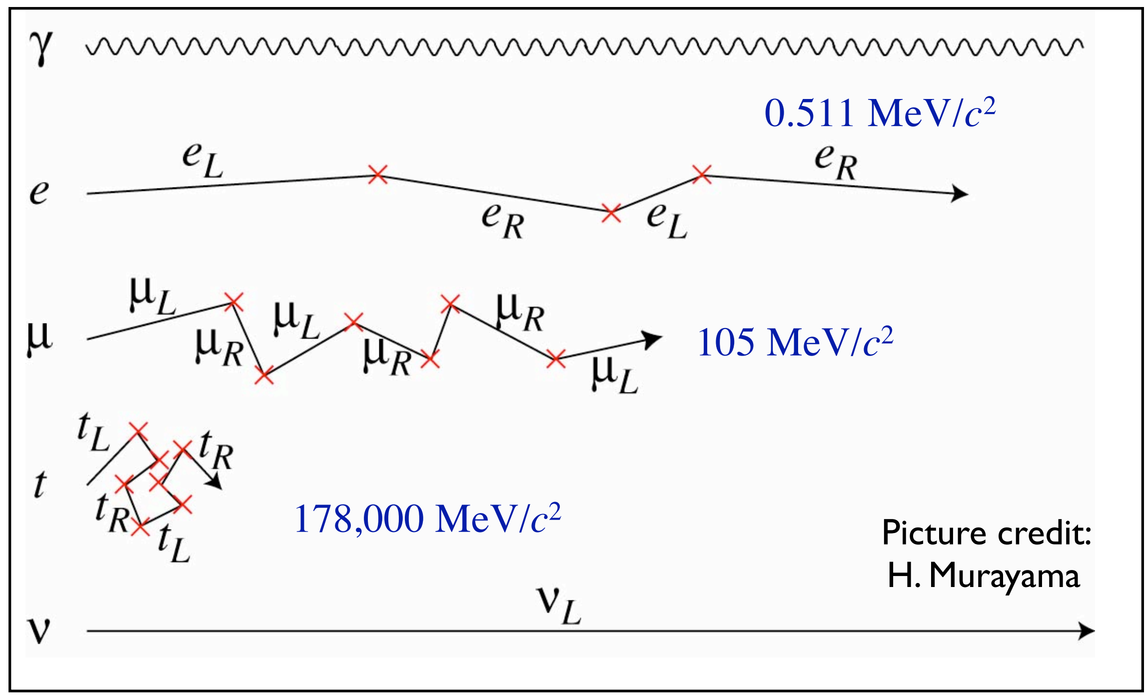
Fermion Mass Generation

- Yukawa Interactions
  - LH and RH particles mix and interact with Higgs VEV to acquire a mass



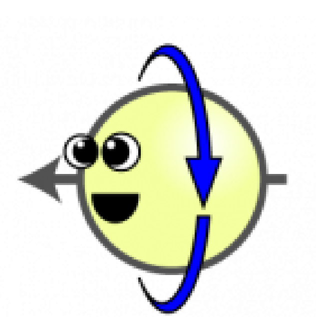
Y: Yukawa coupling constant

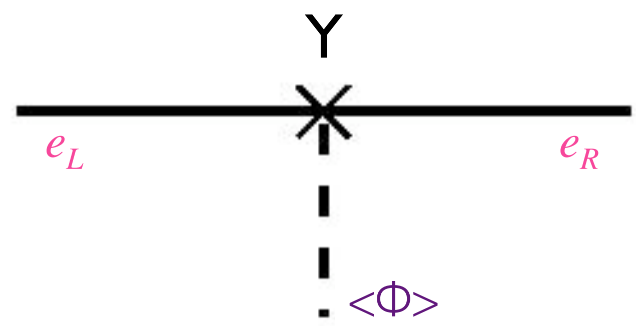




Fermion Mass Generation

- **In Standard Model: no RH neutrinos**
  - **LH neutrinos cannot interact with Higgs**
  - **Neutrinos stay massless**

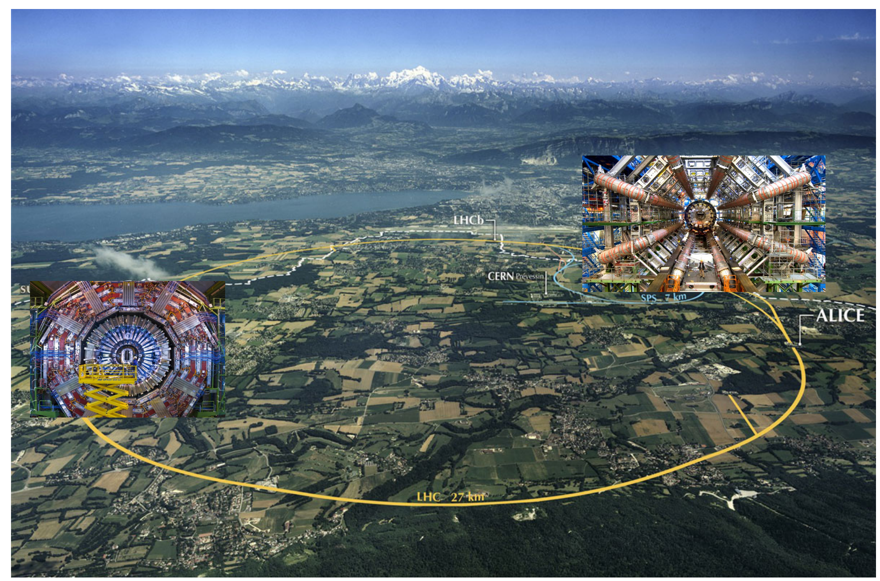




Y: Yukawa coupling constant

Standard Model predicts massless neutrinos

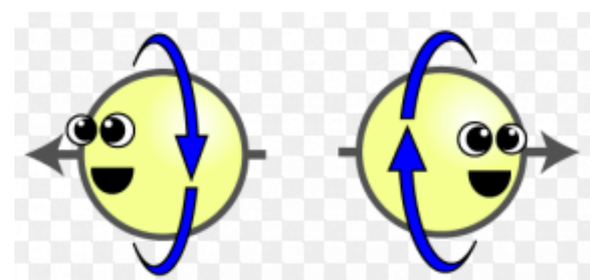
July 4, 2012: Higgs Boson was discovered, at last!



New "Periodic Table" of Particle Physics

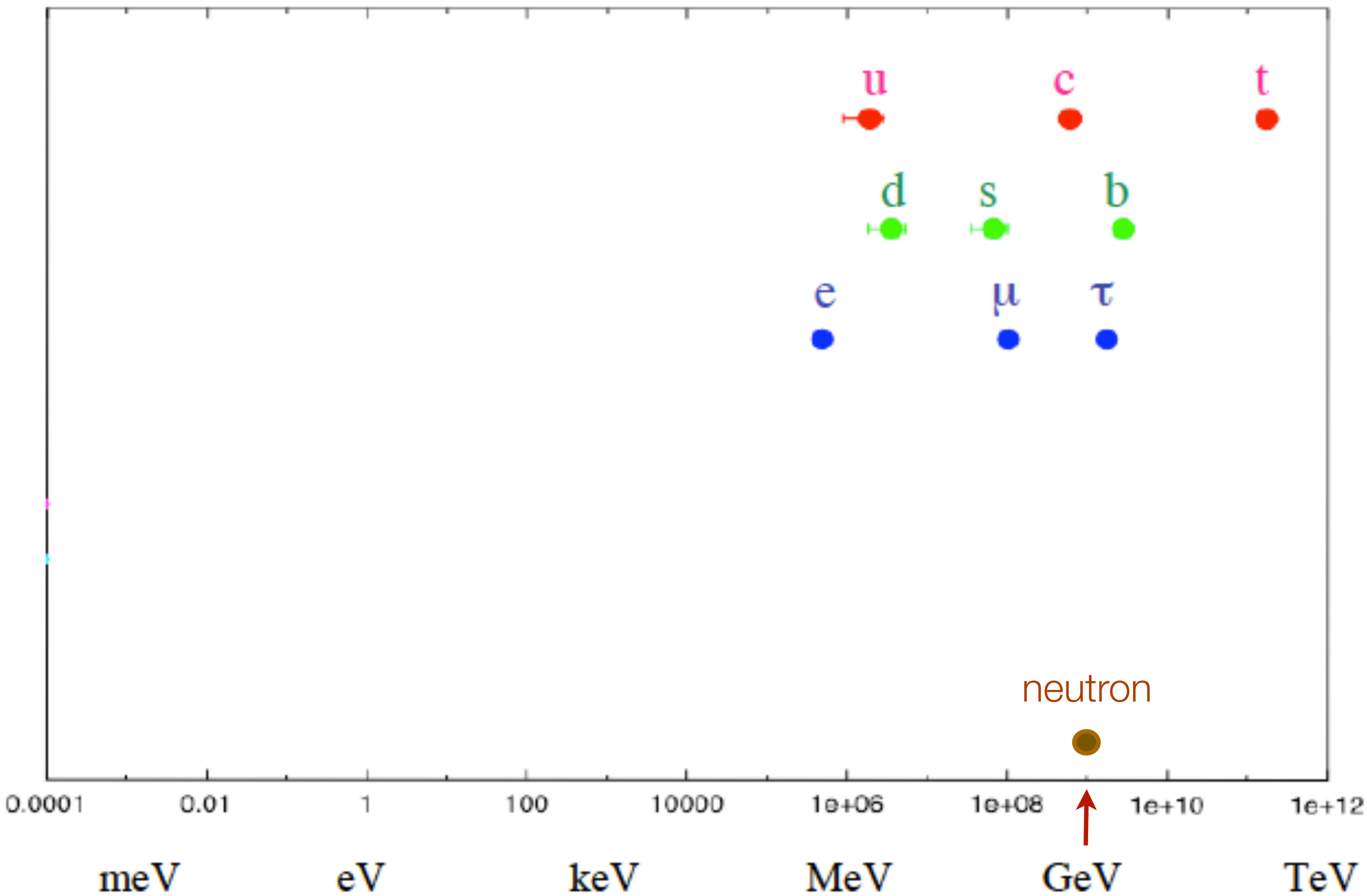
more massive

- 3 generations of quarks and leptons
- LH & RH partners for all particles except for neutrinos

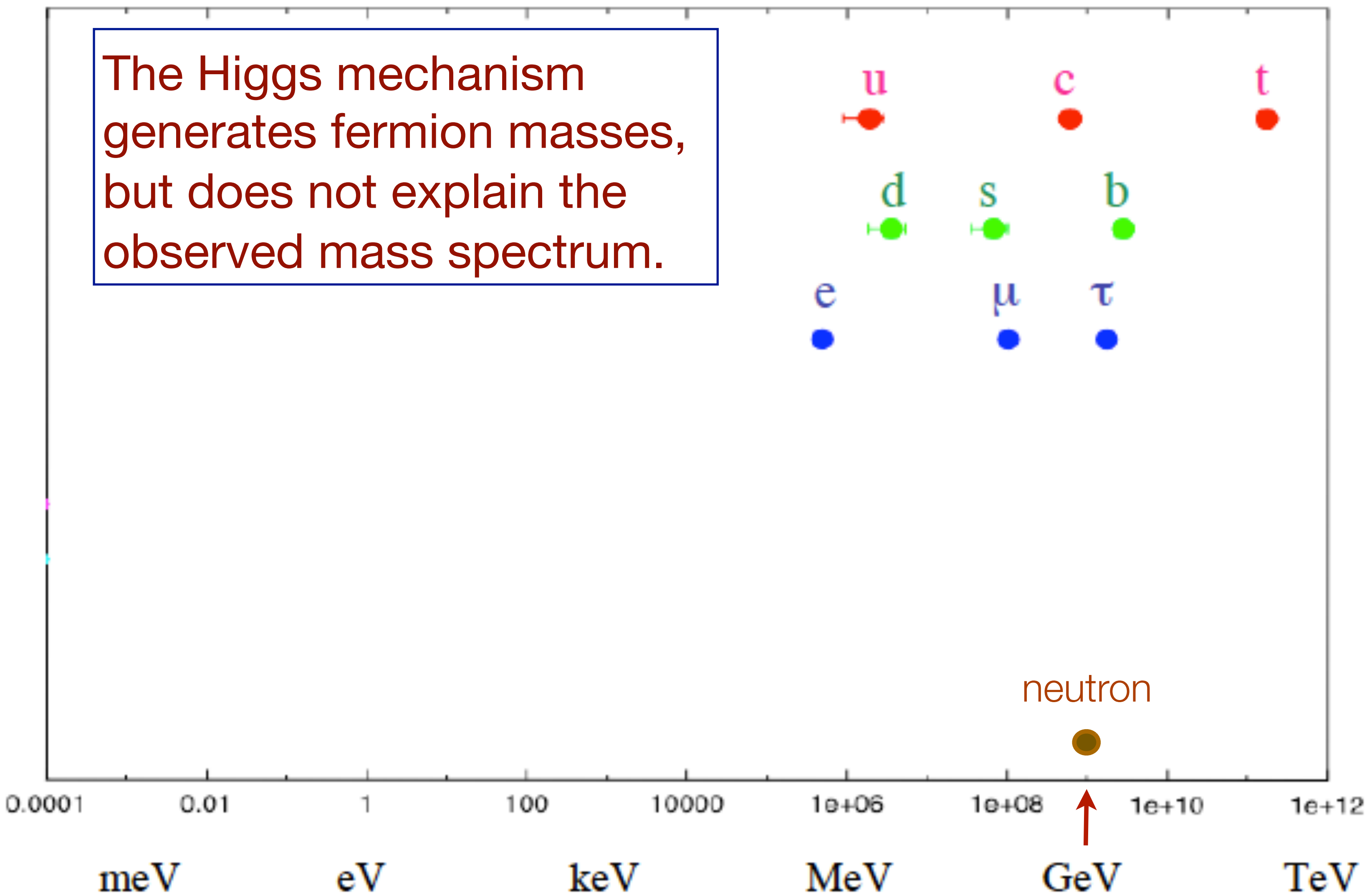


[Picture credit: http://particlezoo.net]

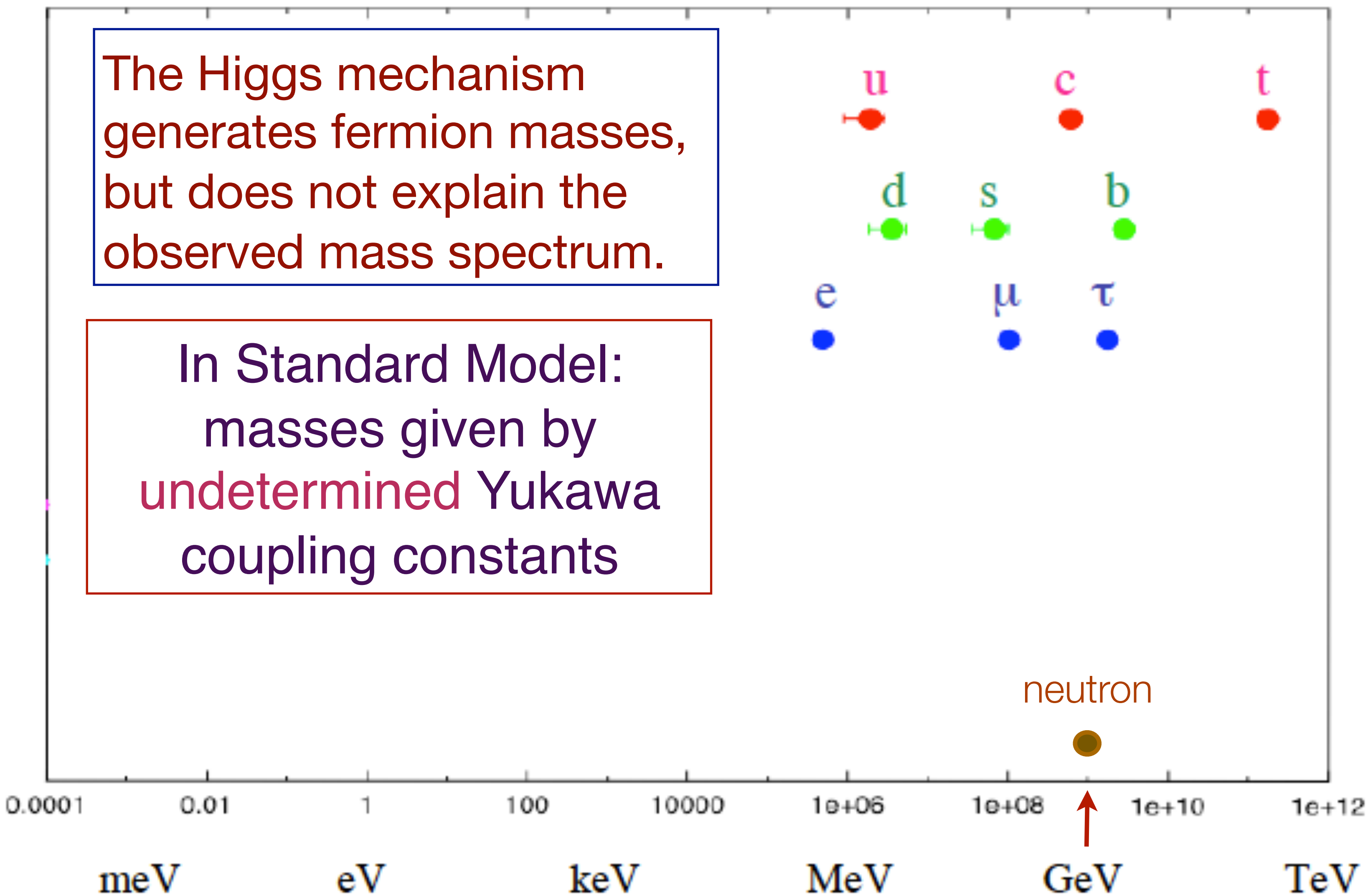
Mass Spectrum of Elementary Particles in SM



