Neutrinos and matter-anti-matter asymmetry
a unification perspective

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All about neutrinos! TIFR webinar 20-5-2020

1 Outline

- Why neutrinos oscillate
- What is matter anti-matter asymmetry
  - How neutrinos become important
- What is unification?
  - To unification via the see-saw mechanism in neutrino physics

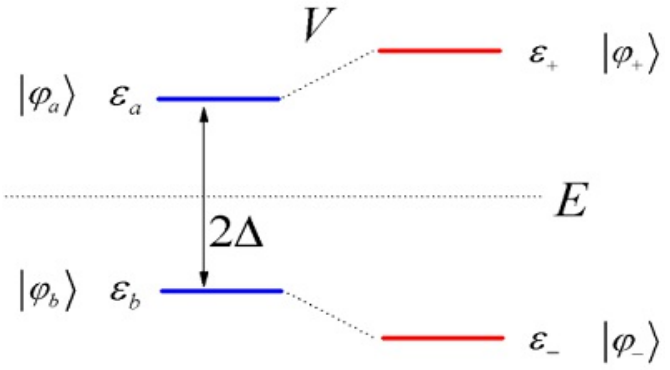
2 Oscillation of neutrinos

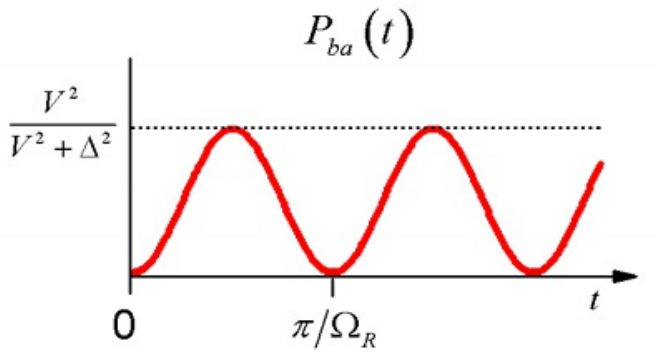
Two level system

$$i\frac{\partial}{\partial t}\begin{pmatrix} \varphi_a \\ \varphi_b \end{pmatrix} = \begin{pmatrix} \varepsilon_a & V \\ V & \varepsilon_b \end{pmatrix}\begin{pmatrix} \varphi_a \\ \varphi_b \end{pmatrix}$$

φ_a and φ_b the observationally preferred eigenstates

But the complete Hamiltonian "mixes" them through V term





Chemlibretexts

Neutrinos :

- Observationally preferred –> Weak interaction basis
- Free propagation –> mass eigenbasis
- Also, emission in momentum eigenstate and not energy

2.1 The mass matrix

The equations of motion can be derived from variation of a Lagrangian density.

$$\mathcal{L} = i\sum_{a} \overline{\psi}_{a}\gamma^{\mu}\frac{\partial}{\partial x^{\mu}}\psi_{a} - m\sum_{a,b} \bar{\psi}_{a}M_{ab}\psi_{b}$$

The equations of motion : $\frac{\delta\mathcal{L}}{\delta\bar{\psi}_{a}} = 0$ and $\frac{\delta\mathcal{L}}{\delta\psi_{a}} = 0$

Need to diagonalise mass matrix $M_{a\,b}$ to identify mass eigenbasis species.

2.2 Majorana mass term

The 4-component Dirac equation contains Left helicity and Right helicity components, $\psi_{_R}$ and $\psi_{_L}$ each 2-component.

