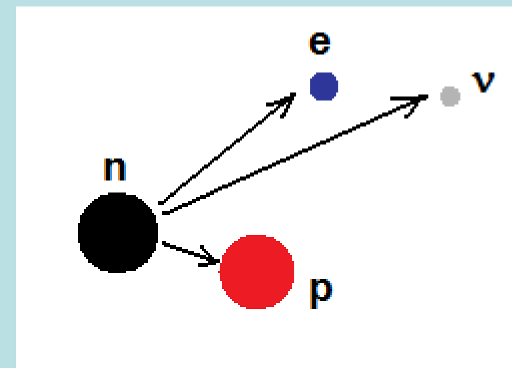
Extending the frontiers of Particle Physics

Lecture from the course
« Cosmoparticle physics »

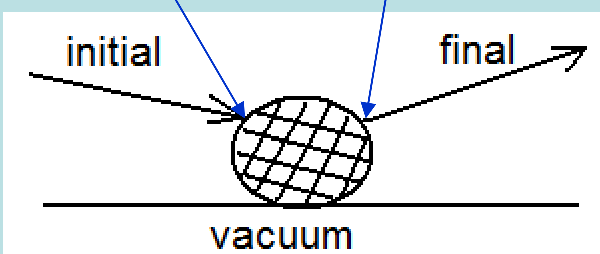
Elementary Particles

•Classical mechanics, Quantum mechanics – an elementary particle is eternal

•The problems with *Energy* and *Angular momentum* conservation in β-decay (1930) – electron and neutrino are created in this process



=> **annihilation** and **creation** of particles



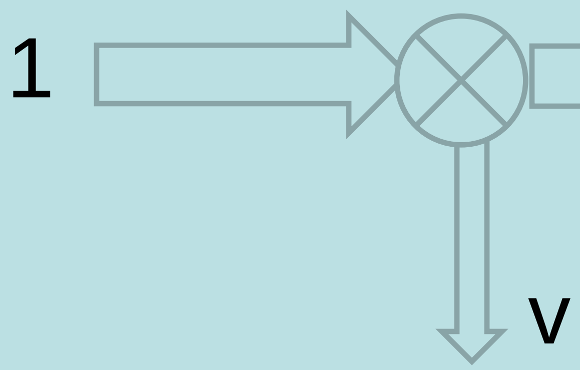
=> New formalism – Quantum field theory

Note: in 1922 A.Friedman discovered non-stationary solutions of Einstein equations for the Universe, proved in the end of 20-s by E.Hubble. Static Universe and its eternal constituents were changed by the modern concepts of particles and expanding Universe nearly simultaneously.

Particle Interactions

- Charge of an eternal particle converts in QFT in transition in which initial particle annihilates and the final particle is created with emission or absorption of v - quantum of the field of interaction (in QED – photon)

$$e\varphi \Rightarrow e|\Psi|^2\ \varphi \Rightarrow e\Psi_2^*\Psi_1\ \varphi$$



Elementary act of particle interaction, mediated by boson v, in which initial particle 1 converts into final particle 2

The Standard Model (SM) of Particle Physics

- Gauge principle (Quantum Electrodynamics (QED)):

$$L = i\overline{\psi}\hat{\partial}\psi + eA_\mu J_\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}, \qquad J_\mu = \overline{\psi}\gamma_\mu\psi, \qquad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$\psi \to \psi \exp(ie\chi(x))$$ ← U(1)-symmetry transformation

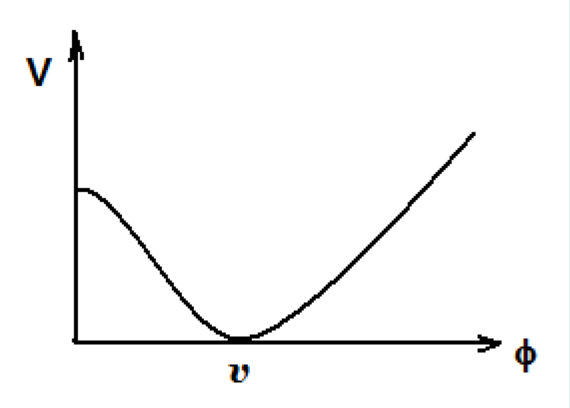
$$A_\mu \to A_\mu + \partial_\mu \chi$$

- Generalization on *weak* and *strong* interactions: **$SU(3)_c x SU(2)_L x U(1)_Y$ = SM**
- Higgs mechanism of spontaneous symmetry breaking

$$m_f = \frac{f\upsilon}{\sqrt{2}}, \qquad m_W = \frac{f\upsilon}{2}, \qquad m_H = \sqrt{2\lambda}\upsilon$$

=>in case of *global* symmetry breaking, a Nambu-Goldstone boson *α* appears which interacts as

$$L_{\text{int}} \propto \frac{1}{\upsilon}\left(\partial_\mu \alpha\right) J_\mu$$



Problems of SM (1)

$SU(3)_c \times SU(2)_L \times U(1)_Y$

1) Excessive number of parameters: g, g', v, λ, $\{f_f\}$,…

2) Problem of number of generations

$$\begin{pmatrix}\nu_e\\ e\end{pmatrix}\begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}\begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}$$

$$\begin{pmatrix}u\\ d\end{pmatrix}\begin{pmatrix}c\\ s\end{pmatrix}\begin{pmatrix}t\\ b\end{pmatrix}$$

3) The problem of neutrino mass.

$m(\nu_e) < 1$ eV << $m(e)$=511 keV

4) CKM mixing matrix

$$\begin{pmatrix}d'\\ s'\\ b'\end{pmatrix}=\begin{pmatrix} & & \\ 3 & \times & 3\\ & & \end{pmatrix}\begin{pmatrix}d\\ s\\ b\end{pmatrix}$$

5) The problem of *C*-, *P*- and *CP*-violation observed (in weak interactions and K-mesons).