Mysteries of Masses in SM



Mysteries of Masses in SM

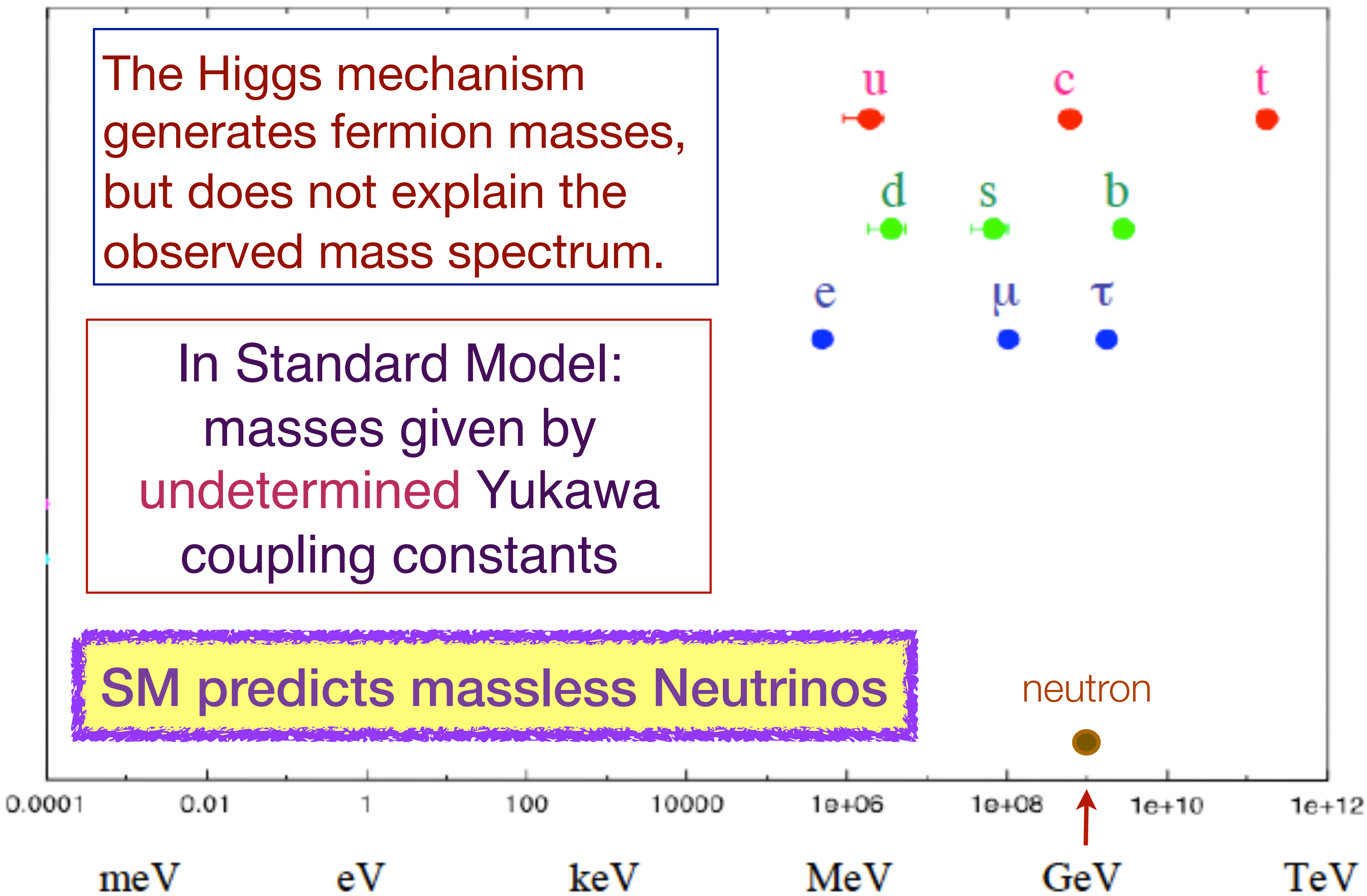


Mysteries of Masses in SM

The Higgs mechanism generates fermion masses, but does not explain the observed mass spectrum.

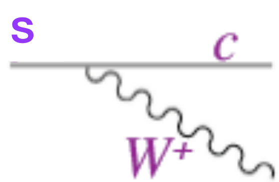
In Standard Model: masses given by undetermined Yukawa coupling constants

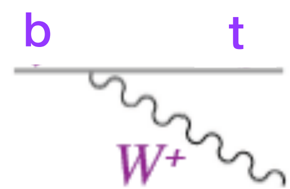
SM predicts massless Neutrinos



Mysteries of Masses and Flavor Mixing in SM

- Charged current weak interaction mediated by $W^{\pm}$ gauge boson:





weak eigenstates = mixture of mass eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{cd} & V_{td} \\ V_{us} & V_{cs} & V_{ts} \\ V_{ub} & V_{cb} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

mass eigenstates — CKM matrix — weak eigenstates

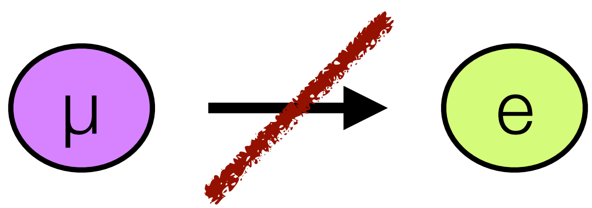
CKM matrix → 3 mixing angles + 1 phase

Cabibbo, 1963;
Kobayashi, Maskawa, 1973

Nobel prize to KM in 2008

Mysteries of Masses and Flavor Mixing in SM

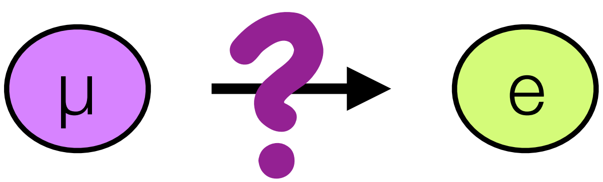
- Neutrino Masses are degenerate (all zero)
  - mass eigenstates = weak eigenstates
- Accidental symmetries in SM
  - lepton flavor numbers: L_e, L_μ, L_τ
  - no processes cross family lines in lepton sector
    - As a result
      - no neutrino oscillation
      - lepton flavor violation decays forbidden



  - total lepton number conserved: $L = L_e + L_\mu + L_\tau$

Neutrino Oscillation ⇒ Massive Neutrinos

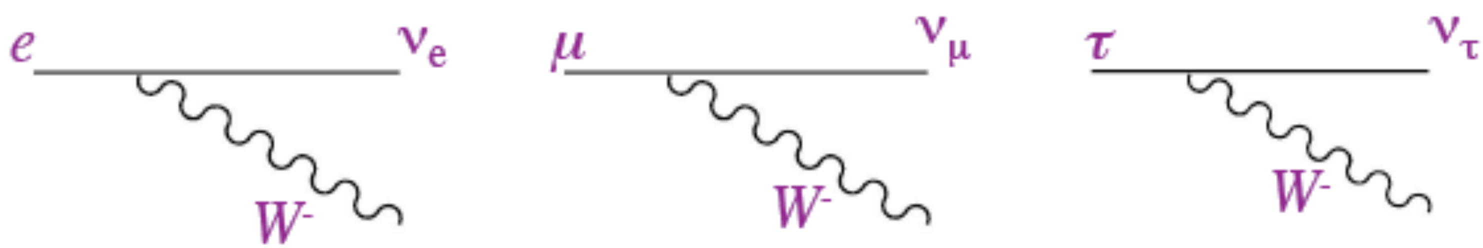
- Neutrino Masses are non-degenerate (at least two are non-zero)
  - mass eigenstates ≠ weak eigenstates
- Accidental symmetries in SM
  - Broken lepton flavor numbers: L_e, L_μ, L_τ
  - Processes cross family lines in lepton sector now possible
    - As a result
      - neutrino oscillation ✔
      - lepton flavor violation decays?



- total lepton number? $L \overset{?}{\neq} L_e + L_\mu + L_\tau$ ⟷

What if Neutrinos Have Mass?

- Similar to the quark sector, there can be a mismatch between mass eigenstates and weak eigenstates
- weak interactions eigenstates: ν_e, ν_μ, ν_τ



- mass eigenstates: ν_1, ν_2, ν_3
- Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix

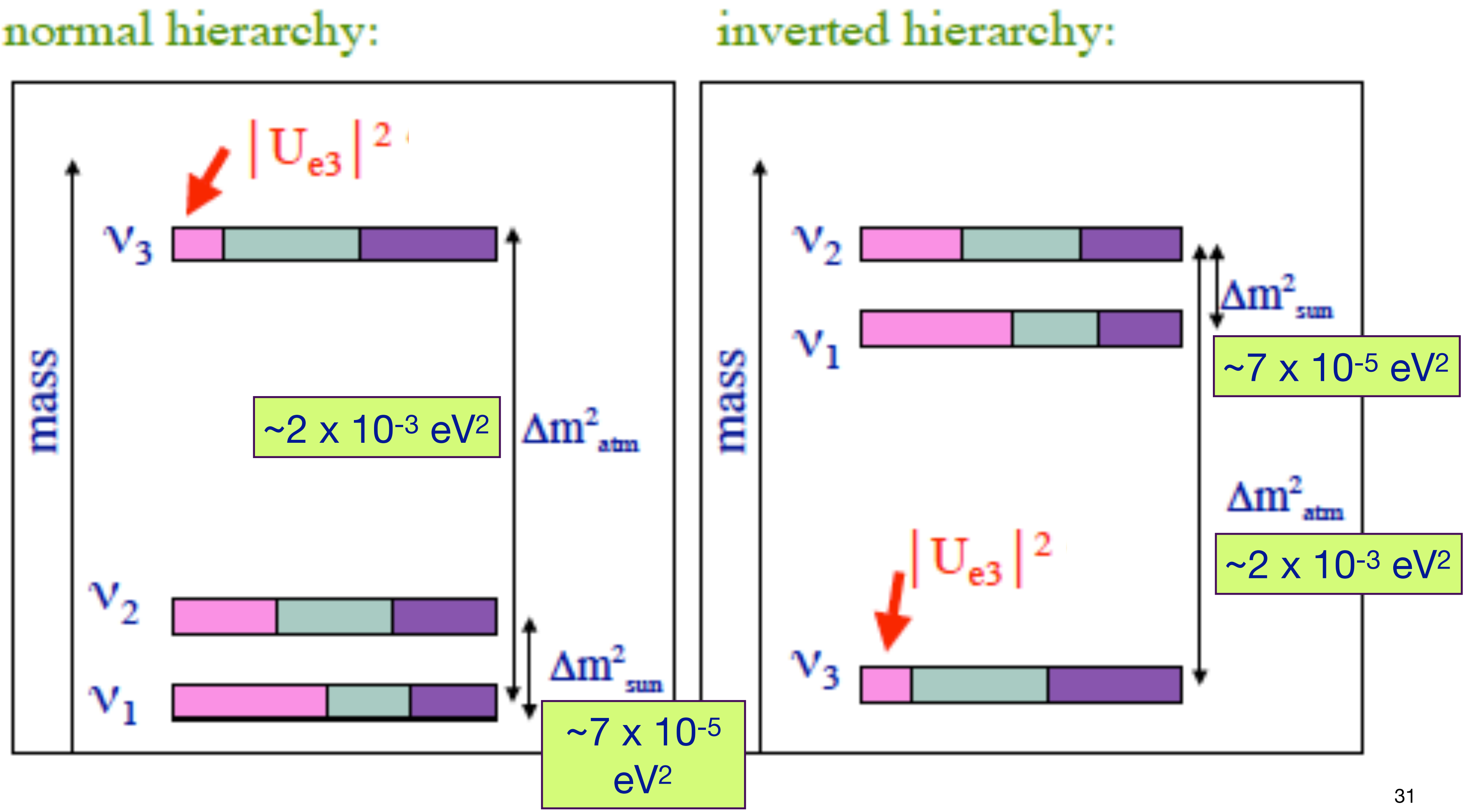
Maki, Nakagawa, Sakata, 1962 ;
Pontecorvo, 1967

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

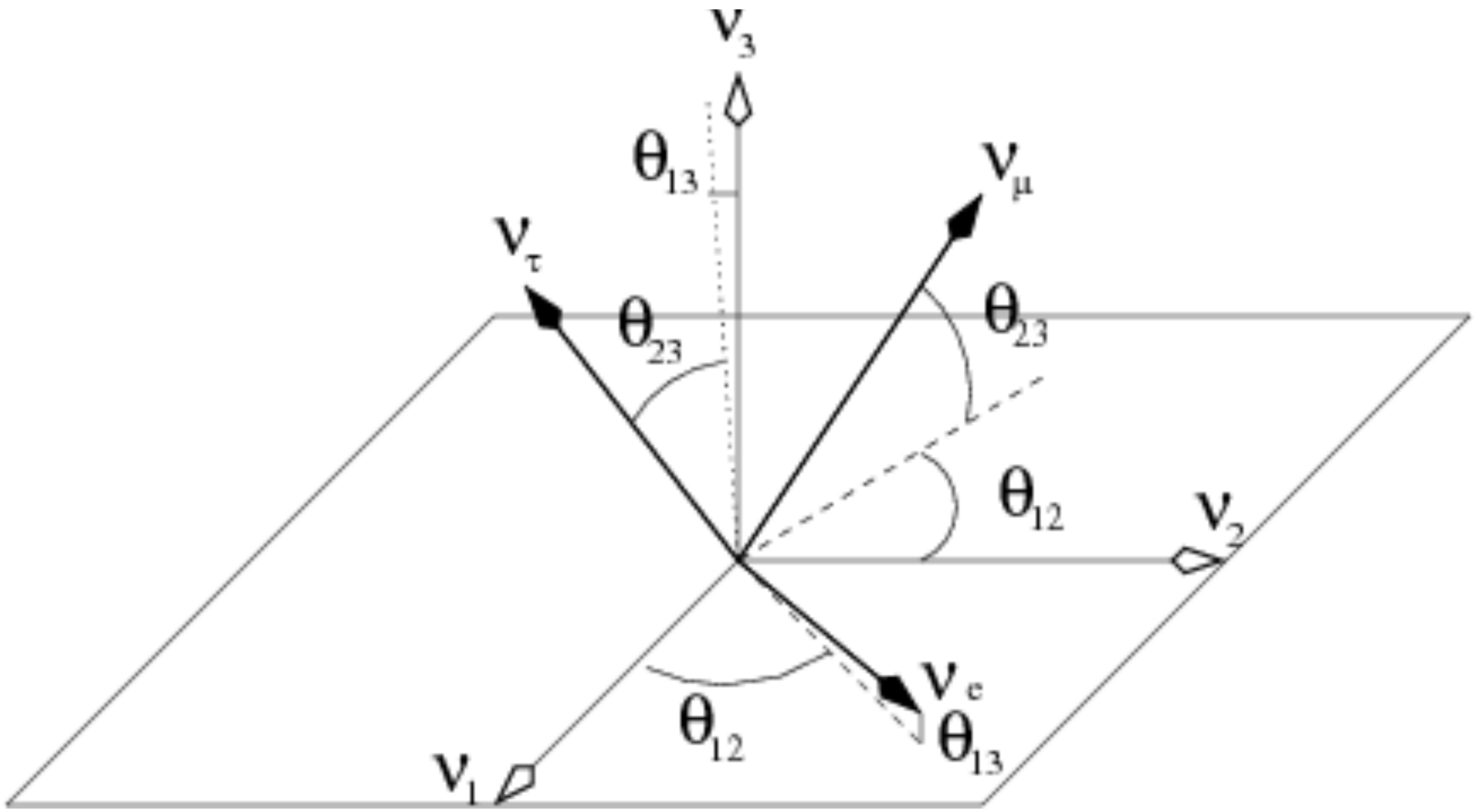
→ 3 mixing angles
+ 1 (3) phase(s) for
Dirac (Majorana)
neutrinos

Where Do We Stand?