Mass matrix $\sum_{a\,b} M^{\rm Dir}_{a\,b}\bar{\psi}_{L\,a}\psi_{R\,b} + h.c.$

Majorana case : Particle its own antiparticle like photons

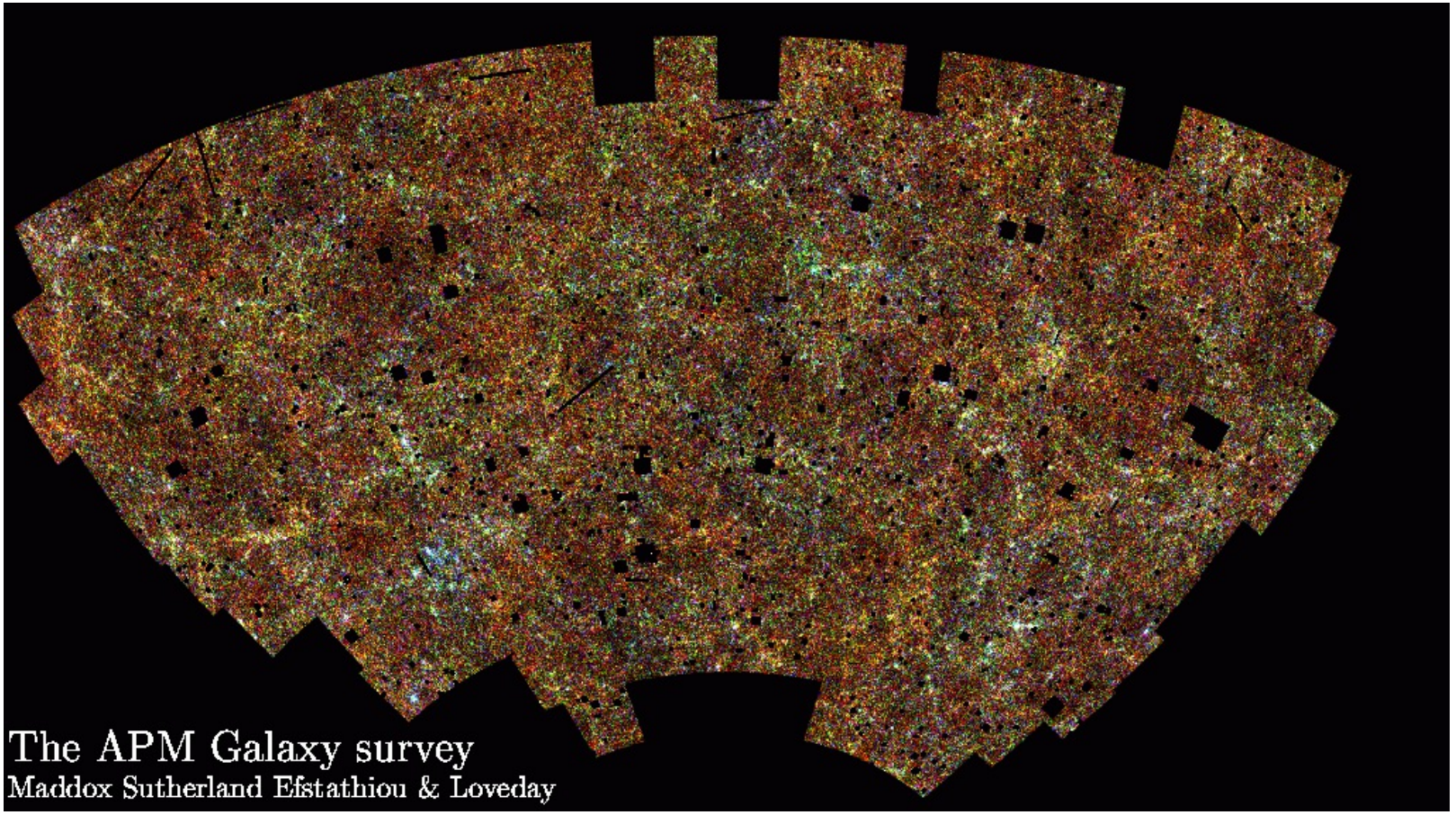
– 2 dof; fermion number can be violated in units of 2

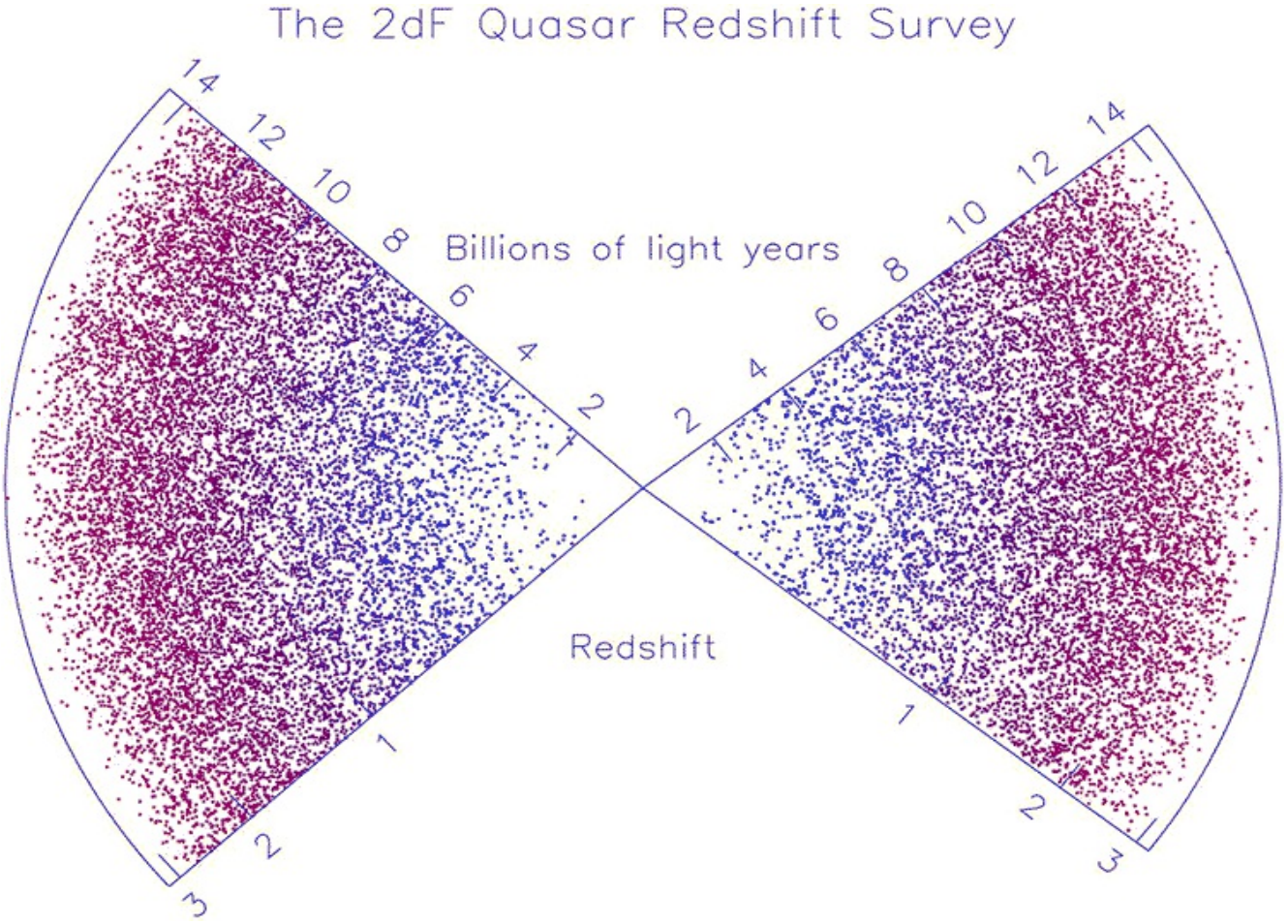
– Mass matrix $\sum_{a\,b} M^{\rm Maj}_{a\,b}\psi^{T}_{L\,a}\mathcal{C}\psi_{L\,b}$ and separately for $\psi_{_R}$