Problems of SM (2)

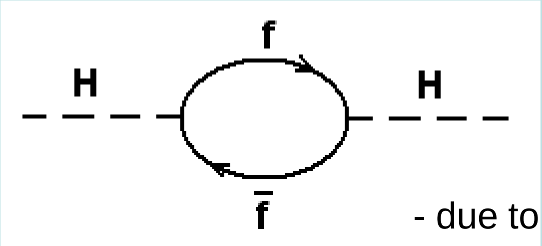
$SU(3)_c x SU(2)_L x U(1)_Y$

6) Problem of CP-violation in QCD

$$\Delta L_{\mathrm{QCD}} = \frac{\alpha_s^2}{16\pi}\theta \cdot \varepsilon_{\alpha\beta\mu\nu} G^{a\,\alpha\beta} G^{a\,\mu\nu} \Rightarrow \text{Strong CP-violation}$$

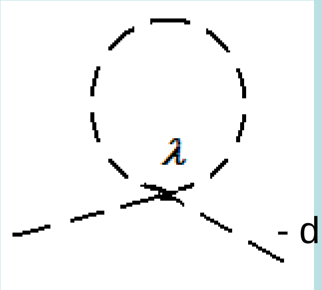
$\Rightarrow$ $d_n \approx e\theta m_u / m_n^2 \sim \theta \cdot 10^{-16}\, e \cdot \mathrm{cm}$ From experiment one has $|\theta| < 10^{-9}$

7) Divergence of Higgs boson mass (due to radiation corrections),
and, as consequence, instability of Higgs potential against radiation corrections



$\sim\Lambda^2$

- due to $g_f \varphi \bar{f} f$.



$\sim\Lambda^2$

- due to $\lambda\varphi^4$.

Other arguments for extension of SM

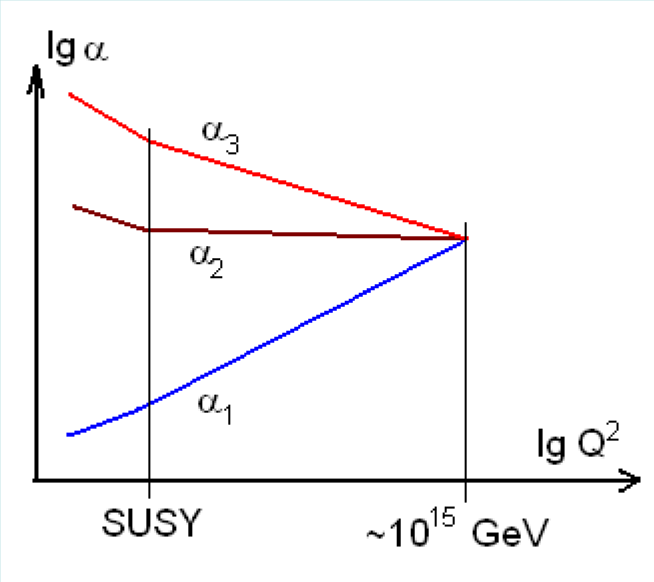
$SU(3)_c x SU(2)_L x U(1)_Y$

Unifying all interactions:

for aesthetical reasons

for reasons of similarity in their descriptions: $L \sim g A_\mu J_\mu$

convergence of gauge constants (SUSY changes the lines and gives it naturally)



Trends in extension of SM (1)

"**See-saw**" **mechanism** of generation of neutrino mass

$$\Delta L_m = m_D\left(\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L\right) + m_R\left(\bar{\nu}_R^c \nu_R + \bar{\nu}_R \nu_R^c\right) + m_L\left(\bar{\nu}_L^c \nu_L + \bar{\nu}_L \nu_L^c\right)$$

To avoid problems with SM parameters

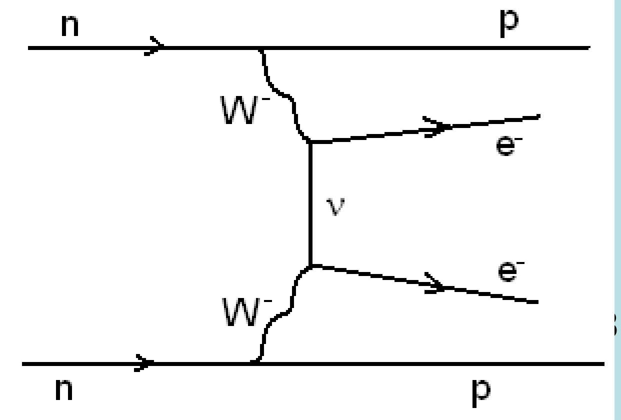
at $m_D << m_R$

$$\Delta L_m = m_1(\bar{\nu}_1^c \nu_1 + \bar{\nu}_1 \nu_1^c) + m_2(\bar{\nu}_2^c \nu_2 + \bar{\nu}_2 \nu_2^c)$$

