NEUTRINOS AND AXION-LIKE PARTICLES

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STANDARD MODEL

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm QCD+EWD} + \mathcal{L}_{\rm H}$$

$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \longrightarrow \mathrm{SU}(3)_c \times \mathrm{U}(1)_{\rm em}$$

- SM has achieved tremendous success in reproducing **accelerator phenomena**
- discovering the origin and structure of $\mathcal{L}_{\rm H}$ is only at its begining
- SM has failed facing the evidence of **dark matter**

- electroweak scale
  - Higgs potential

$$\mathcal{V}_H = \lambda(H^\dagger H - v/2)^2$$

unnaturally small

$v \doteq 246\,\mathrm{GeV} \approx 10^{-16} M_{\rm Planck}$ $\quad M_{W,Z,h}(m_t) \propto v$

STANDARD MODEL

- neutrino masses (oscillations)
  - Dirac neutrinos

$$\begin{aligned} d &= d_L + d_R \\ u &= u_L + u_R \\ e &= e_L + e_R \\ \nu &= \nu_L + \nu_R \end{aligned}$$

$$\mathcal{L}_\nu = -\bar{\nu} m_\nu \nu$$

unnaturally small

$m_\nu < 10^{-11} v$ b-spectrum endpoint, 0nbb, cosmology

- QCD theta parameter
  - *CP* violation in QCD

$$\mathcal{L}_\theta = \bar{\theta} \tilde{G}_c^{\mu\nu} G_{c\mu\nu}$$

unnaturally small

$\bar{\theta} < 10^{-10}$ electric dipole moment of neutron weighing

NEUTRINOS

NEUTRINO OSCILLATIONS

- flavor basis tells us how do neutrinos interact
- mass basis tells us how do neutrinos propagate

$$\mathcal{L}_{w+m} = \frac{g}{\sqrt{2}}(\bar{e}_{Li}\gamma^{\mu}\nu_{Li})W^-_{\mu} + \bar{e}_i M^{(e)}_{ij} e_j + \frac{1}{2}\bar{\nu}_{Li} M^{(\nu)}_{ij} \nu_{Lj}{}^c + \ldots + \text{h.c.}$$

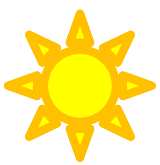
$$= \frac{g}{\sqrt{2}}(\bar{e}^m_i \gamma^{\mu} U_{ij} \nu^m_j)W^-_{\mu} + \bar{e}^m_i m^{(e)}_i e^m_i + \frac{1}{2}\bar{\nu}^m_i m^{(\nu)}_i (\nu^m_i)^c + \ldots + \text{h.c.}$$

U_{PMNS} lepton mixing matrix

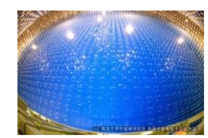
$|\nu_e\rangle = U^*_{e1}|\nu^m_1\rangle + U^*_{e2}|\nu^m_2\rangle + U^*_{e3}|\nu^m_3\rangle$

ultra-relativistic or quasi-degenerate in mass; coherent

$\mathcal{A}_{ee}|\nu_e\rangle + \mathcal{A}_{e\mu}|\nu_\mu\rangle + \mathcal{A}_{e\tau}|\nu_\tau\rangle$



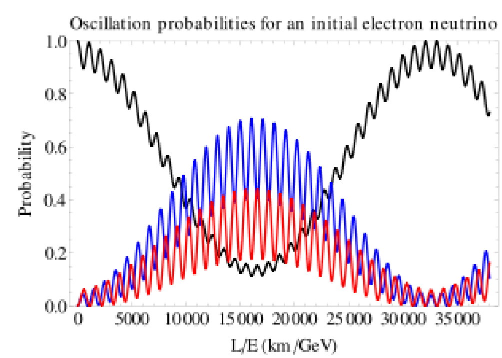
$U^*_{e1}e^{\mathrm{i}E_1 t}|\nu^m_1\rangle + U^*_{e2}e^{\mathrm{i}E_2 t}|\nu^m_2\rangle + U^*_{e3}e^{\mathrm{i}E_3 t}|\nu^m_3\rangle$



$$\mathcal{P}(\nu_i \to \nu_j) = |\mathcal{A}_{ij}|^2 = \sin^2 2\theta_{ij} \cdot \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_{21}} & 0 \\ 0 & 0 & e^{i\lambda_{31}} \end{pmatrix}$$