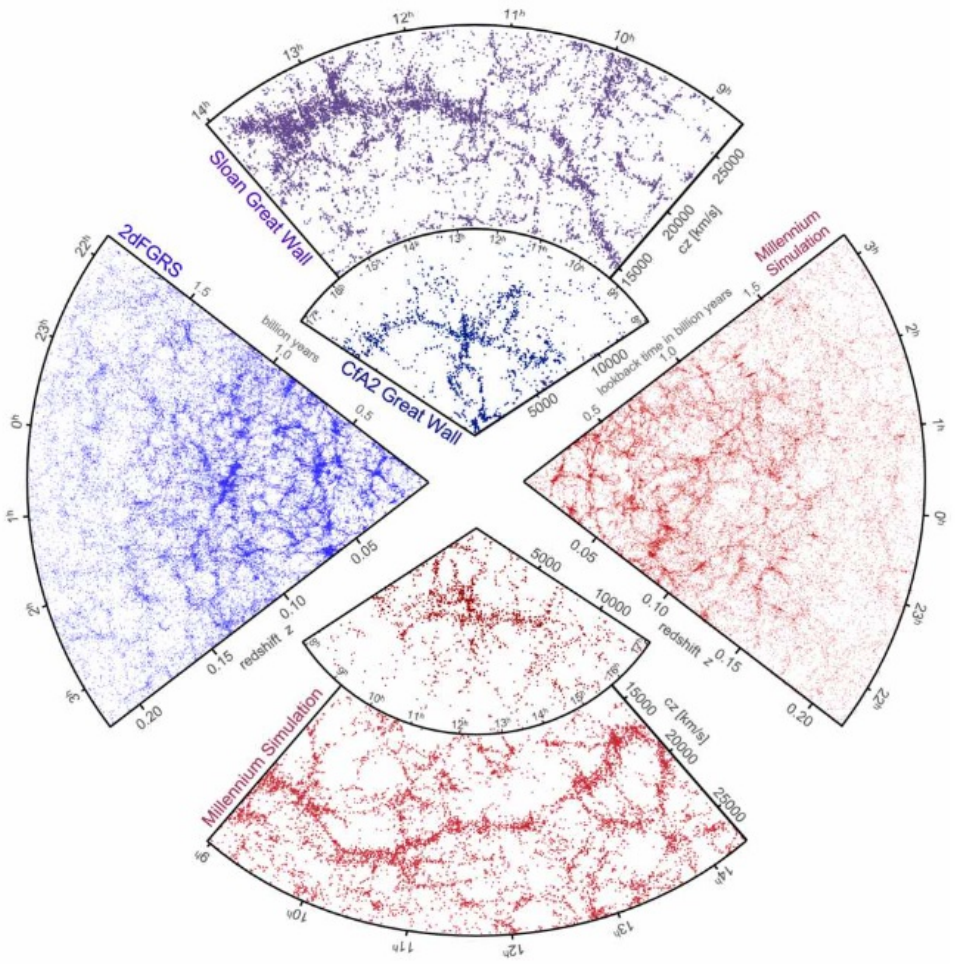
We return to this theme later

3 Matter anti-matter asymmetry

- No smoking gun signs of anti-matter
- Uniform distribution of galaxies - with irregularities within statistical tolerance
- *Where are all the anti-protons?* .... and positrons?
- "Baryon to photon ratio" : $\eta = \frac{n_B - n_{\overline{B}}}{s_\gamma} = 5 \times 10^{-10}$
  - From calculation using laboratory fusion rates
  - Observation of interstellar abundances