$$m_1 \approx \frac{m_D^2}{m_R} << m_D \sim m_l, \qquad m_2 \approx m_R$$

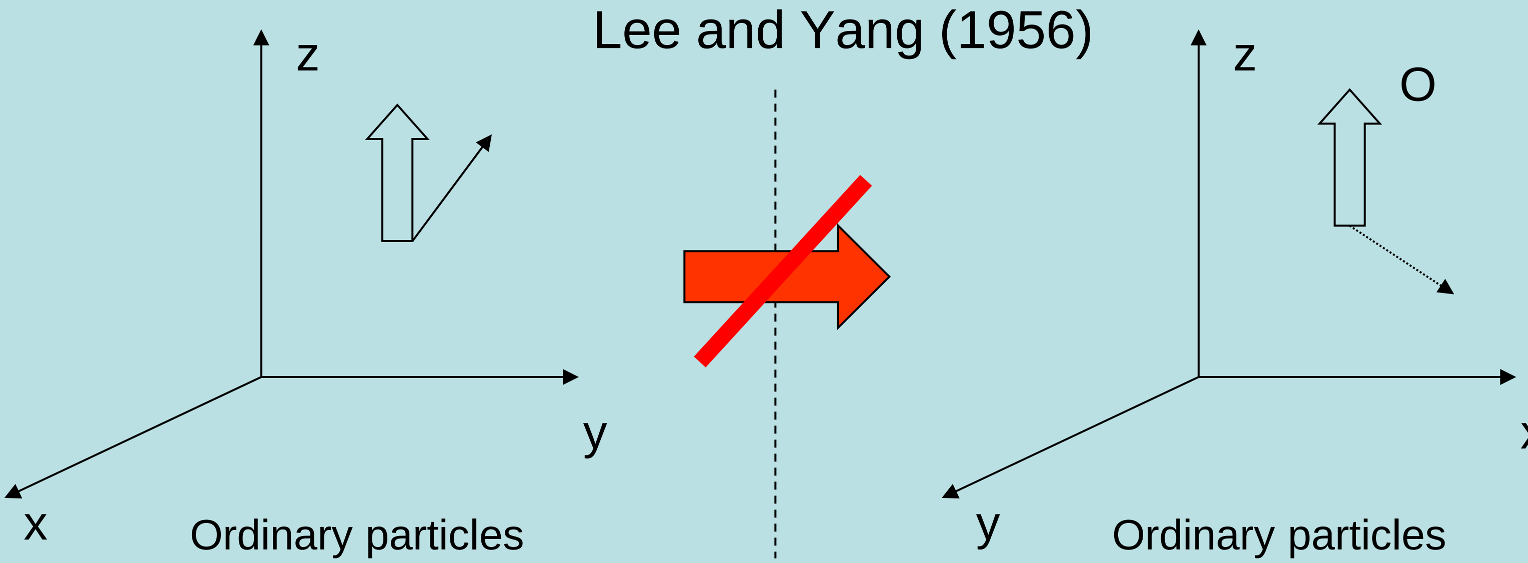
Majorana mass term violates lepton number, which will lead to processes with as ΔL=2.

Consequence: neutrinoless double β-decay



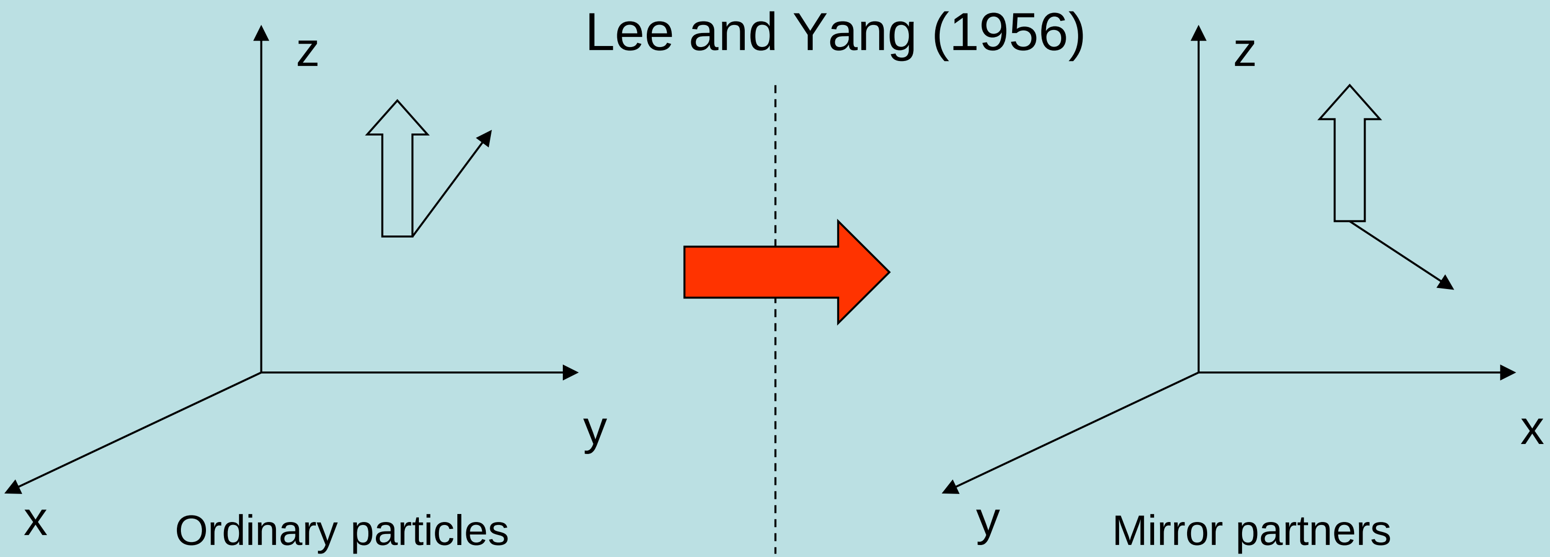
Spontaneous breaking of symmetry of lepton charge implies the existence of Nambu-Goldstone boson – Majoron.

P-violation



Parity (P) violation means that the process, reflected in mirror does not exist in Nature. It means non-equivalence of left- and right-handed coordinate systems. Beta decay of polarized nucleus, reflected in mirror, does not exist. To restore the equivalence of left- and right-handed coordinate systems P-transformation should be generalized. Together with mirror reflections particles should be changed by their mirror partners.

Mirror partners?