- The known knowns:



The Known Knowns



Fogli, Lisi, Marrone, Montanino, Palazzo (2014)

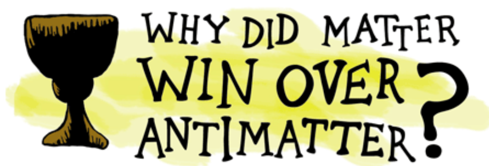
[θ^{lep}_{23} ~ 41.2°] [θ^{lep}_{12} ~ 33.7°] [θ^{lep}_{13} ~ 8.80°]

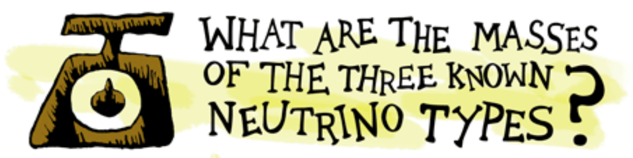
Open Questions - Neutrino Properties

- ☞ **Majorana vs Dirac?**
- ☞ **CP violation in lepton sector?**
- ☞ **Absolute mass scale of neutrinos?**
- ☞ **Mass ordering: sign of (Δm_{13}^2)?**
- ☞ **Sterile neutrino(s)?**
- ☞ **Precision: $\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, $\theta_{23} = \pi/4$?**

a suite of current and upcoming experiments to address these puzzles

Open Questions - Neutrino Properties





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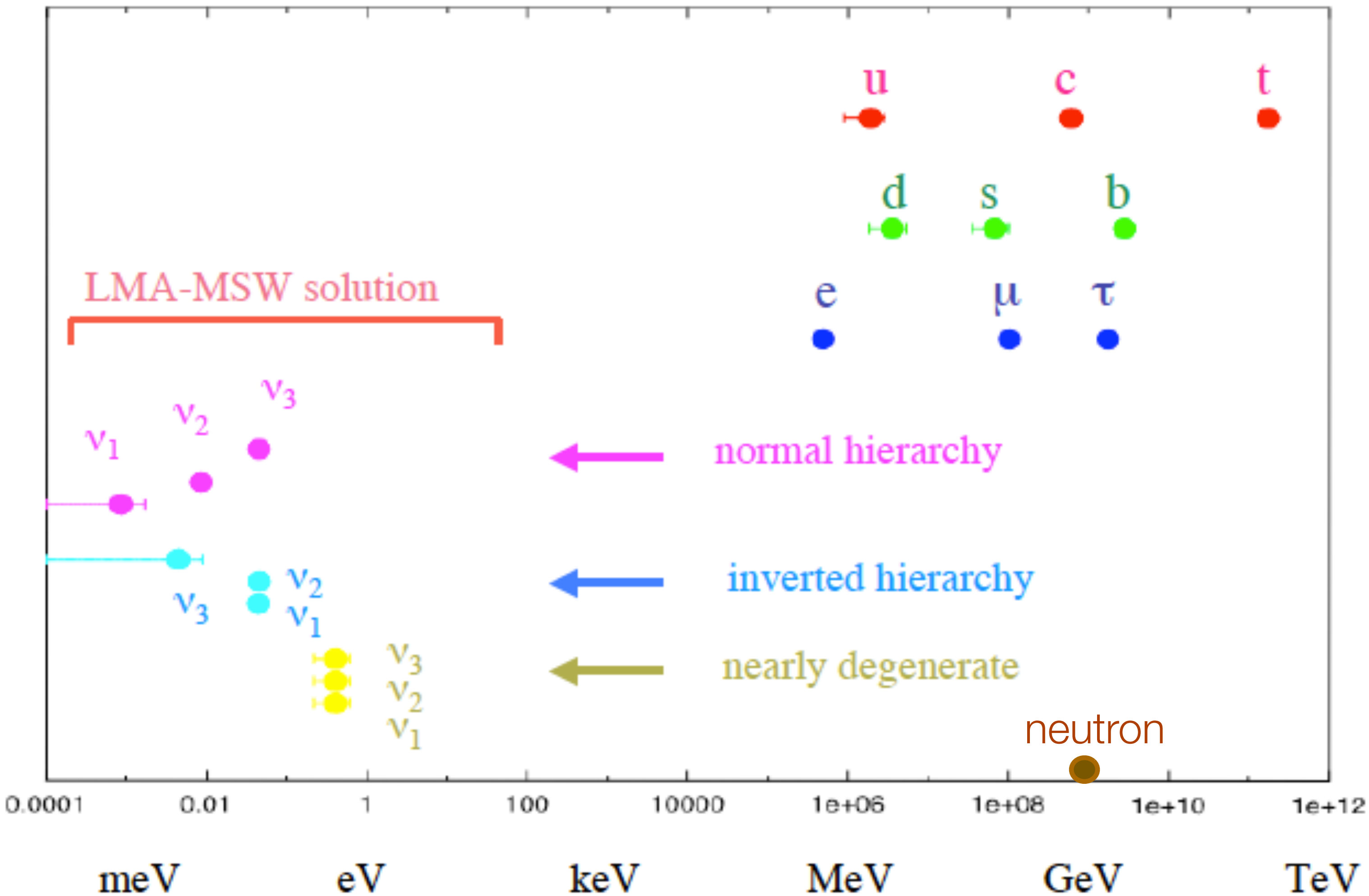
a suite of current and upcoming experiments to address these puzzles

To understand these properties
⇒ BSM Physics

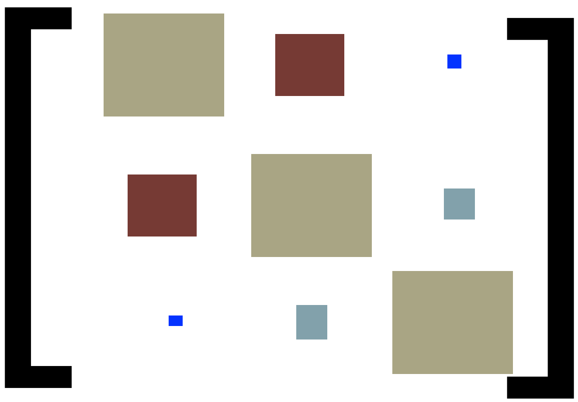
Open Questions - Theoretical

☞ Smallness of neutrino mass: $m_\nu \ll m_{e,\,u,\,d}$



Open Questions - Theoretical

☞ Flavor structure:

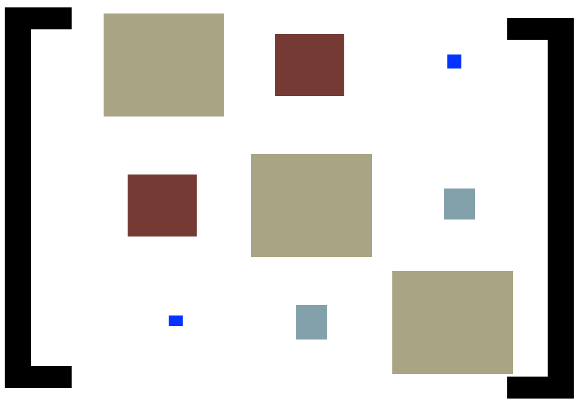


quark mixing

leptonic mixing

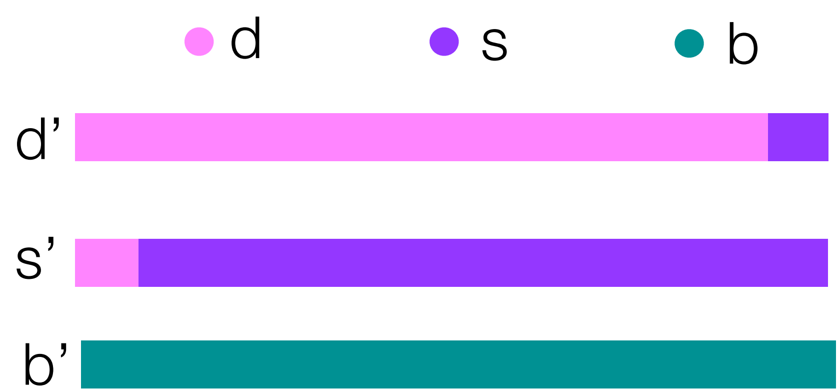
Open Questions - Theoretical

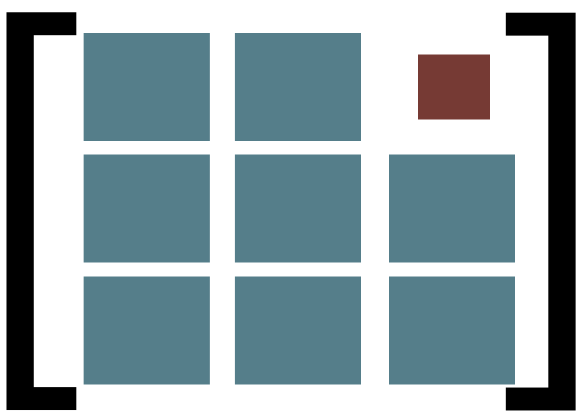
☞ Flavor structure:



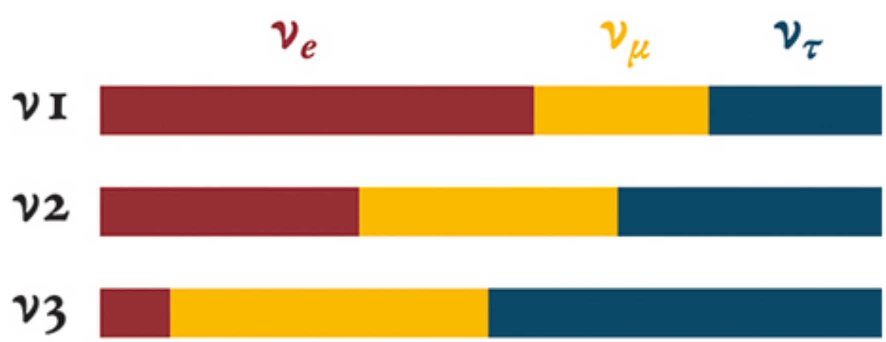
quark mixing

weak interaction eigenstates





leptonic mixing



mass eigenstates

Fermion mass and hierarchy problem ➡ Many (22) free parameters in the Yukawa sector of SM

Where do fermion mass hierarchy, flavor mixing, and CP violation come from?

Where do fermion mass hierarchy, flavor mixing, and CP violation come from?

Is there a simpler organization principle?

Where do fermion mass hierarchy, flavor mixing, and CP violation come from?

Is there a simpler organization principle?

Where do neutrinos get their masses?

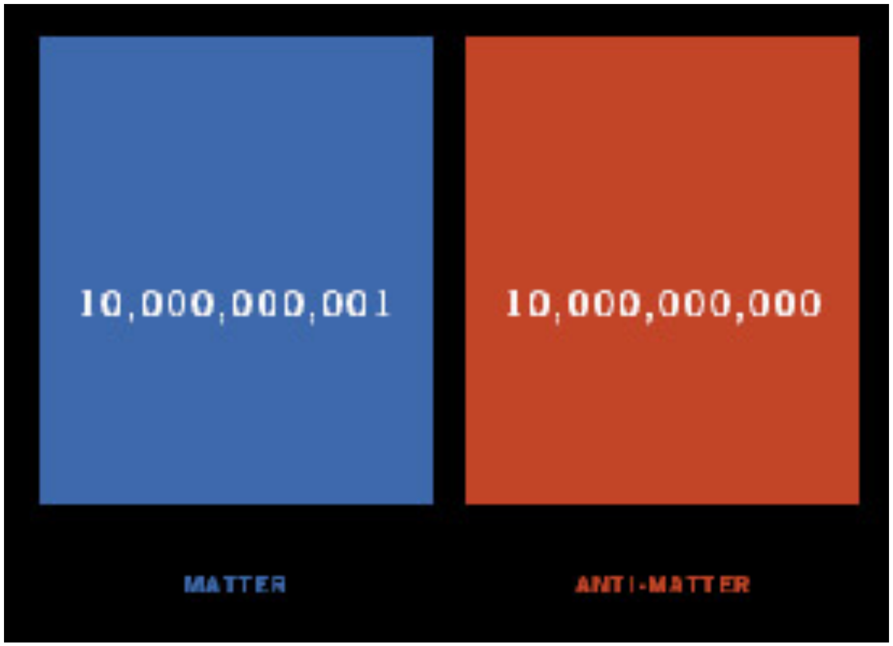
Where do fermion mass hierarchy, flavor mixing, and CP violation come from?

Is there a simpler organization principle?

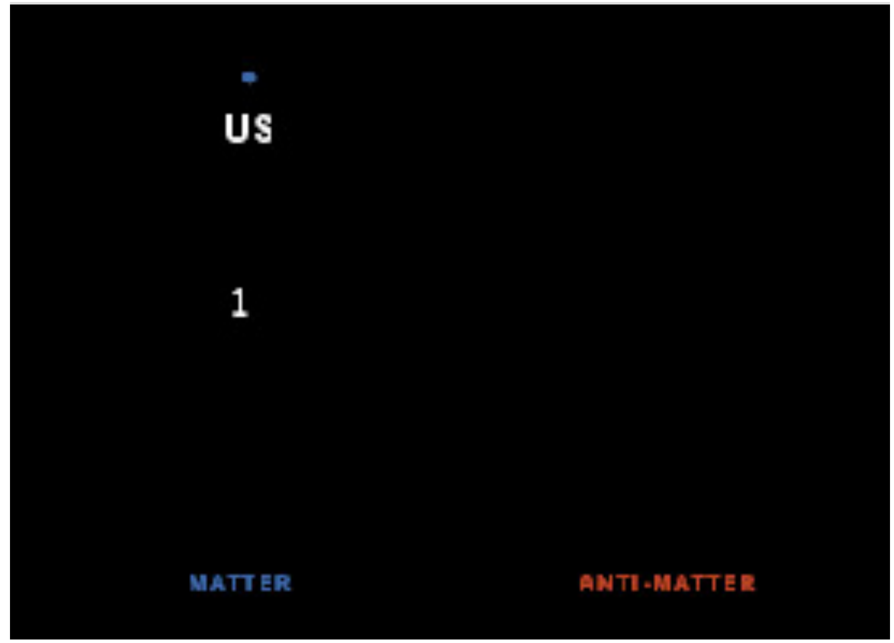
Where do neutrinos get their masses?

Is it the Higgs or something else that gives neutrino masses?

Matter-Antimatter Asymmetry



Early Universe



Universe Now

[Picture credit: H. Murayama]

What is the origin of matter antimatter asymmetry? Why do we exist?

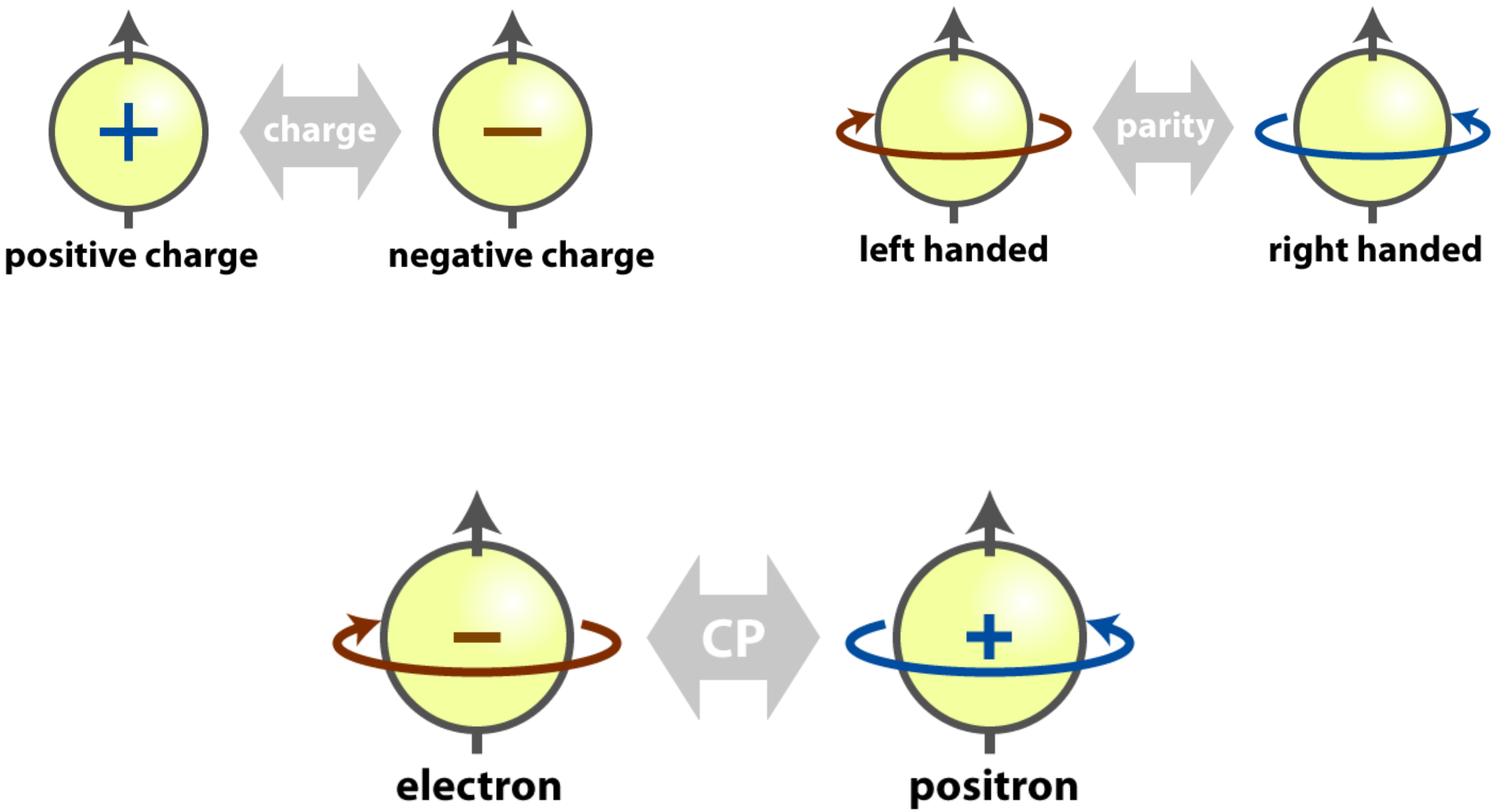
Sakharov Conditions for Baryogenesis

Bayon Number Violation

CP (Charge-Parity) Violation

Out-of-equilibrium Processes

CP Violation



What is the origin of matter antimatter asymmetry? Why do we exist?

SM: CP violation in quark too small

What is the origin of matter antimatter asymmetry? Why do we exist?