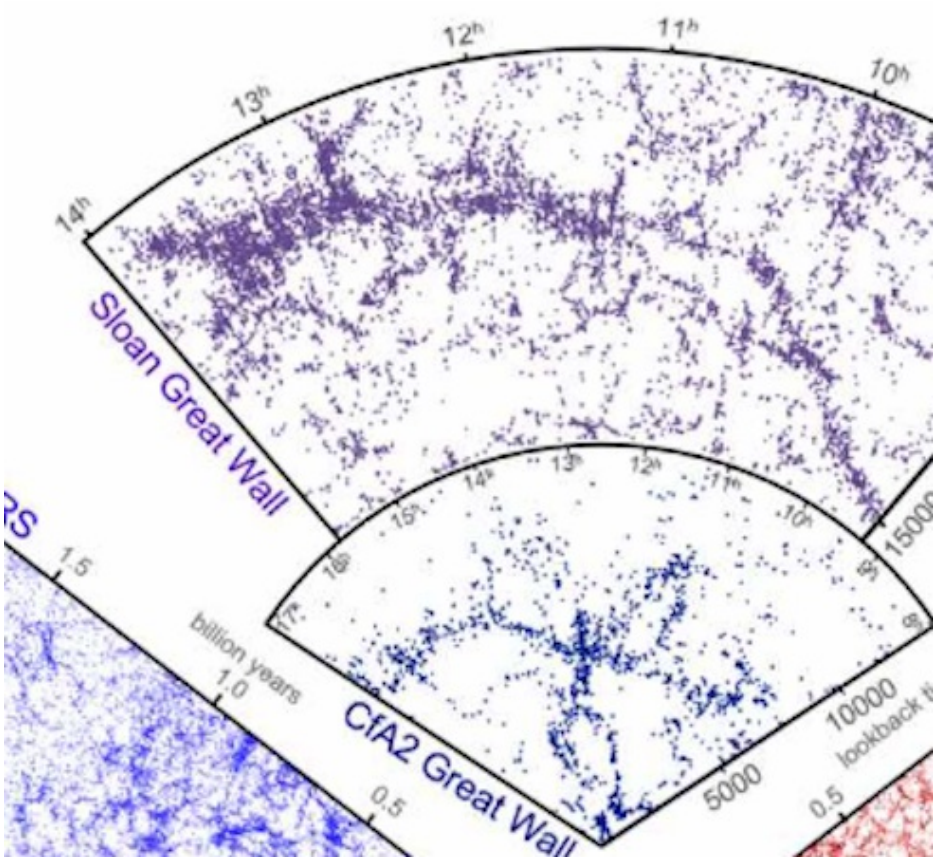

The APM Galaxy survey
Maddox Sutherland Efstathiou & Loveday


The 2dF Quasar Redshift Survey
Billions of light years
14
12
10
8
6
4
2
Redshift
1
2
3



Springel et al
Nature 2006

Surveys upper left
simulations lower right



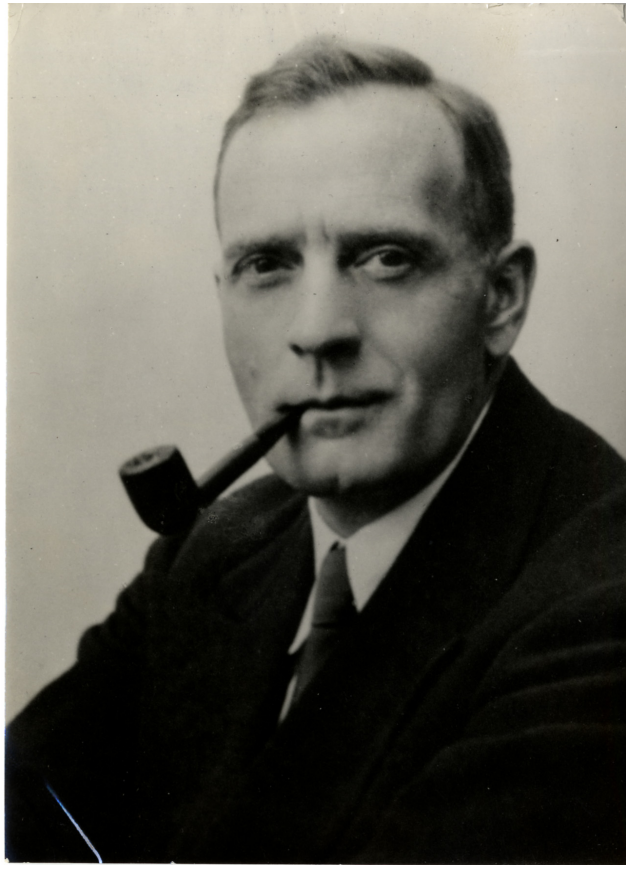
The great walls

3.1 Cosmology becomes a science

The Universe is not willed as a simplistic design ...

.... its simplicity is the outcome elegant dynamics

- Einstein believed in static Newtonian universe
- Friedmann 1921 - 22 found dynamical solutions
- Edwin Hubble boldly drew the straight line 1929 ....
- LeMaitre grasped it all 1926 but shared cautiously



Edwin Hubble

Henrietta Leavitte

3.2 Particle cosmology is born ...

- 1920's the decade of expanding Universe
  - Friedmann, Hubble, LeMaitre ...
- 1948-49 Nucleosynthesis and CMB in "Big Bang" universe
  - Alpher "Bethe" and Gamow; Alpher and Herman
- 1964-65 : the classic year
  - Accidental discovery of cosmic microwave background
  - Discovery of CP violation in K-meson decays