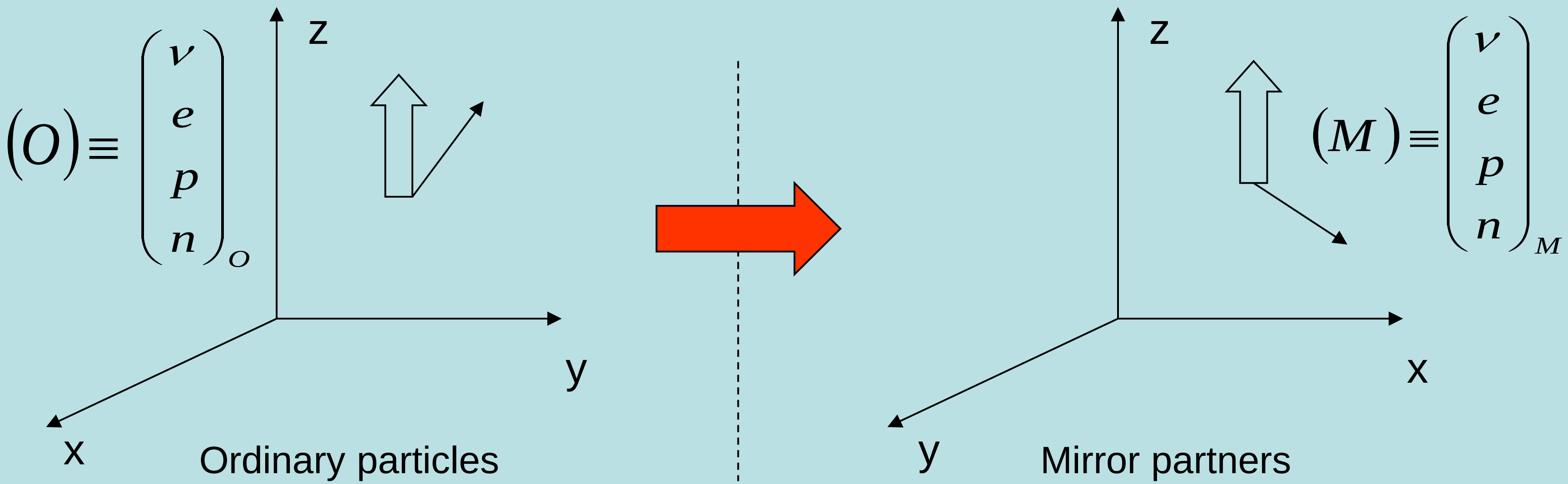


The equivalence between left- and right-handed coordinate systems is restored, if reflection in mirror is accompanied by change of ordinary particles by their mirror partners. Lee, Landau,… (1957) offered an economic solution: CP invariance assumes that antiparticles play the role of mirror partners. Discovery of CP-violation in 1964 put again the question of proper choice for the set of mirror partners.

Trends in extension of SM (2)

"Mirror" world

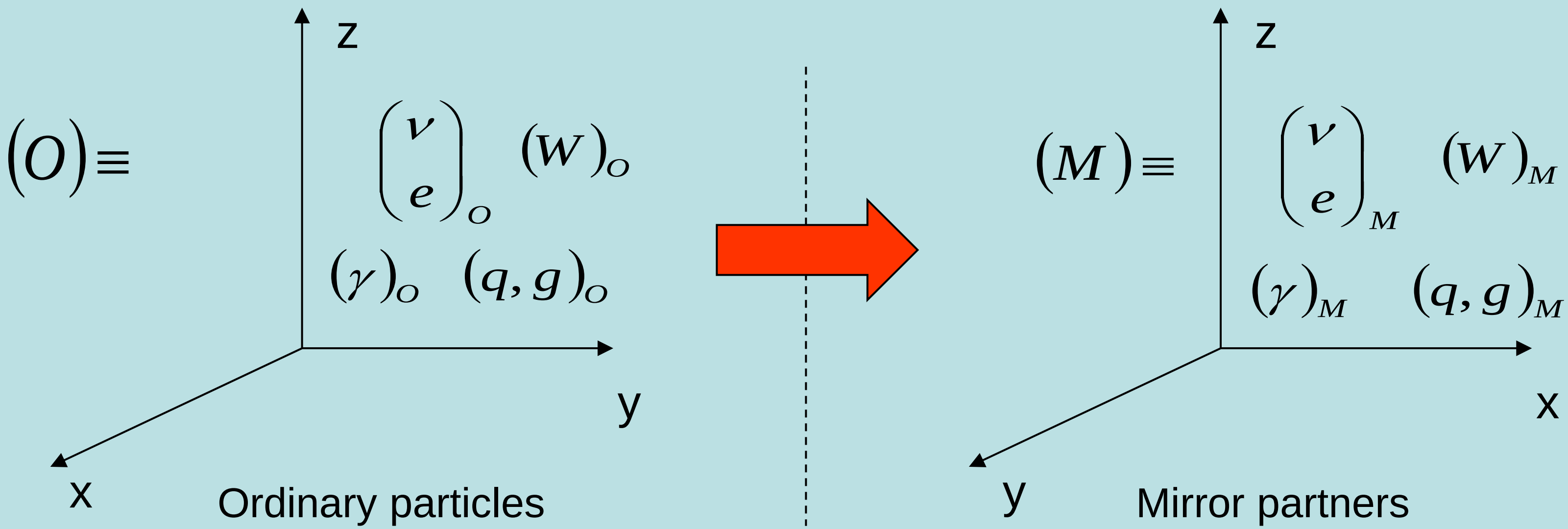
Kobzarev, Okun, Pomeranchuk (1966)



The equivalence between left- and right-handed coordinate systems is restored, if reflection in mirror is accompanied by change of ordinary particles by their mirror partners. Mirror partners are strictly symmetric to ordinary particles. Therefore they can not have ordinary electromagnetic and strong interactions (doubling of atomic levels, or pion states). Successive analysis have shown that (O) and (M) also can not share W and Z boson mediated weak interaction.