Neutrinos may play an important role in generating the matter-antimatter asymmetry

$\Rightarrow$ Leptonic CP violation

(Time Reversal Symmetry Breaking)

Why are neutrinos light? Seesaw Mechanism

- Adding the right-handed neutrinos:

Minkowski, 1977; Yanagida, 1979; Gell-Mann, Ramond, Slansky, 1979; Mohapatra, Senjanovic, 1981

$$\begin{pmatrix} \nu_L & \nu_R \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

$$m_\nu \sim m_{light} \sim \frac{m_D^2}{M_R} << m_D$$

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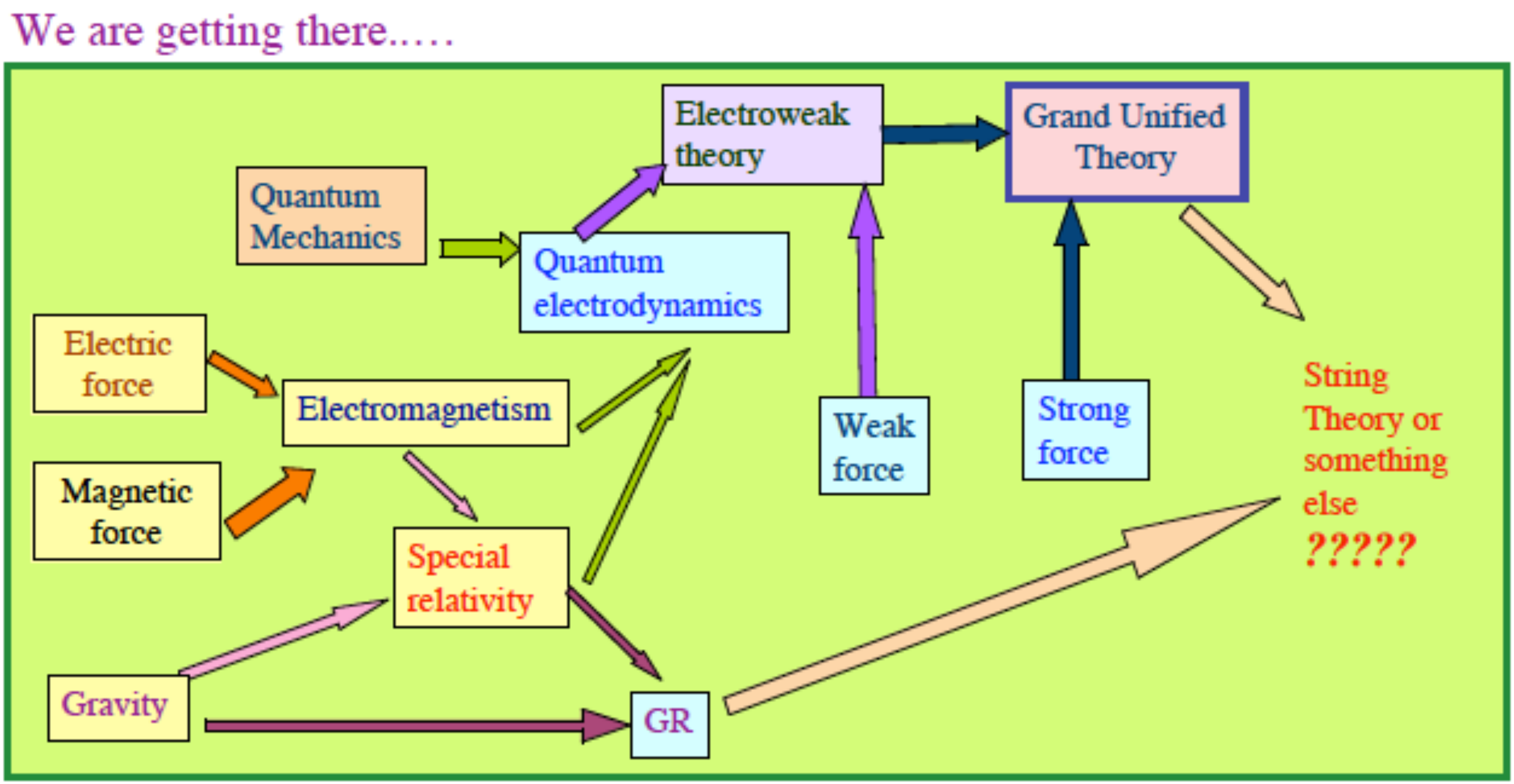
For $m_{\nu_3} \sim \sqrt{\Delta m^2_{atm}}$

If $m_D \sim m_t \sim 180\ \ GeV$

$\Rightarrow$ $M_R \sim 10^{15}\ GeV$ (GUT !!)

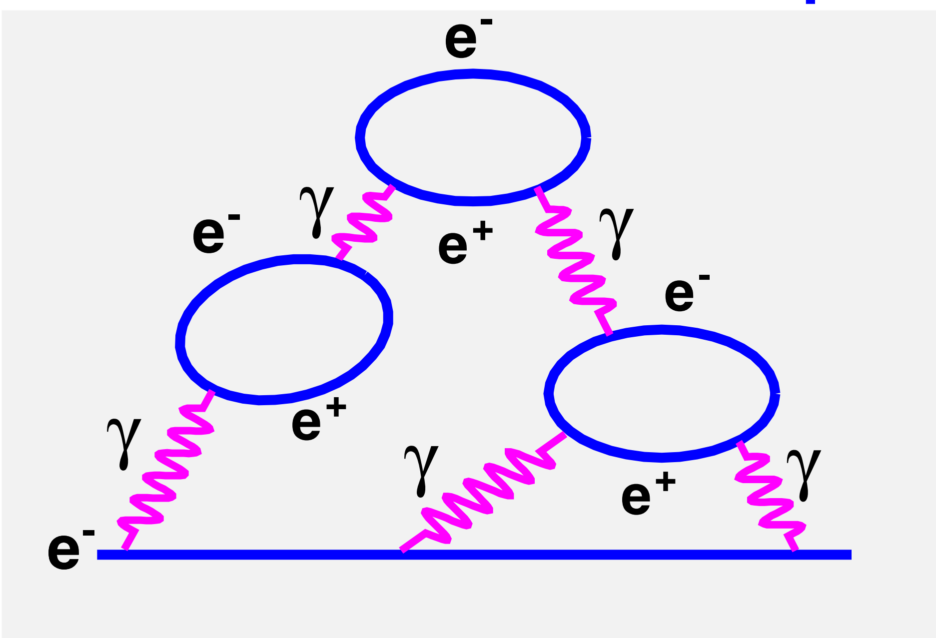
Ultimate Goal of Grand Unification

- Maxwell: electric and magnetic forces are different aspects of electromagnetism
- Einstein: early attempt to unify electric force and gravity



Coupling Constants Run!

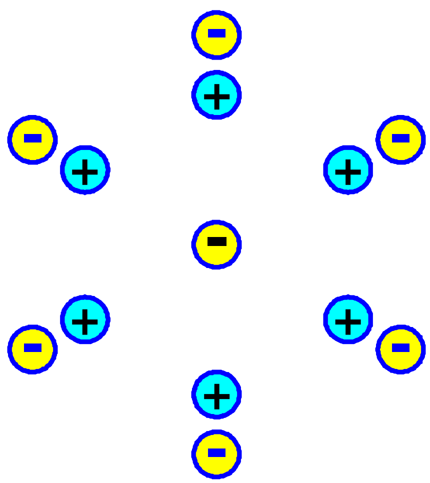
Consider a free electron: **Quantum fluctuations lead to a 'cloud' of virtual electron/positron pairs**



this is just one of many (an infinite set) such diagrams.

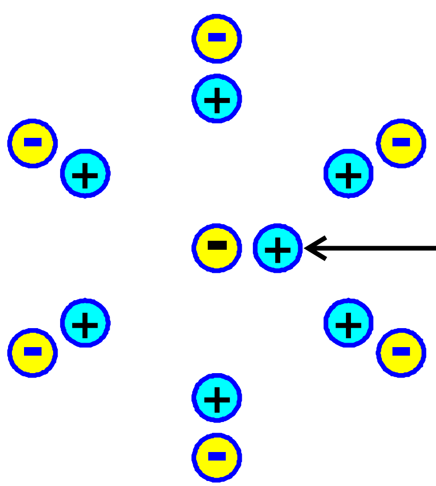
[Slide credit: Mark Thomson]

Coupling Constants Run!



At large R test charge sees screened e^- charge

Test Charge



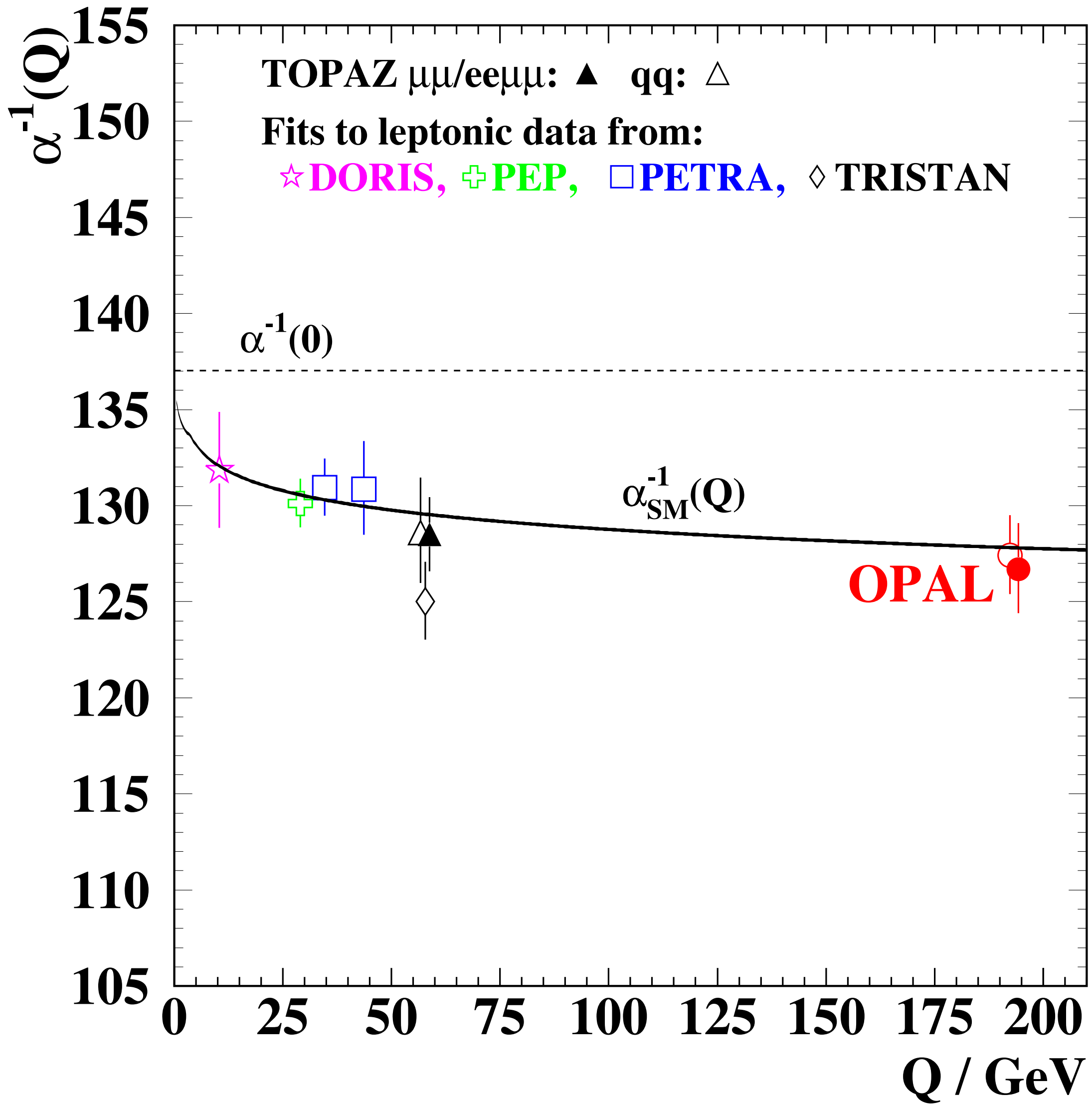
At small R test charge sees bare e^- charge

Test Charge

[Slide credit: Mark Thomson]

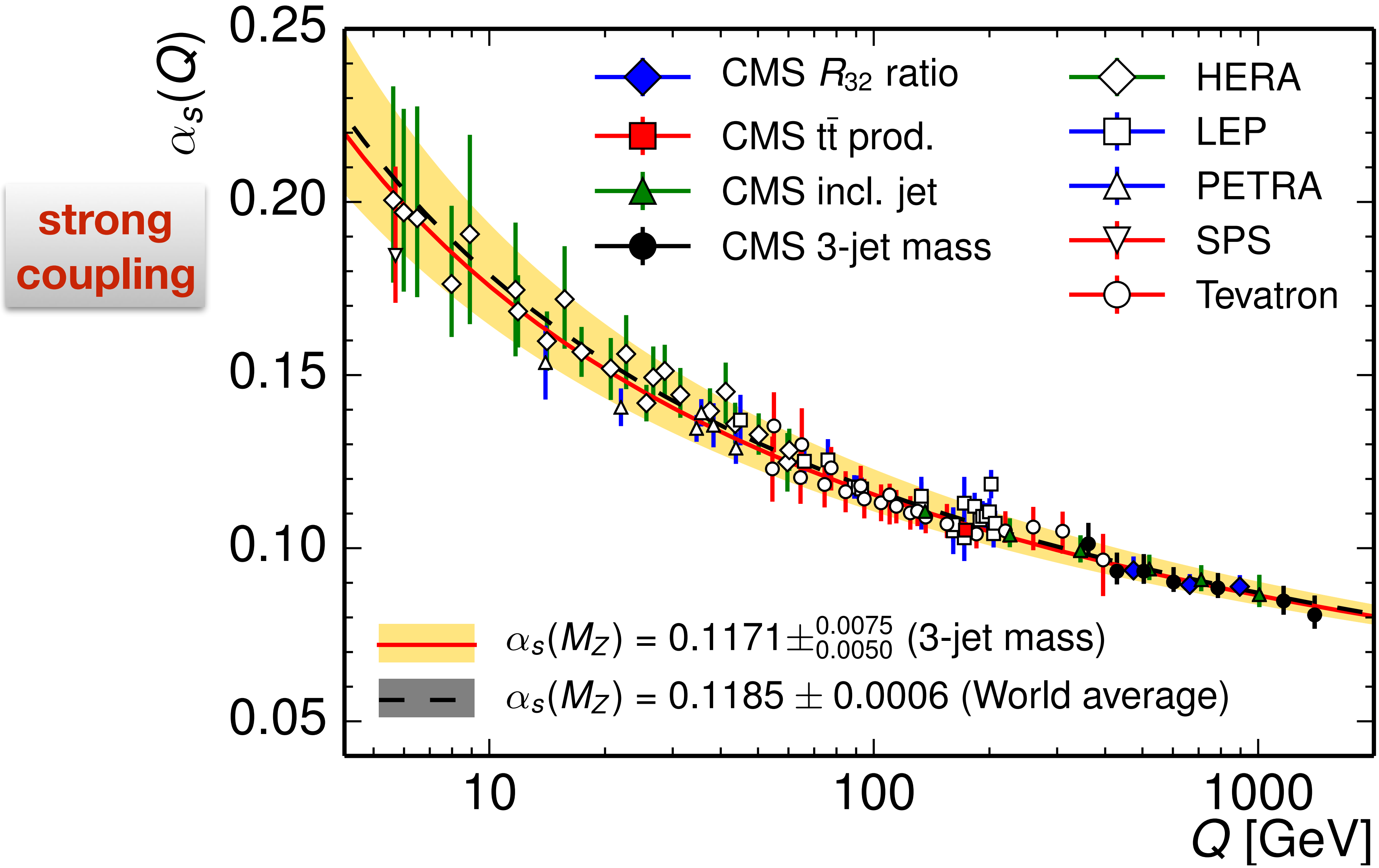
Coupling Constants Run!

EM coupling



[Slide credit: Mark Thomson]

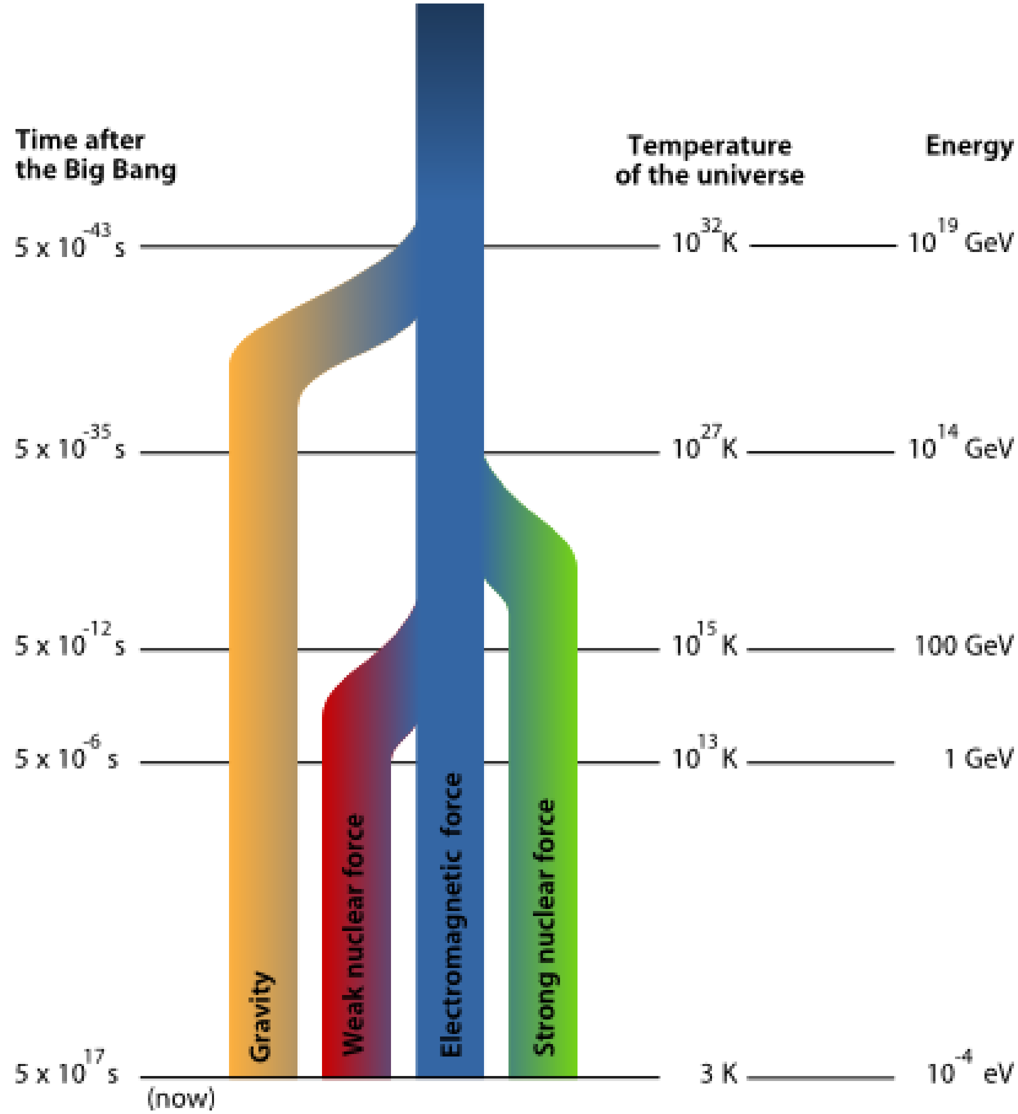
Coupling Constants Run!