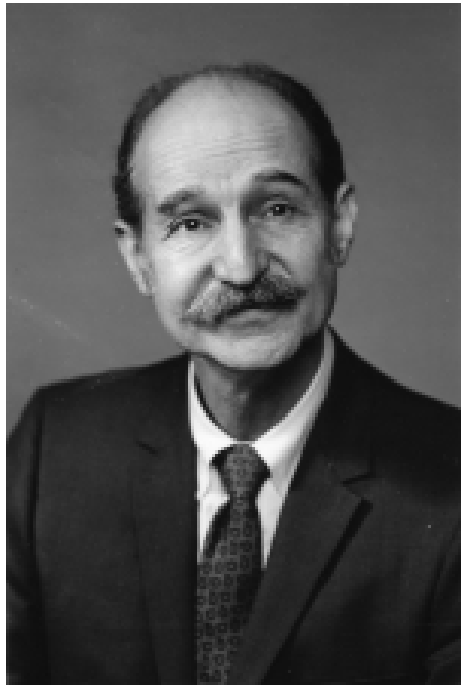
3.3 The cosmology – nuclear physics connection

- Alpher, "Bethe" and Gamow paper estiamtes He to H ratio 1948

- Alpher and Herman estimate 5K as the temperature of residual photons 1949

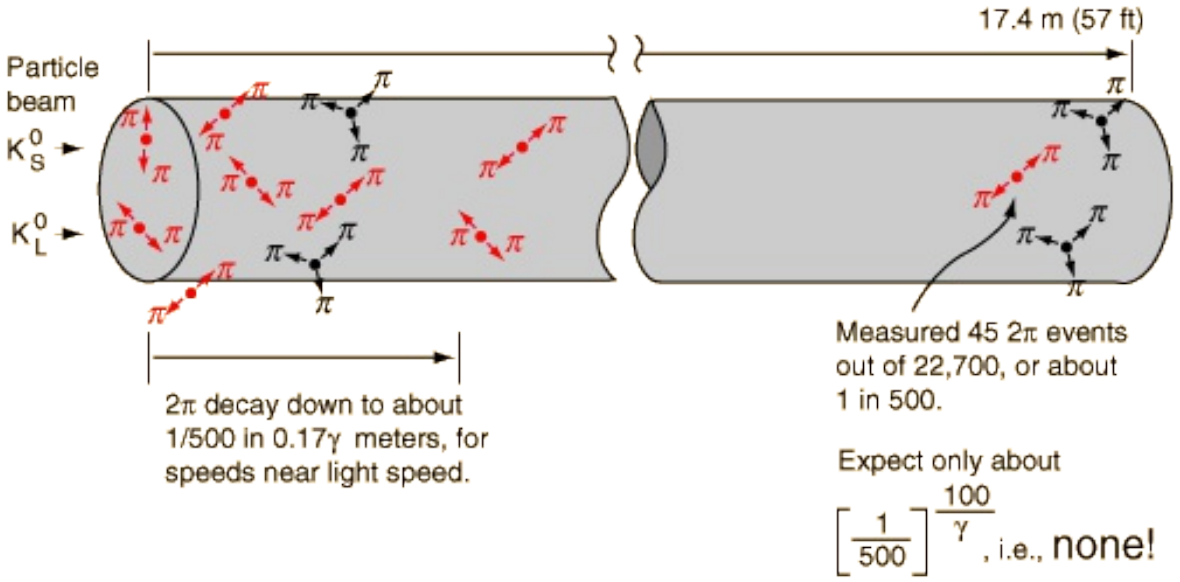
One concerns the MeV scale, the other concerns the eV scale!