Mirror world

Blinnikov,Khlopov(1980,1982,1984)



Assume that there is no common interaction between ordinary particles and their mirror partners, except for gravity. All the masses and coupling constants of mirror particles are strictly symmetric to the ordinary ones.The initial conditions are also assumed strictly symmetric.

Trends in extension of SM (3)

SU(5) GUT model

$SU(5) \supset SU(3)_c x SU(2)_L x U(1)_Y$

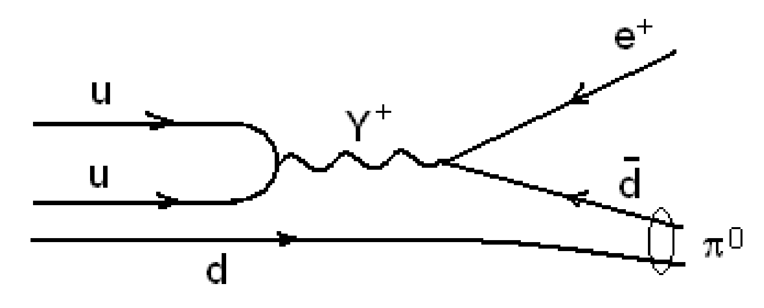
- There are 24 gauge bosons, which contain 12 known ones (g,Z,W,γ) and 12 new ones (X,Y)
- All known fermions (15, excluding ν_R) are distributed into SU(5) 5-plets and 10-plets.
- **Λ_{GUT}~10^{15} GeV**

Example of 5-plet: $$\left(\bar{d}_{red} \quad \bar{d}_{yellow} \quad \bar{d}_{blue} \quad e^- \quad \nu_e\right)_L$$

Proton decays

Note: $\Delta B=\Delta L$

$$\tau_p^{\text{theor}} \sim \frac{\Lambda_{\text{GUT}}^5}{m_p^4} \sim 10^{31}\text{years}$$ vs $$\tau_{p\to e\pi}^{\exp} > 10^{33}\text{years}$$



It strongly restricts the model.

Trends in extension of SM (4)

Symmetry of families and Familons

To resolve **the problem of quark-lepton families** a new global symmetry $SU(3)_H$ can be introduced. It's spontaneous breaking leads to 8 new scalar fields Nambu-Goldstone bosons - *familons*.

Familons interact with quarks and leptons at energy scale υ_a as

$$L_{aff} = ic_{aff} \frac{m_f}{\upsilon_a} a\bar{f}\gamma_5 f$$

Their interactions lead to various transitions between fermions of different families.

In the model of singlet familon there is only 1 such Nambu-Goldstone boson.

Trends in extension of SM (5)

Model of **Peccei-Quinn**

To resolve **the problem of strong CP-violation** a new global symmetry $U(1)_{PQ}$ with new scalar field is introduced.

Scalar field is associated with spontaneous $U(1)_{PQ}$ violation at energy scale υ_a, and provides mechanism of dynamical suppression of θ (due to its Nambu-Goldstone boson – axion).

Axion interacts with quarks as

$$L_{aff} = ic_{aff} \frac{m_f}{\upsilon_a} a\bar{f}\gamma_5 f$$

and have potential $$V_{\mathrm{eff}} \sim m_u \Lambda^3_{\mathrm{QCD}} \left(1 - \cos(\theta + a/\upsilon_a)\right)$$

minimizing at $a = \langle a \rangle = -\theta \upsilon_a$

$$\Rightarrow \quad \Delta L_{\mathrm{QCD}} = \frac{\alpha_s^2}{16\pi}\left(\theta + \frac{a}{\upsilon_a}\right) \cdot \varepsilon_{\alpha\beta\mu\nu} G^{a\,\alpha\beta} G^{a\,\mu\nu} \to 0$$

Trends in extension of SM (5)

Model of **Peccei-Quinn: properties of axion**

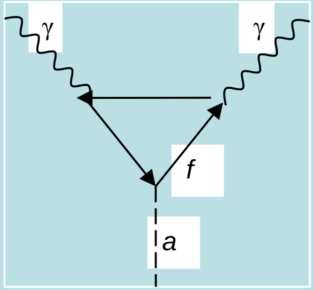
The axion has the mass, which is related with its energy scale

$$m_a \approx 0,6\,\text{meV}\,\frac{10^{10}\,\text{GeV}}{v_a}$$

It decays into two photons at

$$\tau(a \to \gamma\gamma) = \frac{64\pi^3}{c_{a\gamma\gamma}^2 \alpha^2}\frac{v_a^2}{m_a^3} \approx \frac{2\cdot 10^{17}\,\text{years}}{c_{a\gamma\gamma}^2}\left(\frac{\text{eV}}{m_a}\right)^5 \approx$$

$$\approx \frac{2\cdot 10^{33}\,\text{years}}{c_{a\gamma\gamma}^2}\left(\frac{v_a}{10^{10}\,\text{GeV}}\right)^5.$$