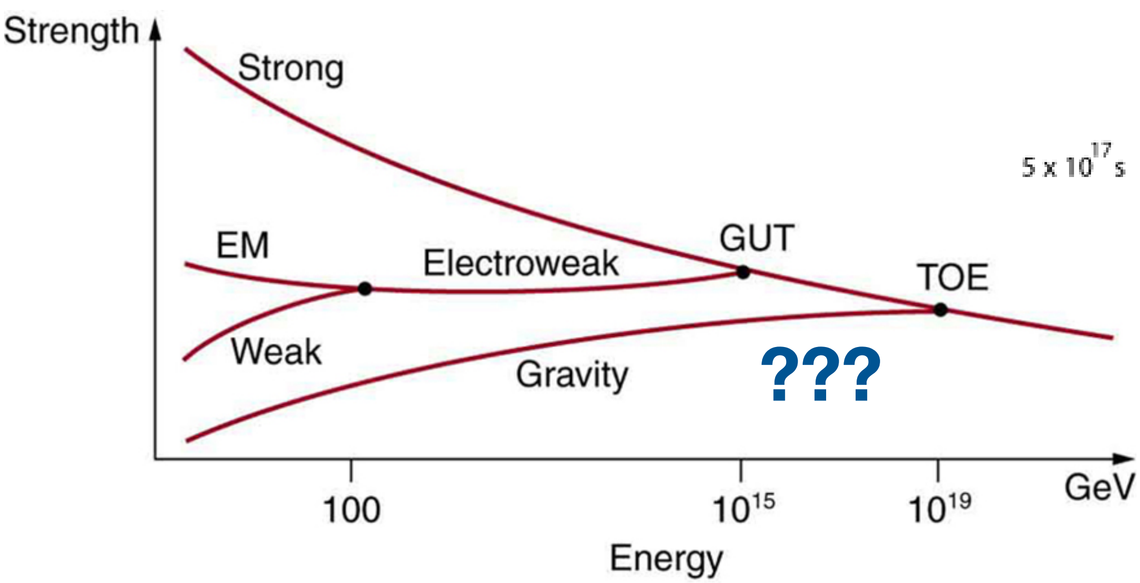


Electroweak Unification

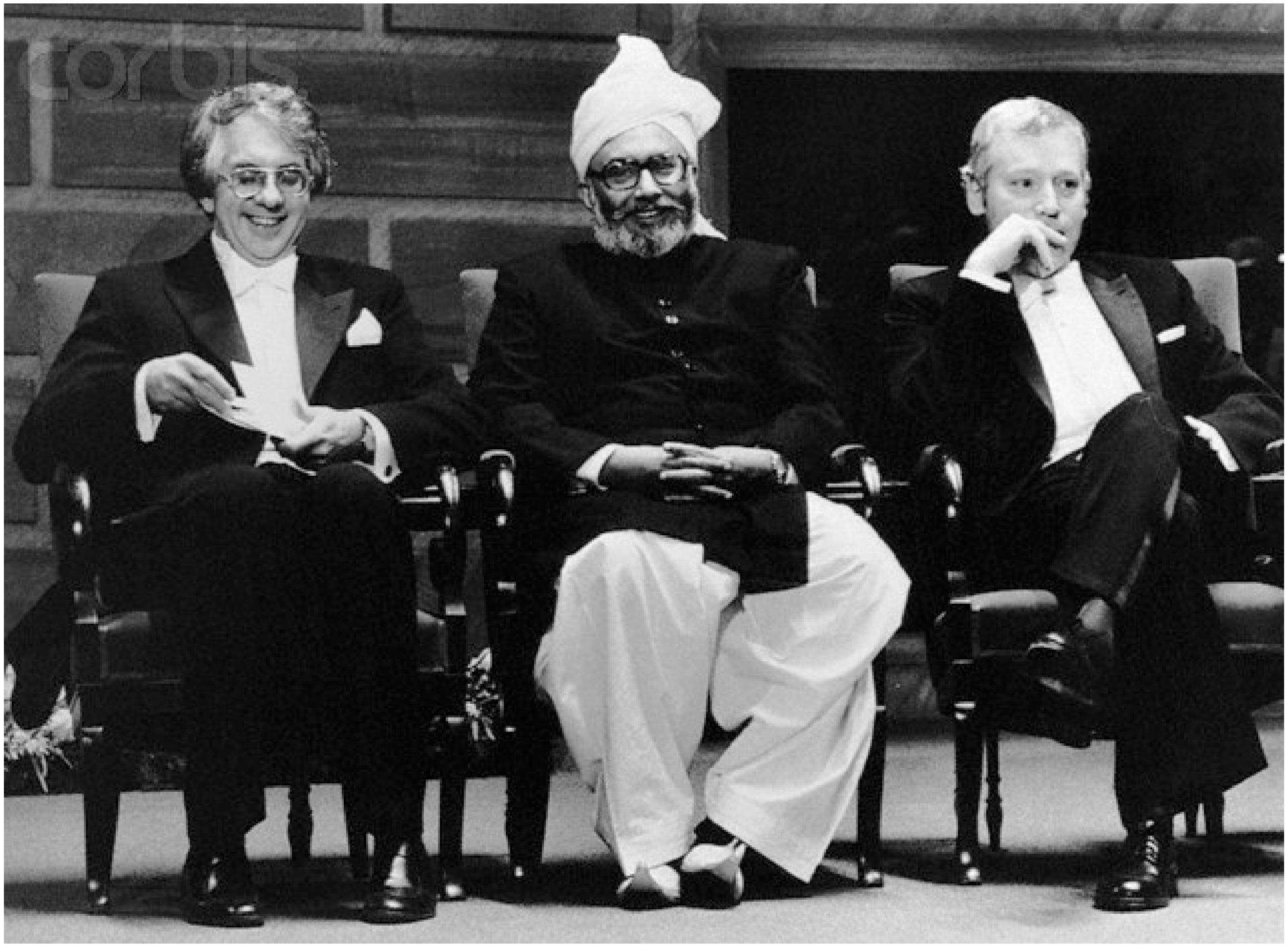
10^{-17}m: **weak force ~ 10^{-4} EM force**

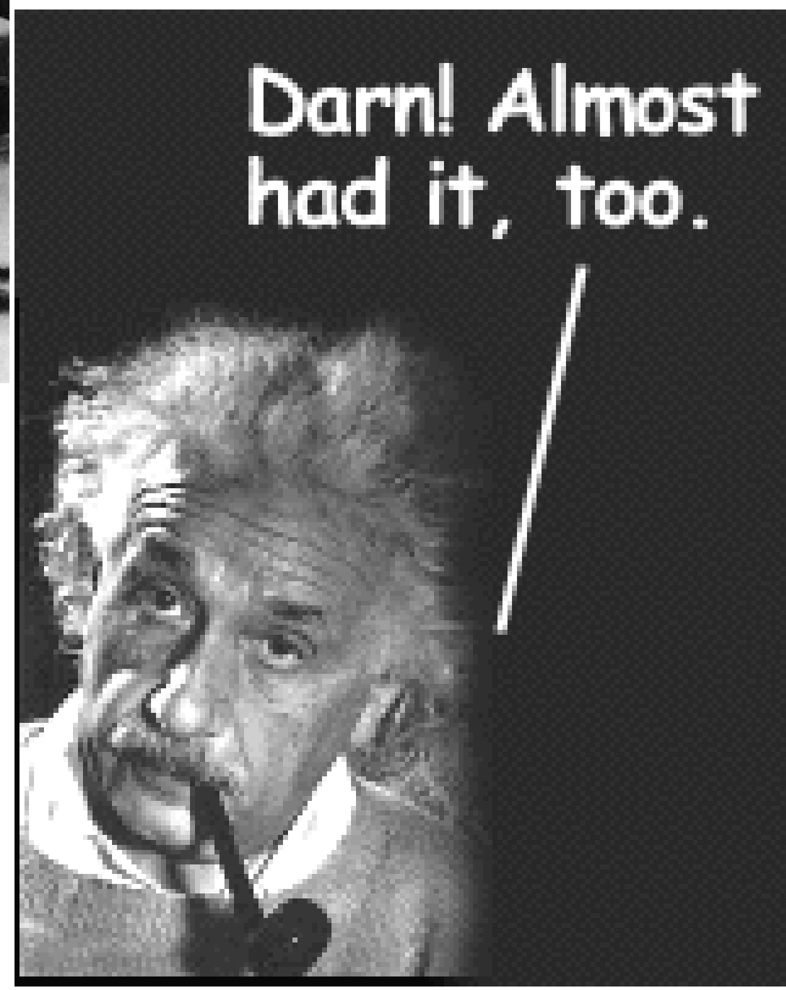
10^{-18}m: **weak force ~ EM force**





Glashow, Salam, Weinberg





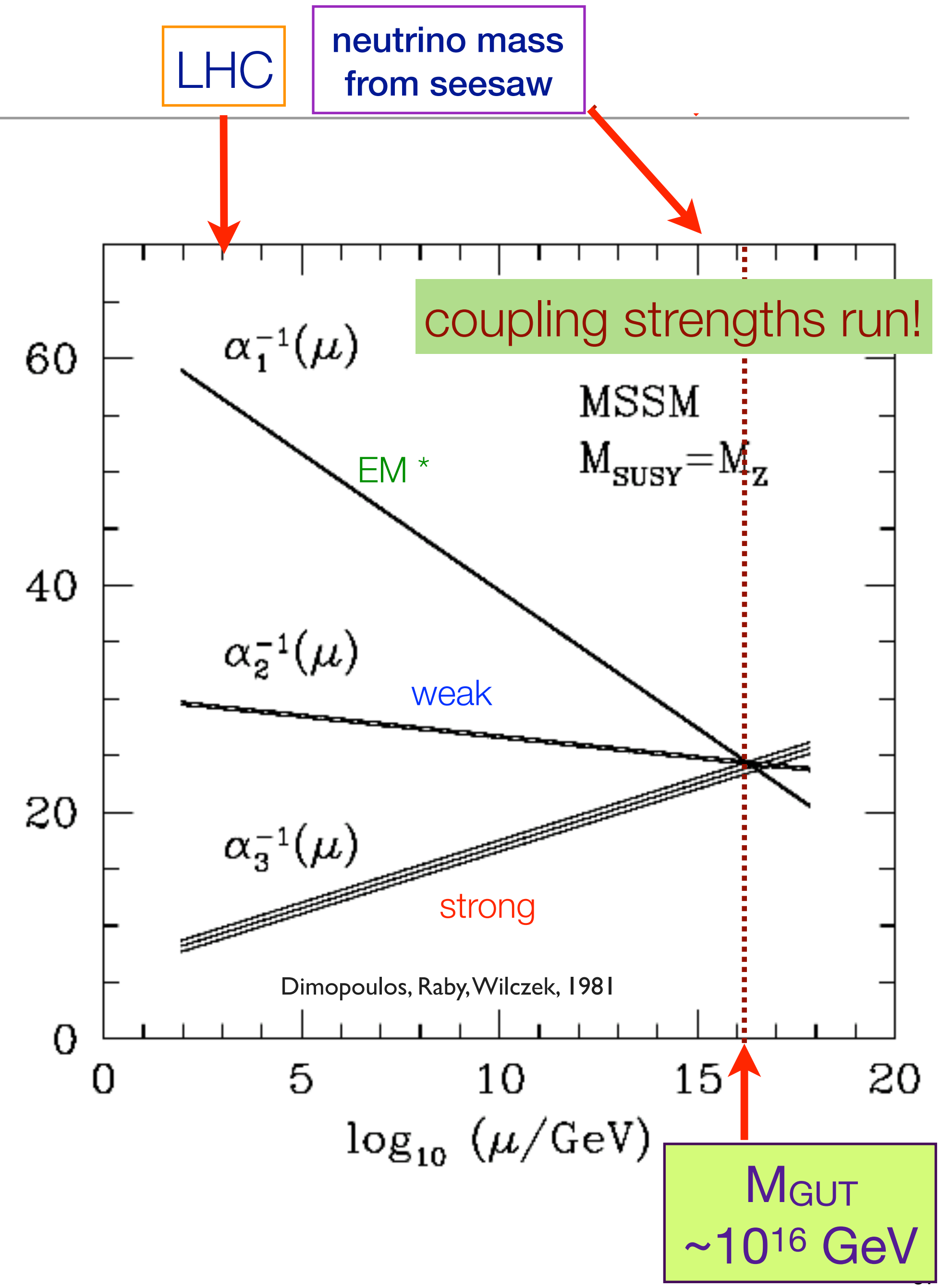
Glashow, Salam, Weinberg
Nobel Prize in Physics 1979

Grand Unification

- Motivations:
  - Electromagnetic, weak, and strong forces have very different strengths
  - But their strengths become the same at 10^{16} GeV if there is supersymmetry

    10^{16} GeV ~ 10^{-30} meters
  - To obtain $m_\nu \sim (\Delta m^2_{atm})^{1/2}$,

    $m_D \sim m_{top}$, $M_R \sim 10^{15}$ GeV
  - **Neutrino oscillations probe physics at unification scale!**



ANNALS OF PHYSICS **93**, 193–266 (1975)

Unified Interactions of Leptons and Hadrons*

HARALD FRITZSCH AND PETER MINKOWSKI

California Institute of Technology, Pasadena, California 91125

Received March 19, 1975

It is suggested that a unifying description of leptons and hadrons can be obtained within a nonabelian gauge theory where the gauge group is a symmetry group of a set of massless elementary fermions (leptons, quarks). We investigate the consequences of such an approach for the strong, electromagnetic, and weak interactions. We study both gauge theories with and without fermion number conservation, e.g., theories based on the groups $SU_n \times SU_n$ ($n = 8, 12, 16$) and SO_n ($n = 10, 14$).