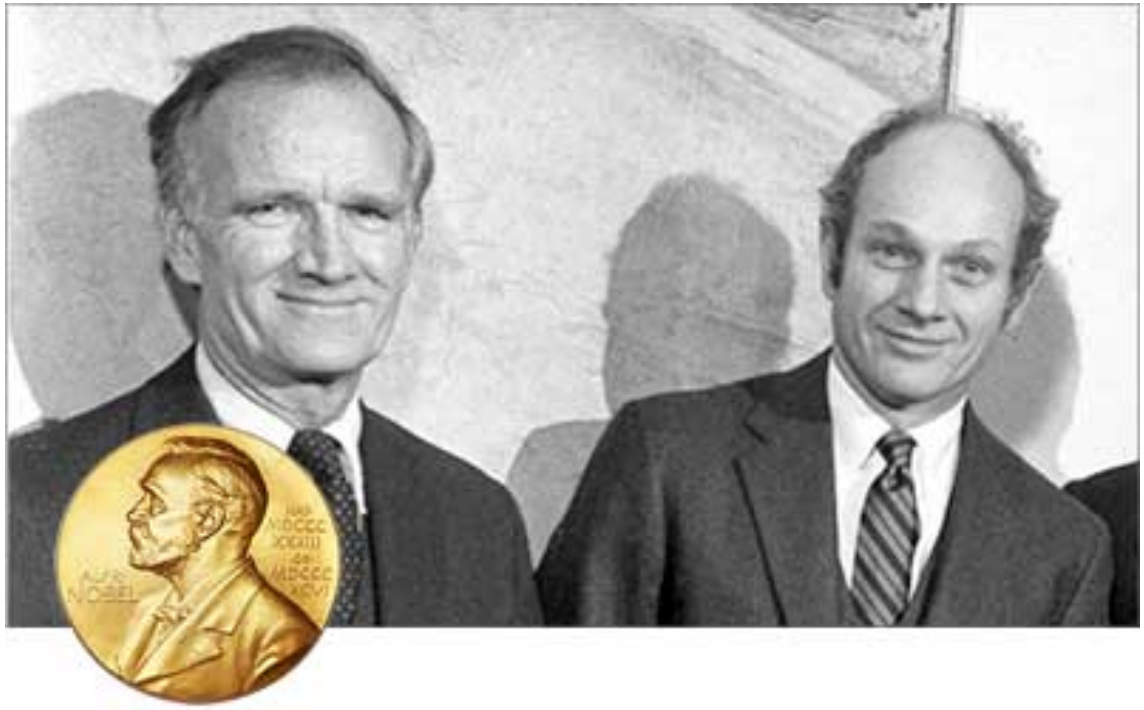


Gamow; *Alpher*; Herman

Discovery of CP violation at Brookhaven National Lab 1964



(schematic courtsy hyperphysics website Georgia State U.)



Val Fitch and James Cronin Nobel 1980

Cosmic Microwave Background Radiation discovered 1965

Discovery of Cosmic Background

Microwave Receiver

Robert Wilson

Arno Penzias

MAP990045

Nobel 1978

4 Genesis of Baryogenesis

(Sakharov 1967; Yoshimura; Weinberg 1978)

1. There should exist baryon number B violating interaction
2. Charge conjugation C must be violated
3. CP violation – unequal forward and reverse rates
4. Out of equilibrium conditions – so that reverse reactions don't get the time to equilibrate

4.1 Realisation in Grand Unified Theories

- GUTs have the required B violation, C and CP violation
- Out of equilibrium requires that Hubble rate should be fast enough to compete with particle physics decay rates

$$\Gamma_X \cong \alpha_X m_X^2 / T; \qquad H \cong g_*^{1/2} T^2 / M_{\rm Pl}$$

- Realised only for GUT scale close to Planck scale

Soon, by 1990, protons not decaying :-(or may be :-) No GUT BGenesis :-(:-(

Summary so far ....

Neutrinos oscillations governed by a "mass matrix".

Big Bang confirmation and discovery of CP violation almost simultaneous

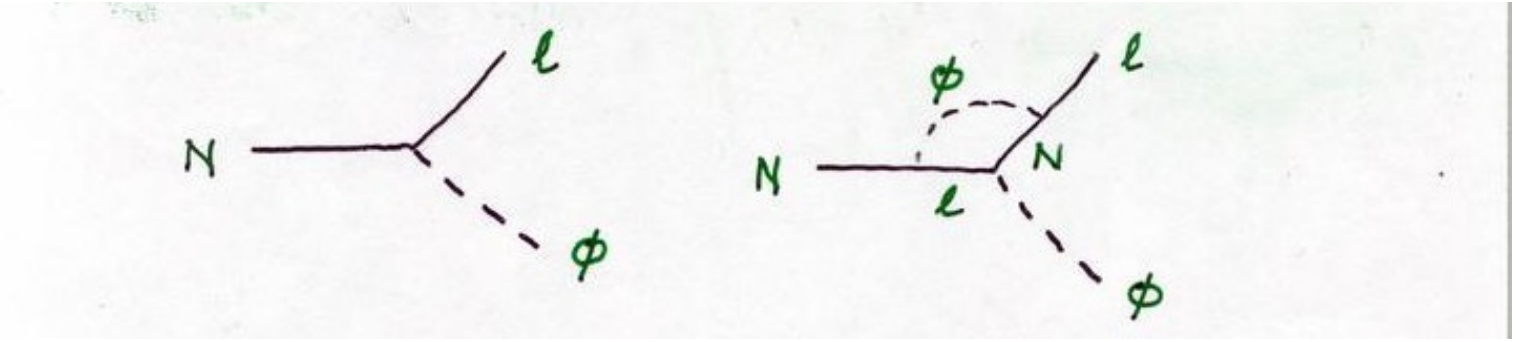
B violation at GUT energy scales + CP violation can explain the matter-anti-matter asymmetry

But B violating proton decays are not yet seen

4.2 Leptogenesis instead ....

(M. Fukugita and T. Yanagida 1986)

- Majorana masses and phases in neutrino mass matrix
- Out of equilibrium decay of heavy Majorana neutrinos



- Why should Majorana masses be at GUT scale?

5 Neutrinos as link to the high scale

Recall Majorana construction $\psi_L^C \equiv \mathcal{C}\psi_L^*$

$$\mathcal{L}^{\text{Maj}} \sim m_L\left(\overline{\psi_L^C}\psi_L + \overline{\psi_L}\psi_L^C\right) + M_R\left(\overline{\psi_R^C}\psi_R + \overline{\psi_R}\psi_R^C\right)$$

while Dirac mass term

$$\mathcal{L}^{\text{Dir}} \sim m_D(\overline{\psi_R}\psi_L + \overline{\psi_L}\psi_R)$$