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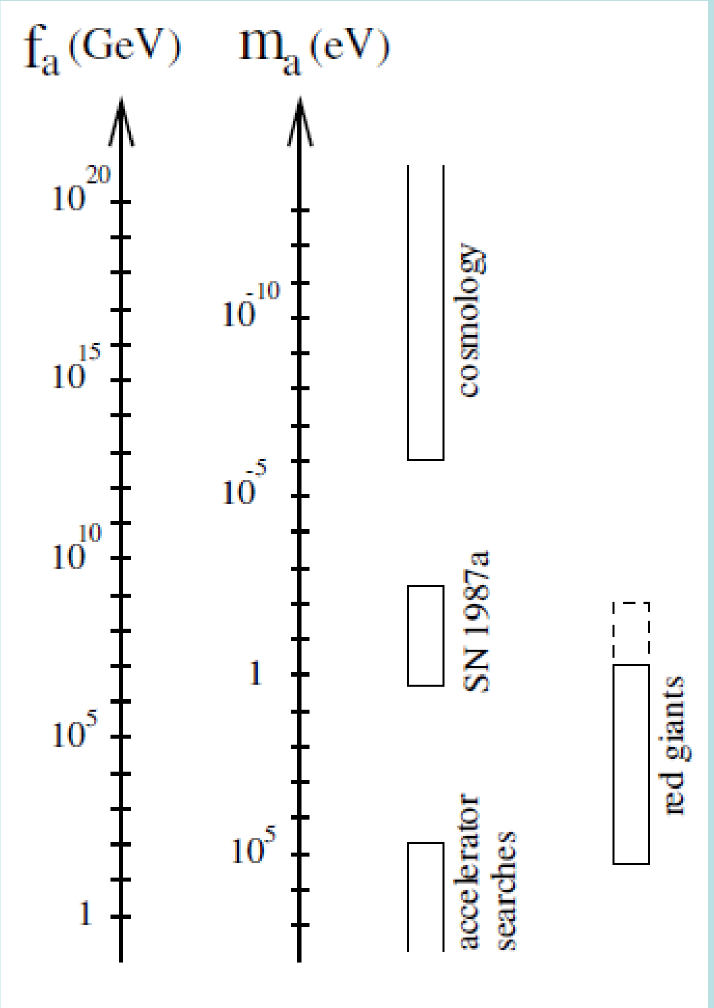


According existing constraints its mass and energy scale must be

$$0.5\cdot 10^{-5}\,\text{eV} < m_a < 0,5\cdot 10^{-2}\,\text{eV}$$

$$2\cdot 10^{9}\,\text{GeV} < v_a < 10^{12}\,\text{GeV}$$

Gauge approach to the problem of quark-lepton families

- There are free families of quarks and leptons with apparent symmetry of their interactions and apparent hierarchy of their mass states.

$$\begin{pmatrix} \nu_e \\ e \\ u \\ d \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \\ c \\ s \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \\ t \\ b \end{pmatrix}$$

Masses of fermions are determined by EW scale.

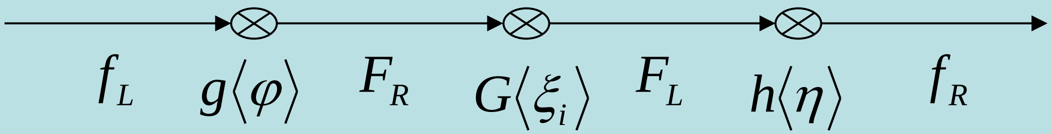
Masses of H-gauge bosons must be much heavier than this scale, due to the absence of flavor changing neutral currents (FCNC)

Gauge model of broken family symmetry

- To avoid symmetric mass terms L- and R-handed states of fermions should belong to different representations. It excludes orthogonal and vector-like groups of family symmetry and reduces the choice to SU(3) for 3 generations [8 H gauge bosons].
- Heavy partners F of ordinary fermions f acquire mass by Yukawa coupling with Higgs fields [3 multiplets $\langle \xi_i \rangle$ and singlet $h\langle \eta \rangle = \mu$]. Mixing of F and f induces SU(3) symmetry breaking pattern in mass pattern of quarks and leptons.
- To compensate anomalies heavy partners N of neutrinos are necessary. It provides the mechanism of neutrino mass.
- Natural choice of Higgs potential leads to additional global U(1) symmetry. It links physics of axion to physics of broken family symmetry.

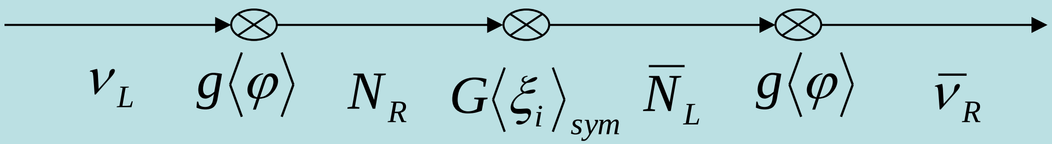
Fermion masses

- Dirac see-saw mechanism of mass generation for quarks and charged leptons



$$m_f = \frac{h\langle\eta\rangle}{G\langle\xi_i\rangle} g_f \langle\varphi\rangle$$

- Maiorana see-saw mechanism for neutrino mass.



$$m_\nu = \frac{g_f\langle\varphi\rangle}{G\langle\xi_i\rangle} g_f \langle\varphi\rangle = m_f \frac{g_f\langle\varphi\rangle}{h\langle\eta\rangle}$$

- Pattern of symmetry breaking

$$SU(3)\otimes U(1) \xrightarrow[\langle\xi_0\rangle]{} SU(2)\otimes U'(1) \xrightarrow[\langle\xi_1\rangle]{} U''(1) \xrightarrow[\langle\xi_2\rangle\equiv V]{} I$$

- Results in mass pattern

$$m_i \propto \langle\xi_i\rangle^2$$

Reduction of number of parameters

Hierarchy of masses is not given by hands, but follows from pattern of family symmetry breaking