1. INTRODUCTION

In this paper, we show how several hypotheses proposed during the last few years about nonabelian gauge theories for the weak and electromagnetic interactions [1], permanently confined colored quarks [2, 3] and color octet vector gluons [4, 5] can be combined to give a unified picture of the strong, electromagnetic, weak, and other ineractions. Among the ideas used to construct interacting field theories the nonabelian (Yang–Mills [6]) gauge principle seems to be singled out by nature. The reason for this preference is not yet well understood,

Grand Unification

Georgi, Glashow, 1974

SO(10):

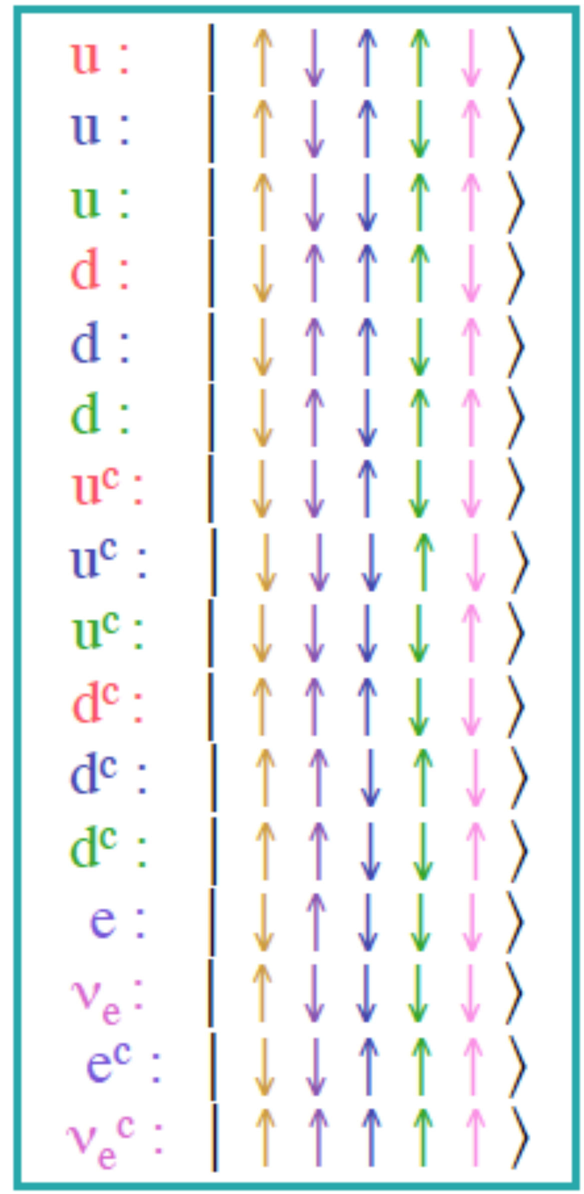
Fritzsch, Minkowski, 1975

quarks and leptons are close relatives

matter fields come in 3 copies

charge quantization can be understood

$16 = 10 + 5^* + 1$



Grand Unification

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$16 = 10 + 5^* + 1$

RH neutrino
predicted

u :	| ↑ ↓ ↑ ↑ ↓ ⟩
u :	| ↑ ↓ ↑ ↓ ↑ ⟩
u :	| ↑ ↓ ↓ ↑ ↑ ⟩
d :	| ↓ ↑ ↑ ↑ ↓ ⟩
d :	| ↓ ↑ ↑ ↓ ↑ ⟩
d :	| ↓ ↑ ↓ ↑ ↑ ⟩
u^c :	| ↓ ↓ ↑ ↓ ↓ ⟩
u^c :	| ↓ ↓ ↓ ↑ ↓ ⟩
u^c :	| ↓ ↓ ↓ ↓ ↑ ⟩
d^c :	| ↑ ↑ ↑ ↓ ↓ ⟩
d^c :	| ↑ ↑ ↓ ↑ ↓ ⟩
d^c :	| ↑ ↑ ↓ ↓ ↑ ⟩
e :	| ↓ ↑ ↓ ↓ ↓ ⟩
ν_e :	| ↑ ↓ ↓ ↓ ↓ ⟩
e^c :	| ↓ ↓ ↑ ↑ ↑ ⟩
$\nu_e{}^c$:	| ↑ ↑ ↑ ↑ ↑ ⟩

Seesaw Mechanism Natural in GUTs

- Adding the right-handed neutrinos:

$$\begin{pmatrix}\nu_L & \nu_R\end{pmatrix}\begin{pmatrix}0 & m_D \\ m_D & M_R\end{pmatrix}\begin{pmatrix}\nu_L \\ \nu_R\end{pmatrix}$$

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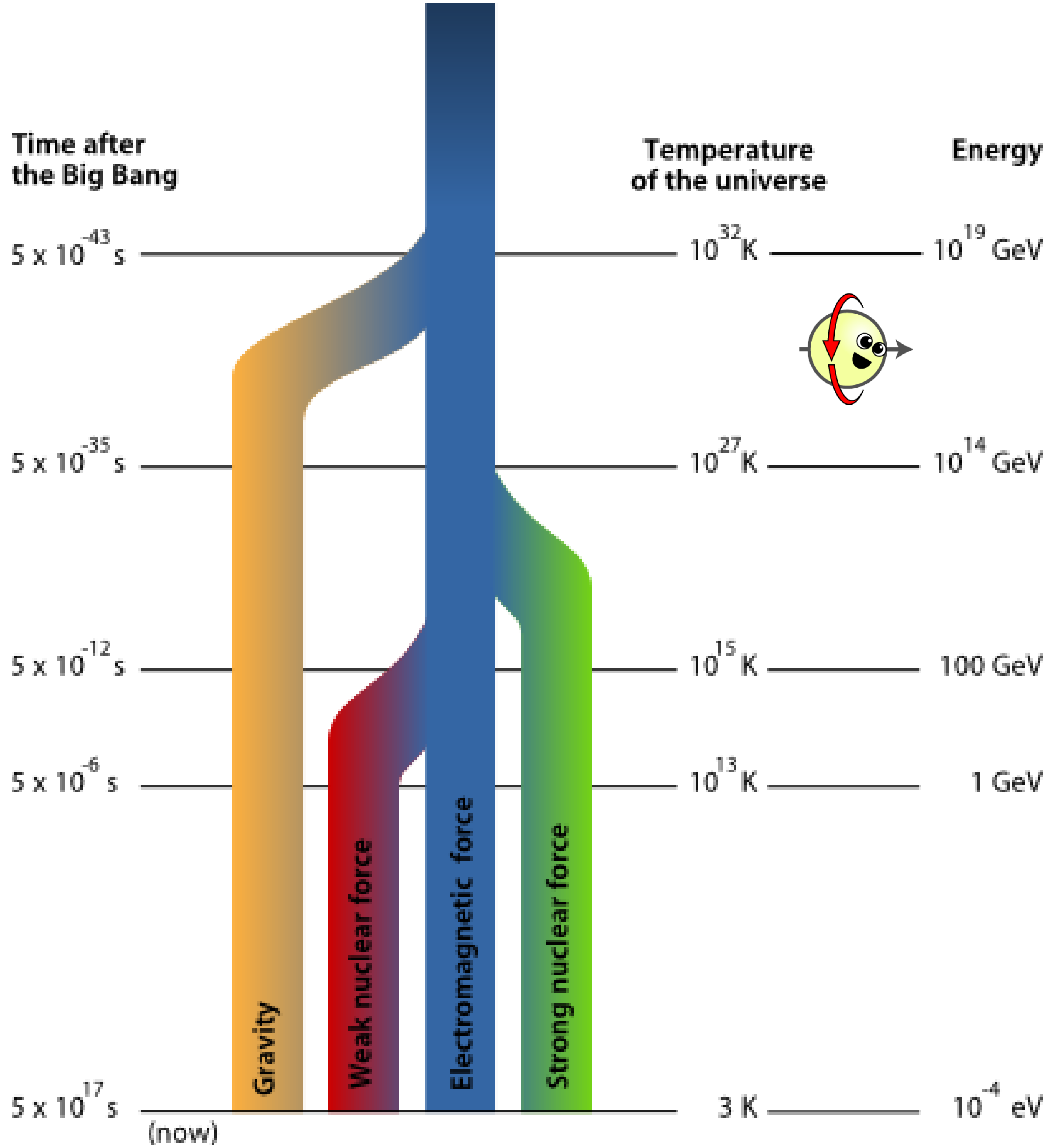
$\Rightarrow$ $M_R \sim 10^{15}\ GeV$ (GUT !!)

Minkowski, 1977; Yanagida, 1979; Gell-Mann, Ramond, Slansky, 1979; Mohapatra, Senjanovic, 1981

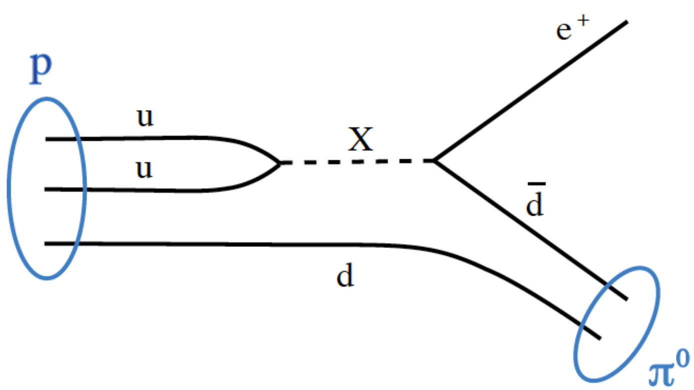
Neutrino Oscillation: Probing Universe at the first 10^{-36} sec

LHC: Probing Universe at the first 10^{-12} sec

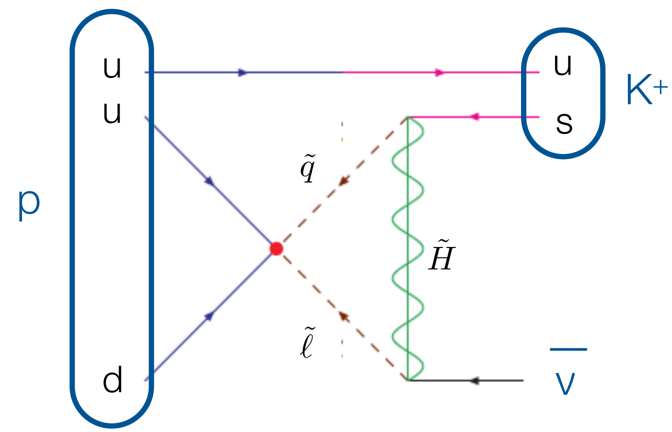


Grand Unification: Proton Decay

- GUT predicts proton decay



SUSY GUTs: additional contributions mediated by superpartners



X: exotic heavy force carriers

$\tilde{H}$ **: color-triplet Higgsinos**

lifetime: $\tau_p \propto M_X^4$

$\tau_p \propto M_{\tilde{H}}^2$

Grand Unification: Proton Decay

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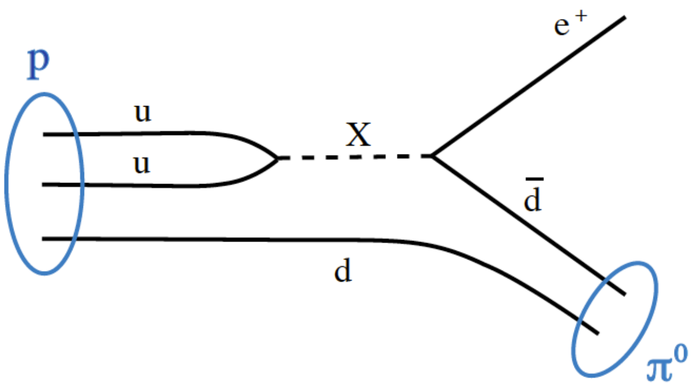
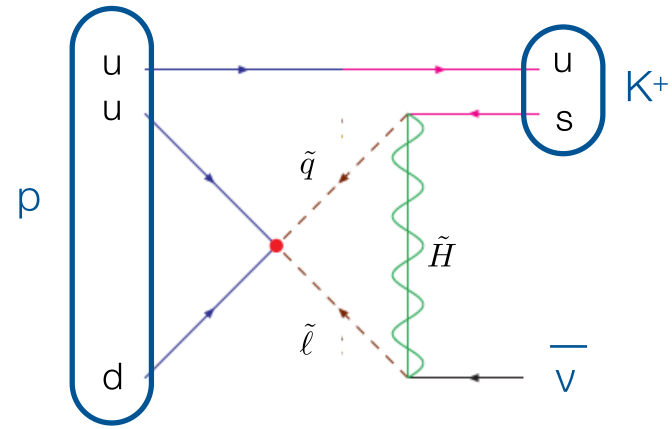


SUSY GUTs: additional contributions mediated by superpartners



X: exotic heavy force carriers

$\tilde{H}$: **color-triplet Higgsinos**

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LArIAT

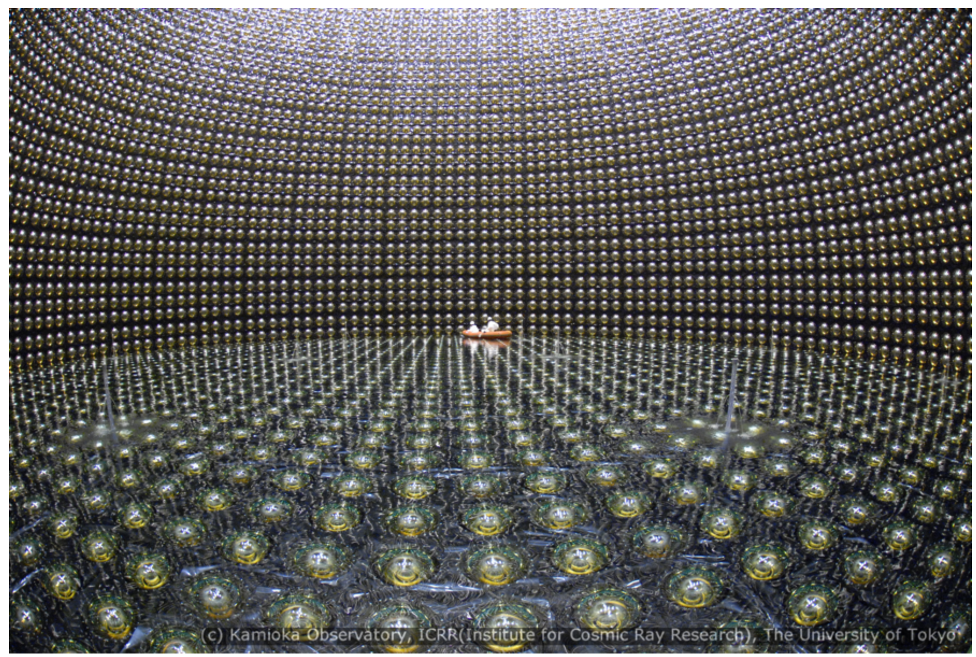
DEEP UNDERGROUND NEUTRINO EXPERIMENT

Grand Unification: Proton Decay

- Experimental limits on proton lifetime:

$\tau(p \to e^+\pi^0) > 8.2 \times 10^{33}$ years (90% CL, SuperK 2009) $\Rightarrow M_X > 5 \times 10^{15}$ GeV

$\tau(p \to \overline{\nu} K^+) > 2.3 \times 10^{33}$ years (90% CL, SuperK 2005) $\Rightarrow M_{\tilde{H}} > 10^{19}$ GeV !!



Grand Unification: Proton Decay

p-decay around the corner?!

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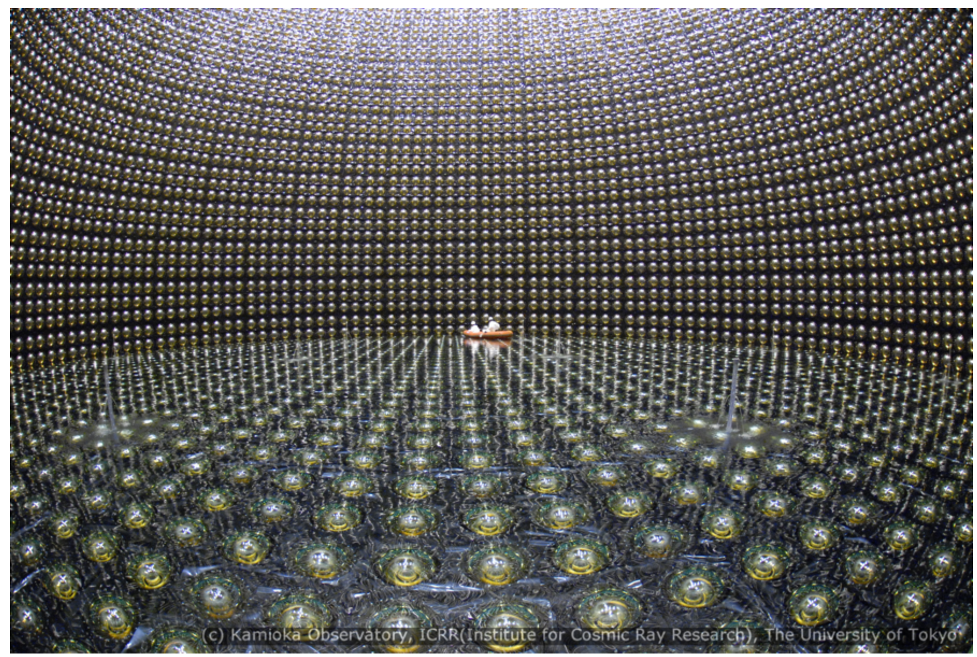

Grand Unification: Proton Decay

Minimal SUSY GUTs under siege?