5.1 General mass matrix – the "see-saw" mechanism

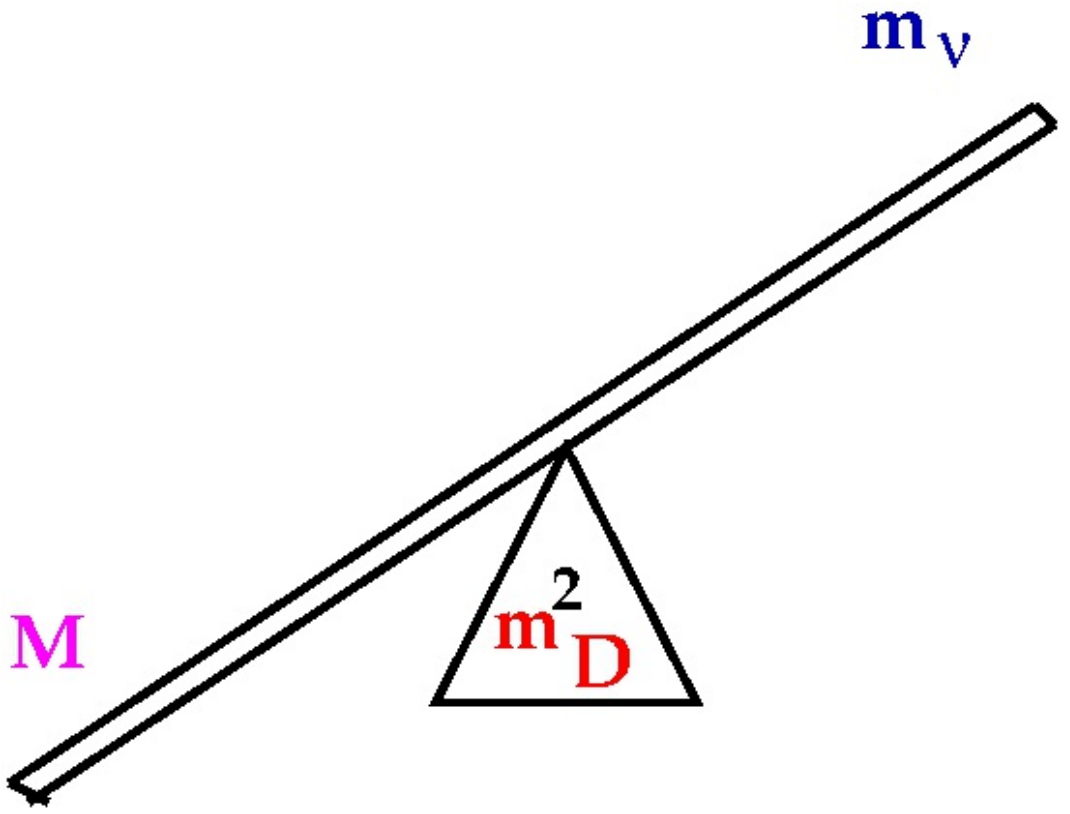
we need to diagonalise the mass matrix :

$$\begin{array}{c} \\ \overline{\psi_L} \\ \overline{\psi_R} \end{array} \begin{array}{c} \begin{array}{cc} \psi_L & \psi_R \end{array} \\ \begin{pmatrix} \mathcal{C} m_L & m_D \\ m_D & \mathcal{C} M_R \end{pmatrix} \end{array}$$

The eigenvalues are $m_1 \simeq M_R$ and,

$$m_2 \simeq -\frac{m_D^2}{M_R} + O\left(\frac{m_L}{M_R}\right) \simeq 0.1\text{eV}\left(\frac{m_D}{100\,\text{GeV}}\right)^2\left(\frac{10^{14}\text{GeV}}{M_R}\right)$$

Gell-Mann, Ramond and Slansky



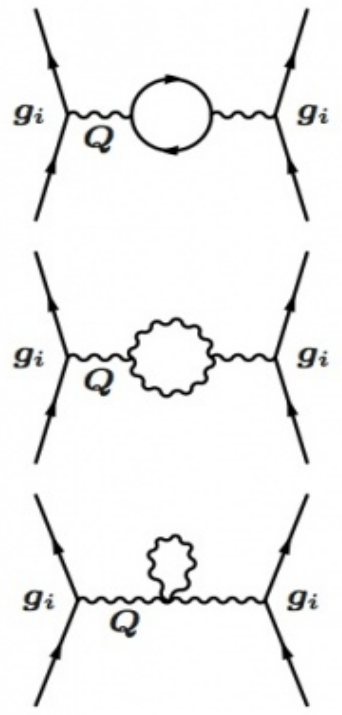
5.2 Unification scale - the "running" couplings

Couplings are not constants

The theory makes perturbative sense only if

we agree to rescale the couplings with

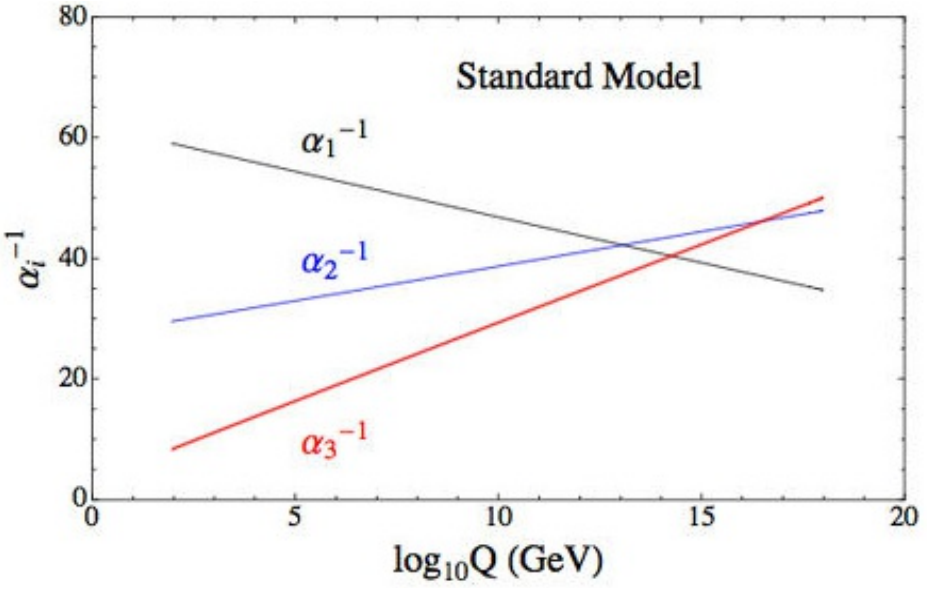
energy scale of the scattering experiment.