	e	μ	τ
e	m_e	s_{12}	s_{13}
μ	s_{12}	m_μ	s_{23}
τ	s_{13}	s_{23}	m_τ

	e	μ	τ
e	0	p	0
μ	p	0	q
τ	0	q	r

3 parameters instead of 9

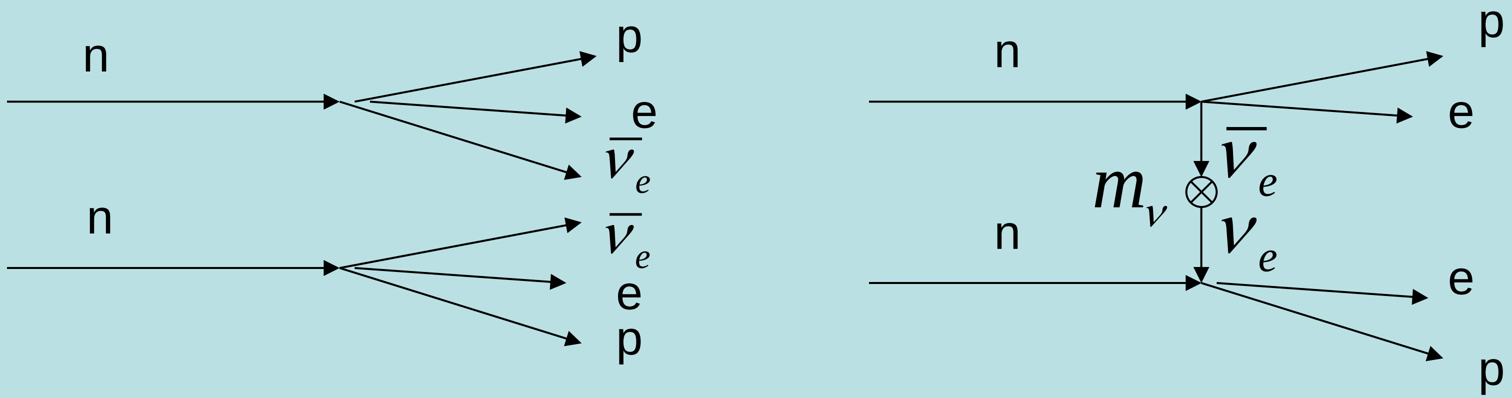
Archion

- The assumption that Higgs potential contains only terms, which can be generated by radiative effects of gauge and Yukawa couplings excludes the term $\propto p\xi_i\xi_j\xi_k$.
- It leads to additional global U(1) symmetry. Breaking of this symmetry results in the existence of Goldstone boson α .
- This boson shares the properties of Majoron, familon and axion and was called archion.
- Archion couplings are proportional to 1/*V* and its mass is given by

$$m_\alpha = C \frac{f_\pi}{V} m_\pi$$

Physical consequences

- FCNC, due to H-bosons $K \to \mu e; \bar{D}^0 \leftrightarrow D^0; \ldots$
- Mass of neutrino $m_\nu \propto V^{-1}$, neutrino oscillations, double neutrinoless beta-decay due to Majorana mass



- Archion decays $K \to \pi\alpha; \mu \to e\alpha; \ldots$
- Archion decays of massive neutrinos

$$\nu_H \to \nu_L \alpha \qquad \tau = \frac{V^2}{a_{HL}^2 m_H^3} \propto V^5$$

Trends in extension of SM (6)

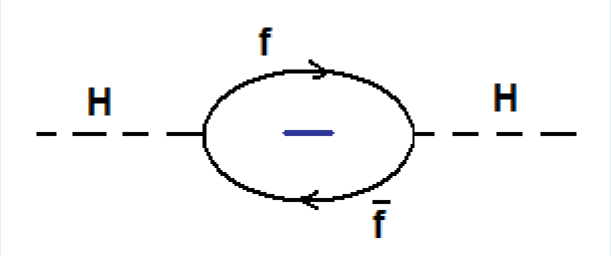
Supersymmetry (SUSY)

All particles with spin ***s*** get supersymmetric partner – particle with spin ***s'***=|***s***-1/2| and all other identical quantum numbers (except the mass in case of broken SUSY).

$$e_{L,R}(s=0) \leftrightarrow \tilde{e}_{L,R}(s=0)$$
$$\gamma(s=1) \leftrightarrow \tilde{\gamma}(s=1/2)$$
$$\text{or } B(s=1) \leftrightarrow \tilde{B}(s=1/2)$$
$$....$$

Photino (bino) is Majorana particle

1) **SUSY** helps to resolve the problem of large radiation correction in Higgs sector.



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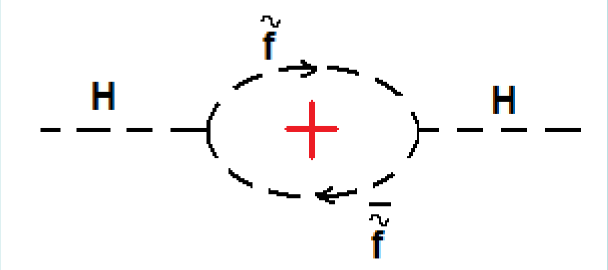


→ 0

2) **SUSY** improves convergence of the gauge constants (in GUT).

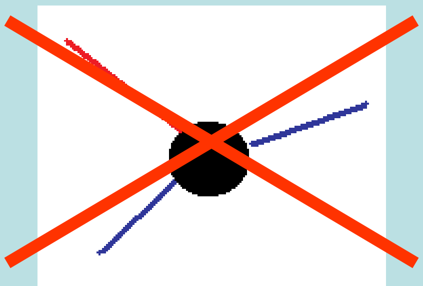
3) **SUSY** may serve as a basic symmetry for construction of quantum gravity.

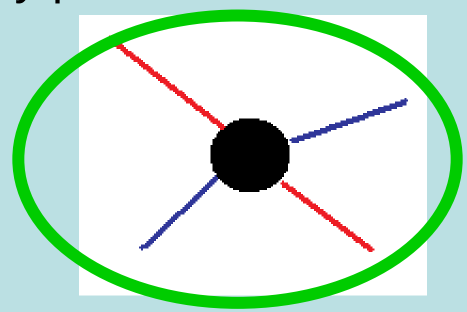
SUSY must be, evidently, broken. A “hidden” sector is introduced which induces soft SUSY breaking in our sector by means of 1) gravity (**SUGRA**), 2) special gauge fields (**GMSB**).

Trends in extension of SM (6)

Supersymmetry (SUSY)

To avoid fast decay of proton in GUT, a multiplicative quantum number – *R*-parity is introduced. *R*=+1 is assigned for all ordinary particles, and *R*=-1 – for SUSY partners.