- Experimental limits on proton lifetime:

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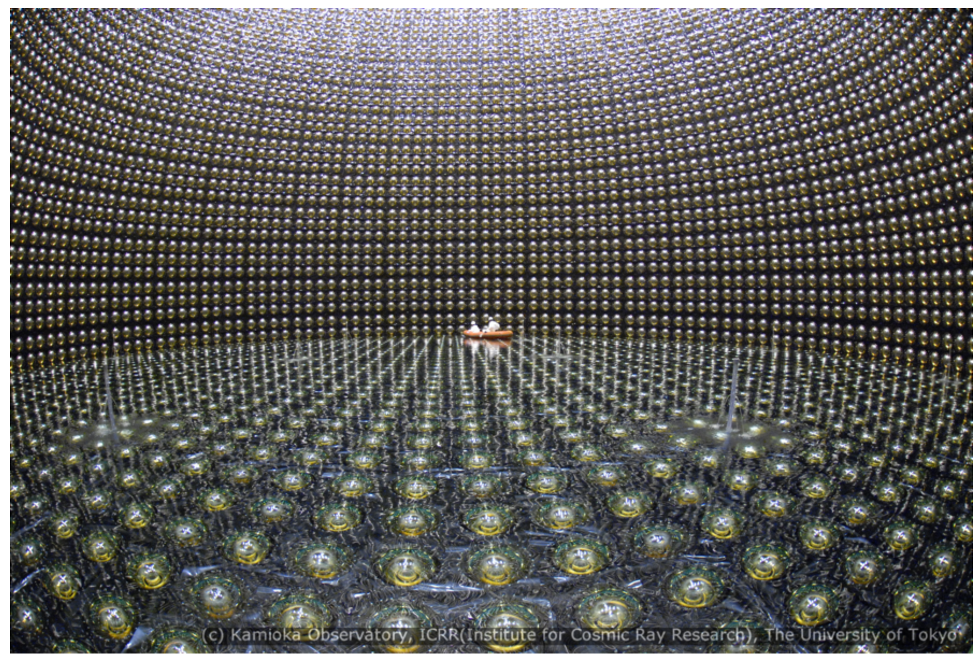

Unique Window into GUT Scale Physics

Neutrino oscillation

Nucleon instability,
Neutron-antineutron oscillation

Worldwide experimental
particle physics efforts

Further Unification ⇒ Sterile Neutrinos

$E_6 \supset SO(10) \supset SU(5) \supset G_{SM} = SU(3) \times SU(2) \times U(1)$

SU(5): $\bar{5}$ + 10 = all SM quarks and leptons in a generation (no RH neutrinos)

SO(10): 16 = ($\bar{5}$ + 10 + 1) of SU(5)

RH neutrino

E6: 27 = (16 + 10 + 1) of SO(10)

can be eV or keV sterile neutrino

Further Unification ⇒ Sterile Neutrinos

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Flavor Structure

anarchy vs symmetry

Symmetry Relations

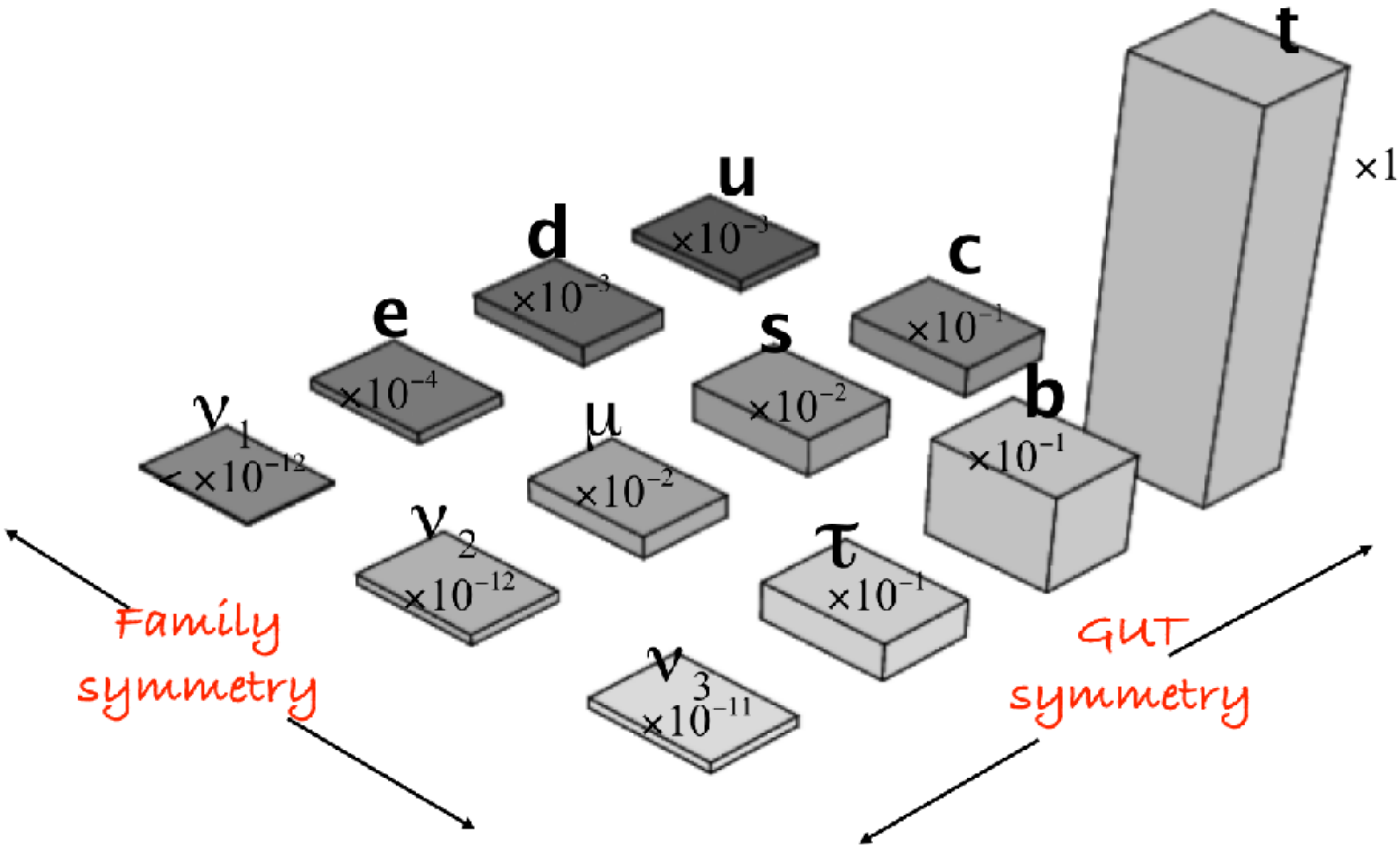
Grand Unified Theories: GUT symmetry

Quarks ↔ Leptons

Family Symmetry:

e-family ↔ muon-family ↔ tau-family

Mass Spectrum of Elementary Particles



Symmetry Relations

Symmetry ⇒ relations among parameters

⇒ reduction in number of fundamental parameters

Symmetry Relations

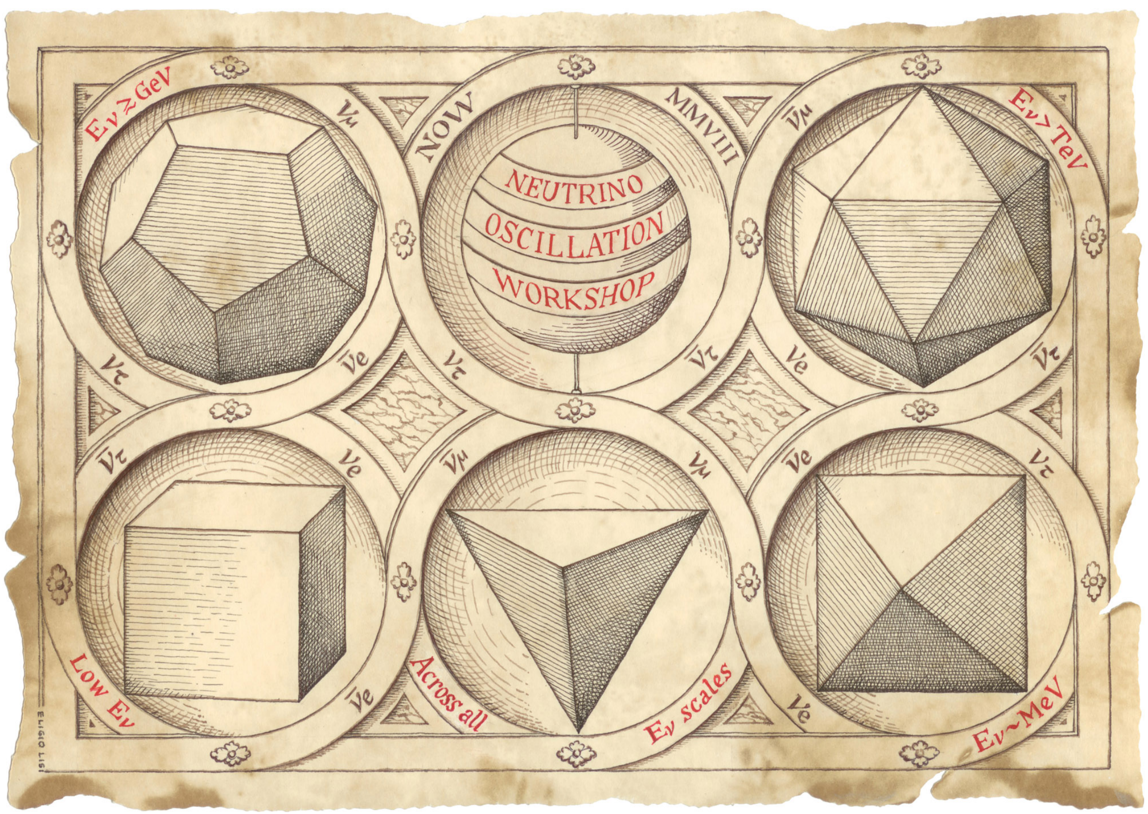
Symmetry ⇒ relations among parameters

⇒ reduction in number of fundamental parameters

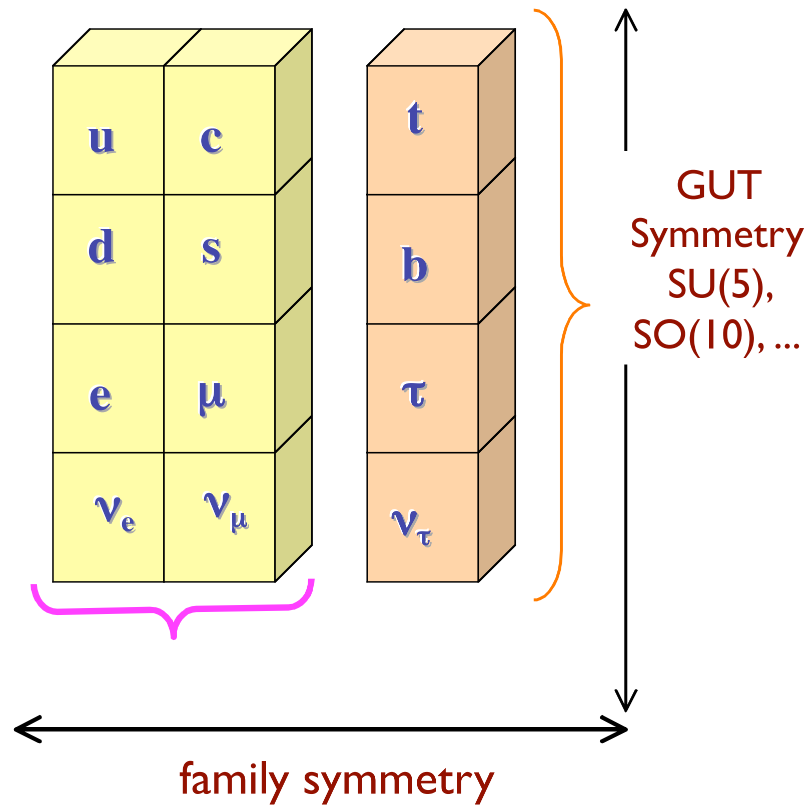
Symmetry ⇒ experimentally testable correlations among physical observables

Origin of Flavor Mixing and Mass Hierarchy

Large neutrino mixing
⇒ discrete family symmetry



[Eligio Lisi for NOW2008]



Tri-bimaximal Neutrino Mixing

- Global Fit (3σ)

$$\sin^2\theta_{23} = 0.437\ (0.374 - 0.626)$$ [$\theta^{lep}_{23} \sim 41.2°$]

$$\sin^2\theta_{12} = 0.308\ (0.259 - 0.359)$$ [$\theta^{lep}_{12} \sim 33.7°$]

$$\sin^2\theta_{13} = 0.0234\ (0.0176 - 0.0295)$$ [$\theta^{lep}_{13} \sim 8.80°$]

- Tri-bimaximal Mixing Pattern

Harrison, Perkins, Scott (1999)

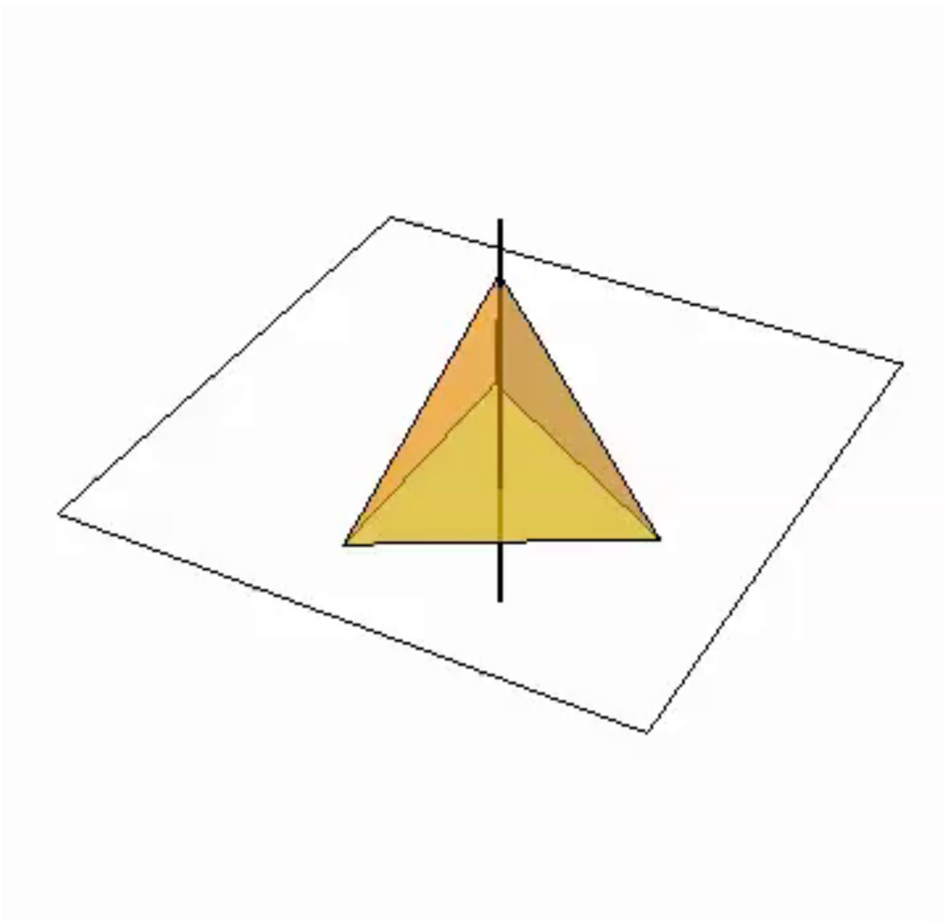
$$U_{TBM} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & -\sqrt{1/2} \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix}$$

$$\sin^2\theta_{\text{atm, TBM}} = 1/2 \qquad \sin^2\theta_{\odot,\text{TBM}} = 1/3$$

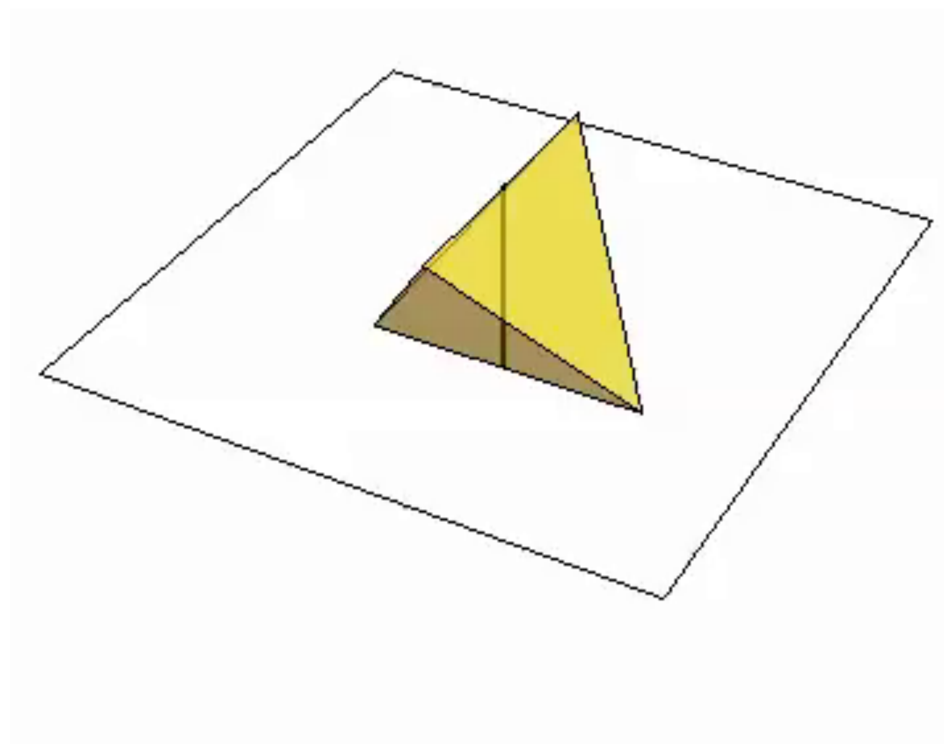
$$\sin\theta_{13,\text{TBM}} = 0.$$

TBM from A4 Group

T: (1234) → (2314)



S: (1234) →(4321)



Symmetry Relations

Symmetry ⇒ experimentally testable correlations among physical observables

CP phase

mass hierarchy

$0\nu\beta\beta$

mixing angles

cLFV

Symmetry Relations

Symmetry ⇒ experimentally testable correlations among physical observables

CP phase

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$0\nu\beta\beta$

mixing angles

cLFV

Testing correlations ⇒ Precision

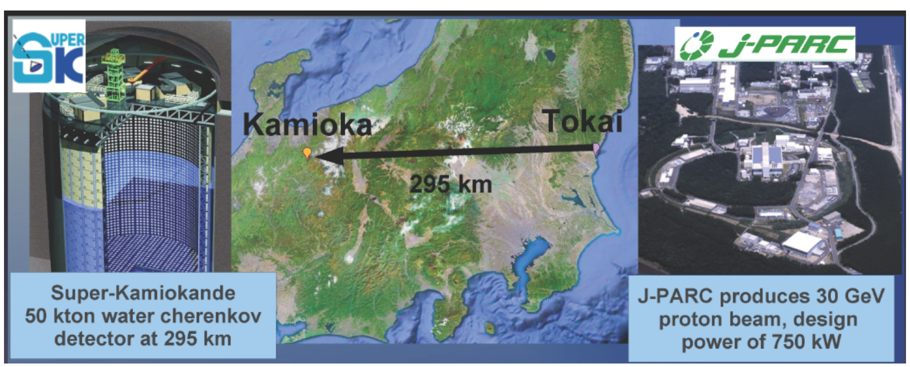
CP Violation in Neutrino Oscillation

- With leptonic Dirac CP phase $\delta \neq 0$ ➜ leptonic CP violation
- Predict different transition probabilities for neutrinos and antineutrinos