$$\frac{1}{\alpha_i(Q^2)} = \frac{1}{\alpha_i(M_Z^2)} - 4\pi b_i \ln\left(\frac{Q^2}{M_Z^2}\right)$$

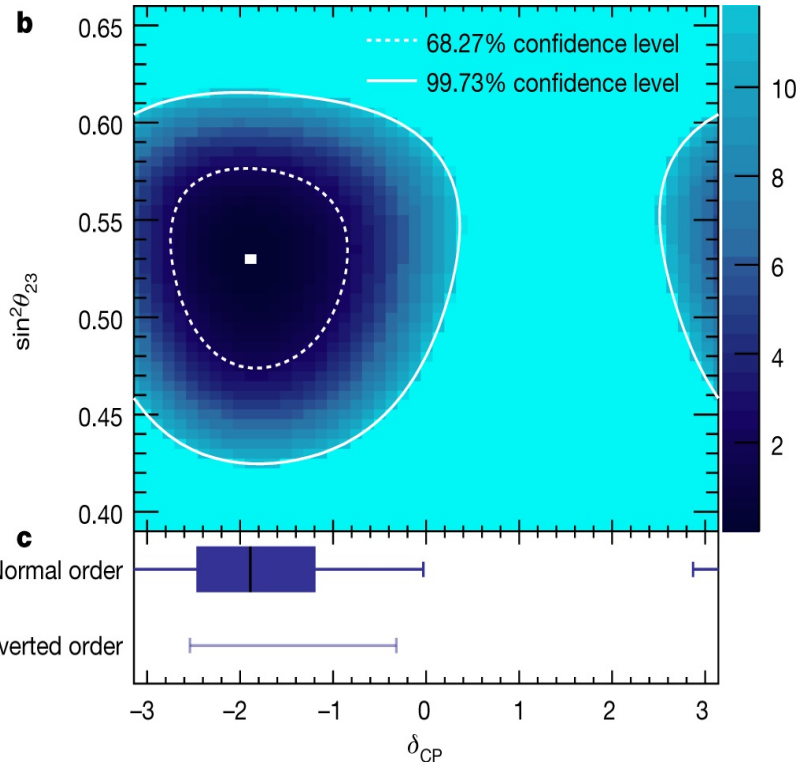
Dreams of Grand Unification (not yet realised)

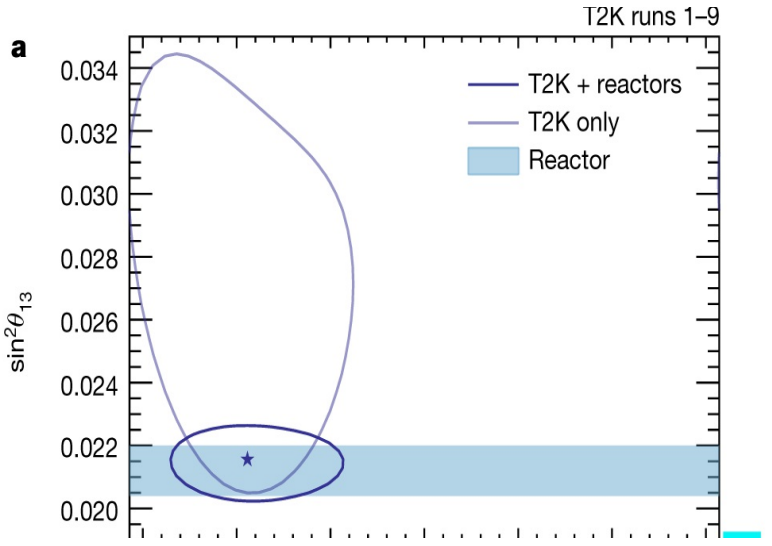
Pati-Salam, Georgi Glashow; Georgi Quinn and Weinberg



Suggests that the see-saw scale may originate in GUT

T2K results (Nature 2020)





The CP-conserving points are not both excluded at the 99.73% level. However, ...a large range of values around $+\pi/2$ [is] excluded.

6 Conclusion

- The full neutrino mass matrix with Dirac and Majorana terms
  - mixing of flavours; CP violating phases
  - violation of lepton number L
- Early Universe creation of matter asymmetry : L and CP violating decays competing with Hubble rate H.
- See-saw can give a mass scale with which H can compete
- See-saw scale highly suggestive of GUT –> Thanks page

THANK YOU

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