Consequence: the lightest SUSY particles (**LSP**) is stable.

Neutralino is often suggested for a role of LSP. Neutralino is a superposition of four SUSY partners of bino, neutral wino, two neutral higgsino.

$$\chi^0_{1,2,3,4} = N^{(B)}_{1,2,3,4}\tilde{B} + N^{(W)}_{1,2,3,4}\tilde{W}^3 + N^{(H_1)}_{1,2,3,4}\tilde{H}^0_1 + N^{(H_2)}_{1,2,3,4}\tilde{H}^0_2$$

Aslo, *gravitino* or *axino* are sometimes suggested for a role of LSP.

Trends in extension of SM (7)

Kaluza-Klein (KK) models

$$g_{MN} = \begin{pmatrix} g_{\mu\nu} & g_{\mu n} \\ g_{m\nu} & g_{mn} \end{pmatrix}$$

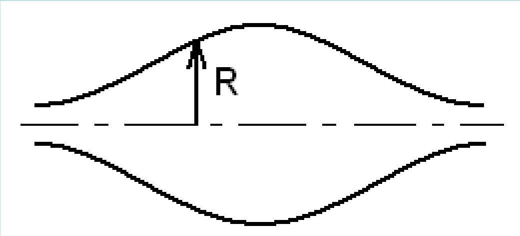
M,N=0,…*D*

μ,ν=0,1..3

m,n=4,…*D* (the range 4,…*D* is marked *d*)

Describes other interactions

If extra *d* dimensions are compactified with *R*=const, then they are manifested in form of the KK-mass states for all particles, if *R*≠const – in form of interaction.

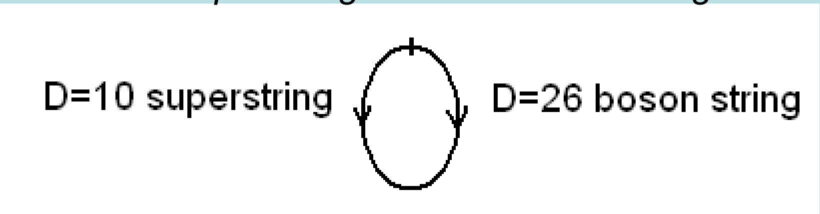


Trends in extension of SM (9)

Superstring theory, M-theory

Each species of particles is a certain vibration mode of a string – fundamental element of zero thickness and of Planckian length. Strings may be *closed* and *open*.

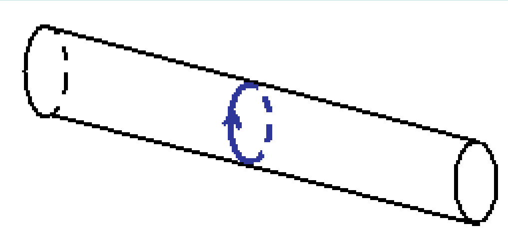
Most popular string model is a so called *heterotic string* (closed) – combines the models of *superstring* and of *bosonic string*.



Fixed gauge groups: $E_8 x E_8'$, SO(32)

Each contains 248 bosons and 248 fermion fields

Possible consequence: existence of homotopically stable particle



Superstring U supergravity ⊂ M-theory (?)

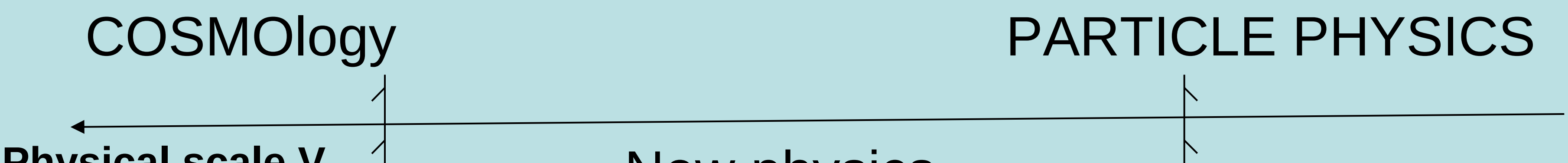
D=10 **D≤11**

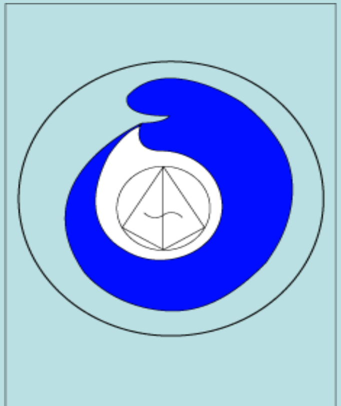
Conclusions

- The Standard model contains internal inconsistencies and is not complete. The first experimental evidence of its incompleteness gives nonzero mass of neutrino.
- The problems of the Standard Model imply its extensions for their solution.
- There are only few experimental probes for these extensions, most of which involve physics of very high energy.
- One should extend the set of such probes by astrophysical and cosmological tests.
- We'll see in the successive lectures that the modern cosmology, in its turn, involves physics beyond the Standard model.
- Mutual relationship of problems of frontiers of physics at extreme microscopic and macroscopic scales is the subject of cosmoparticle physics

Basic ideas of cosmoparticle physics

- **Physics beyond the Standard model can be studied in combination of indirect physical, astrophysical and cosmological effects**
- **New symmetries imply new conserved charges. Strictly conserved charge implies stability of the lightest particle, possessing it.**
- **New stable particles should be present in the Universe. Breaking of new symmetries implies cosmological phase transitions. Cosmological and astrophysical constraints are supplementary to direct experimental search and probe the fundamental structure of particle theory at the scale V**
- **Combination of physical, cosmological and astrophysical effects provide an over-determined system of equations for parameters of particle theory**





Extremes of physical knowledge converge in the mystical Uhrohboros vicious circle of problems, which can be resolved by methods of Cosmoparticle physics