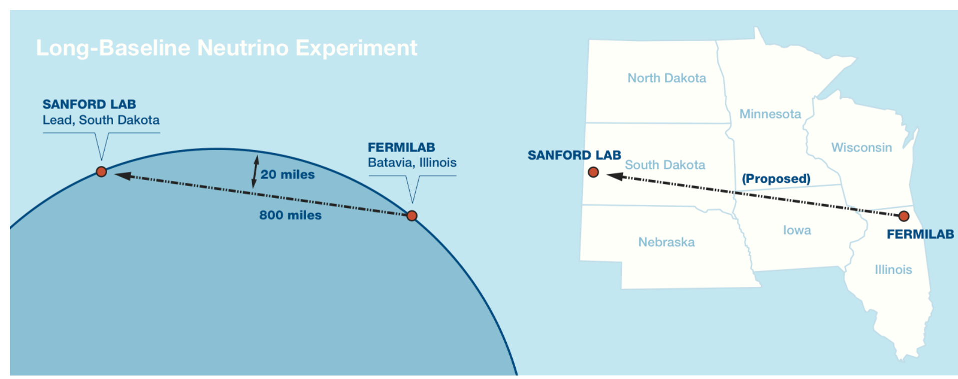
$$P(\nu_\alpha \to \nu_\beta) \neq P(\overline{\nu}_\alpha \to \overline{\nu}_\beta)$$

- One of the major scientific goals at current and planned neutrino experiments

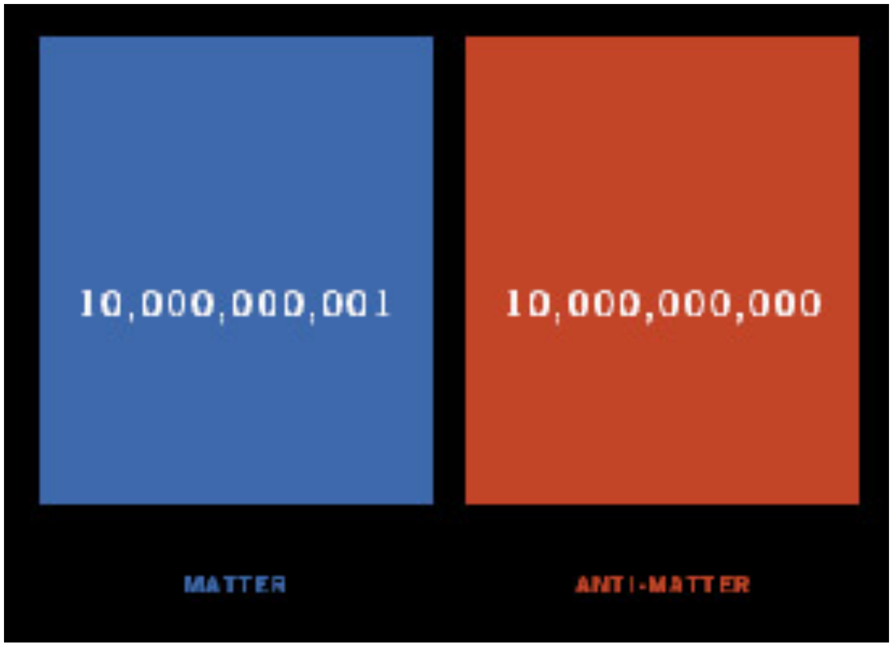
T2K



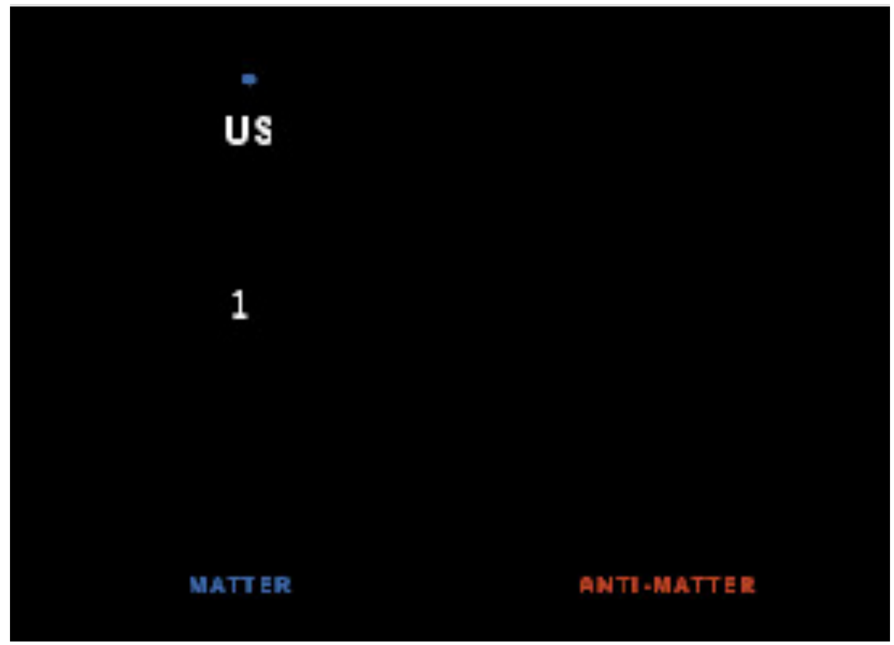
DUNE/LBNF



Matter-Antimatter Asymmetry



Early Universe



Universe Now

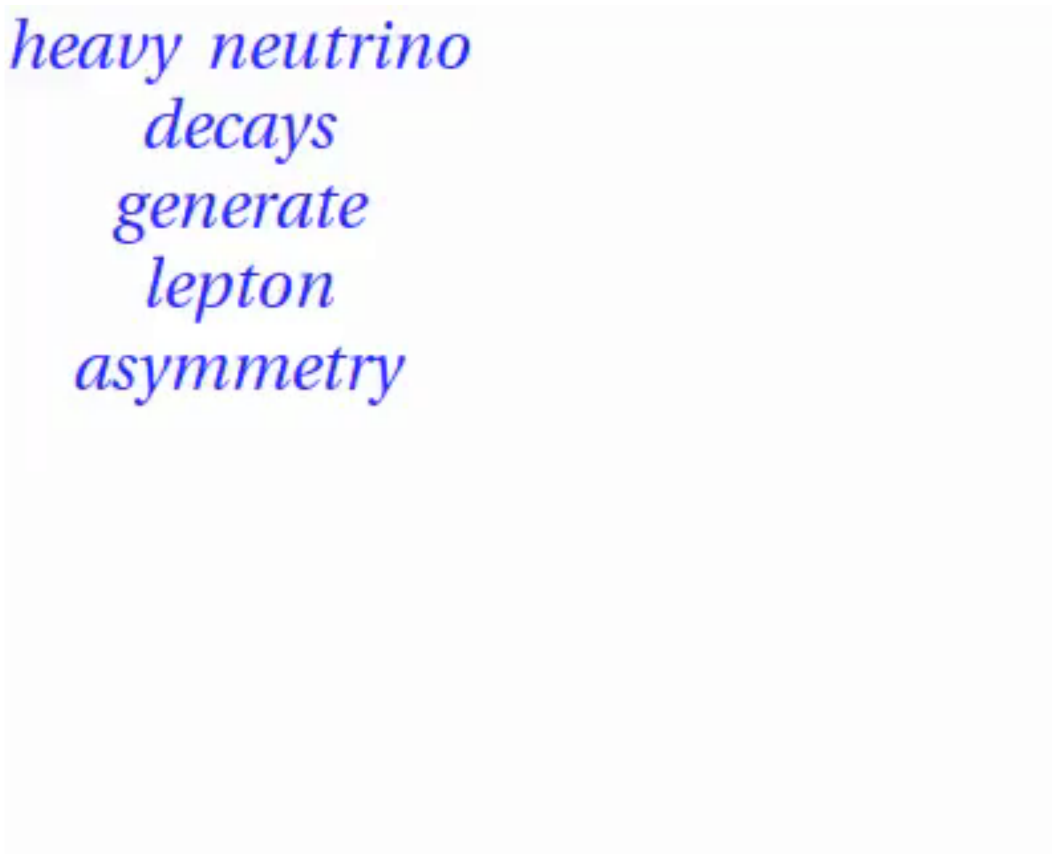
[Picture credit: H. Murayama]

Neutrinos may play an important role in generating the matter-antimatter asymmetry ⇒ Leptonic CP violation

Leptogenesis

- RH neutrino decays → primordial asymmetry ΔL

Fukugita, Yanagida, 1986



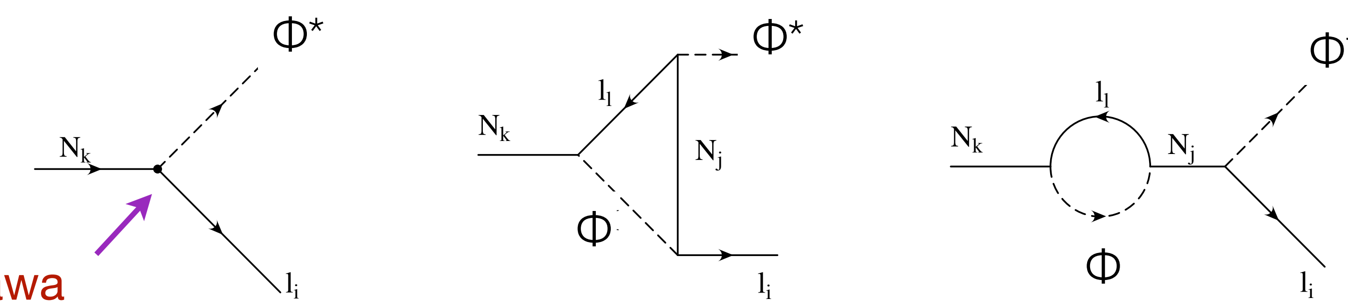
Leptogenesis

- Sphaleron processes convert ΔL → ΔB:

Fukugita, Yanagida, 1986

Leptogenesis

- RH heavy neutrino decay:
  - quantum interference of tree-level & one-loop diagrams ⇒ primordial lepton number asymmetry ΔL



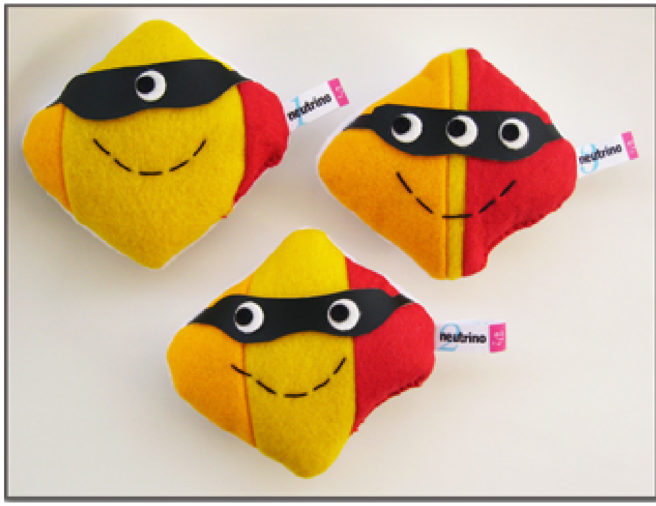
neutrino Yukawa interactions for neutrino masses

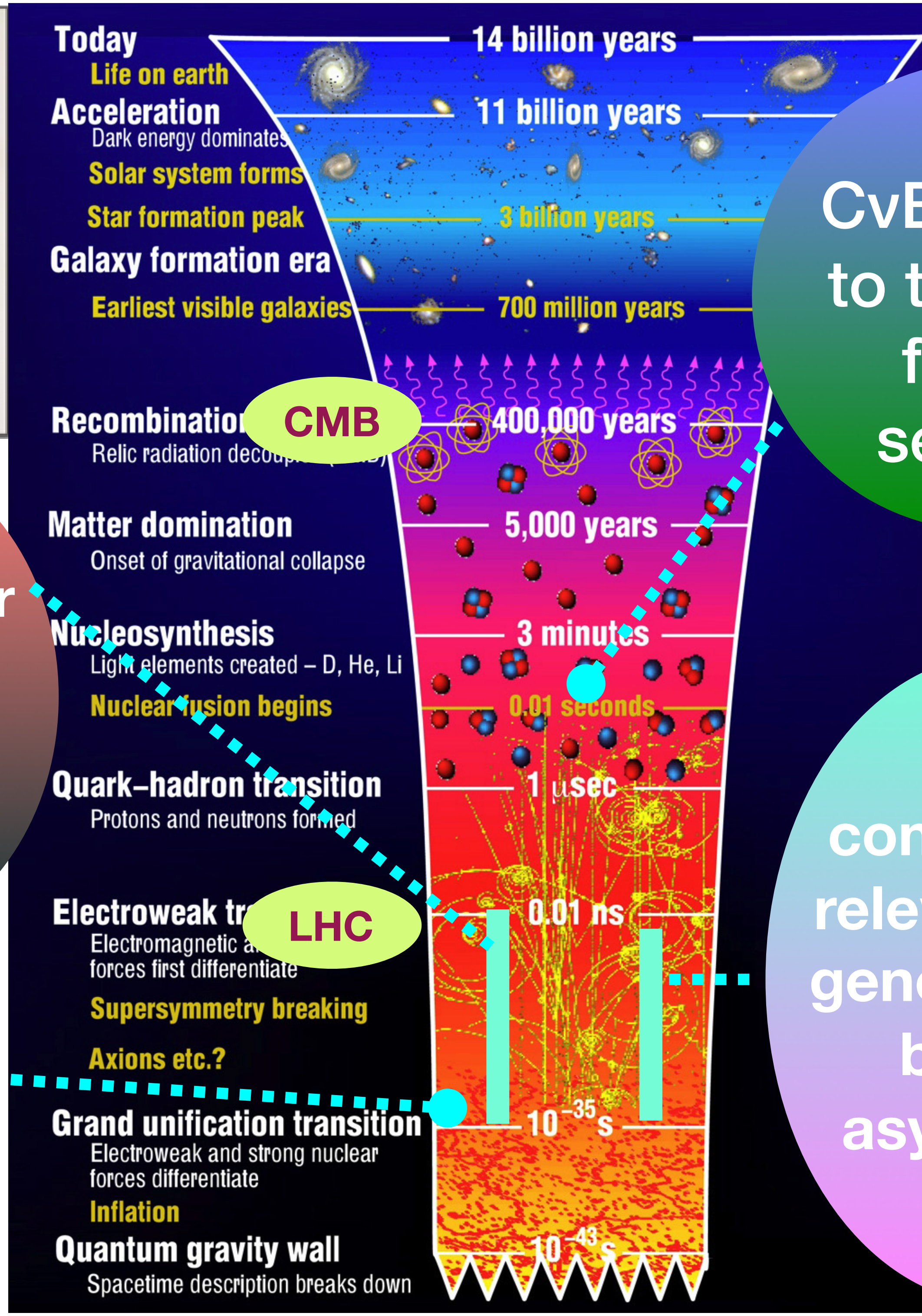
leptons   antileptons

Leptonic CP violation ⇒ $\Delta L \propto \left[\Gamma(N_1 \to \ell_\alpha \Phi) - \Gamma(N_1 \to \overline{\ell}_\alpha \overline{\Phi})\right] \neq 0$

⇔ neutrino parameters

Summary



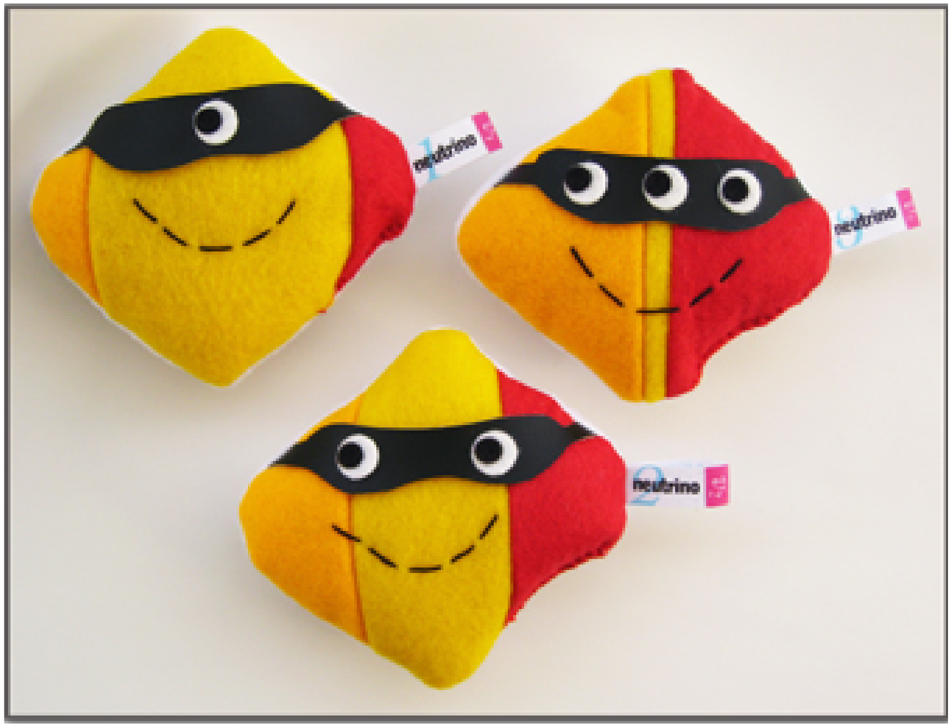


CvB - back to the very first 2 second

operator for ν mass generation unknown

conceivable relevance for generation of baryon asymmetry

unique window into GUT scale physics



Exciting Time Ahead!

Happy LGBT STEM Day!

[Picture credit: Symmetry Magazine]