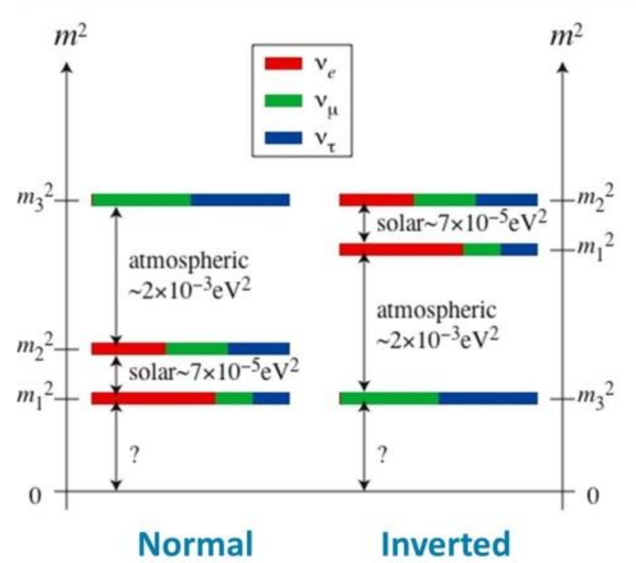


NEUTRINO OSCILLATIONS

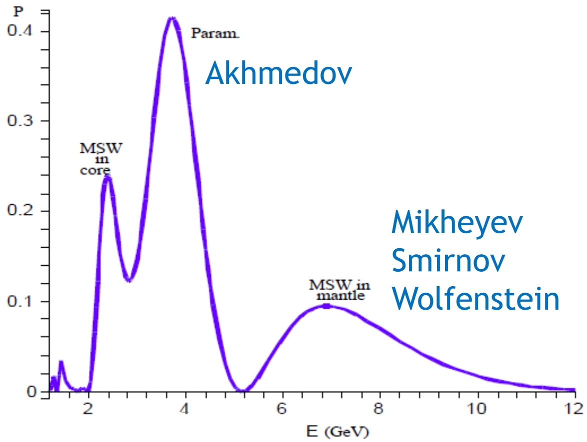
$$|\Delta m^2_A| = (2.5 \pm 0.3) \times 10^{-3} \mathrm{eV}^2$$

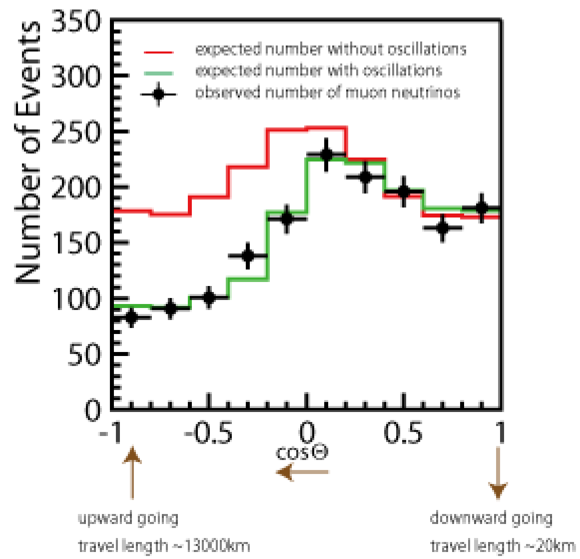
$$\Delta m^2_\odot = (8.0 \pm 0.3) \times 10^{-5} \mathrm{eV}^2$$

$$U_{\mathrm{PMNS}} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$



- matter effects:





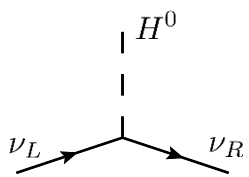
what is the actual value of neutrino masses ?

DIRAC NEUTRINOS

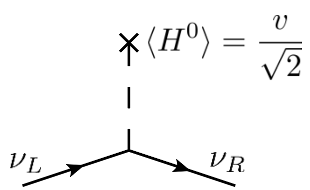
It is natural to complete the lepton right-handed doublet.

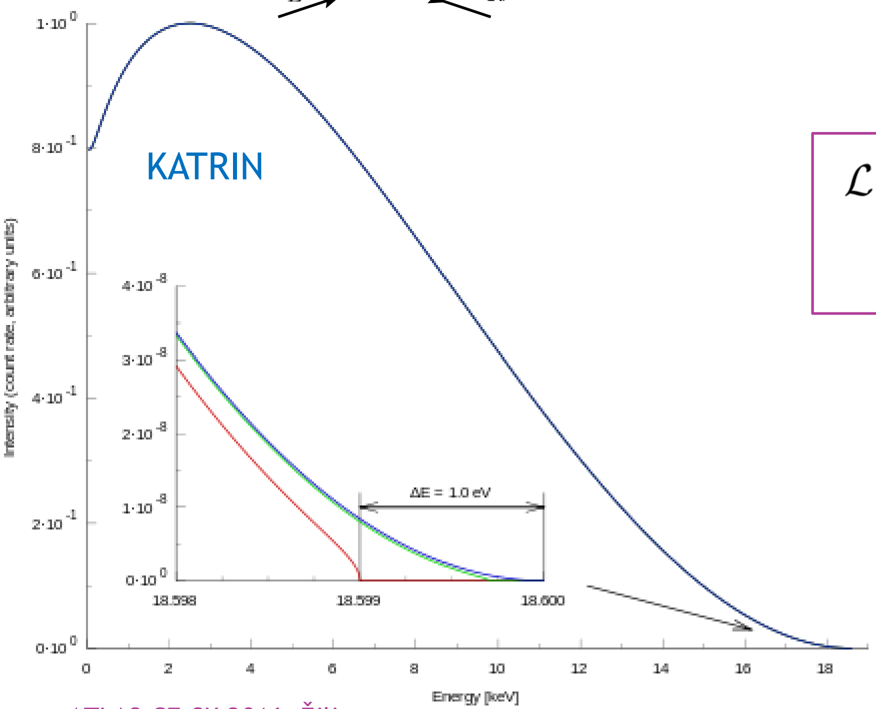
$$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}, \quad \ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad \begin{matrix} \nu_R \\ e_R \end{matrix}$$

$$\begin{aligned} \mathcal{L}_\nu &= -y_\nu \bar{\ell}_L H \nu_R + \text{h.c.} \\ &\supset -y_\nu \bar{\nu}_L H^0 \nu_R + \text{h.c.} \end{aligned}$$



$$H^0 \longrightarrow \frac{1}{\sqrt{2}}(v+h)$$





$$\begin{aligned} \mathcal{L}_\nu &\supset -\frac{y_\nu}{\sqrt{2}}(v+h)\bar{\nu}_L \nu_R + \text{h.c.} \\ &\supset -m_\nu \bar{\nu}_L \nu_R + \text{h.c.} \;=\; -\bar{\nu} m_\nu \nu \end{aligned}$$

$$\nu = \nu_L + \nu_R$$

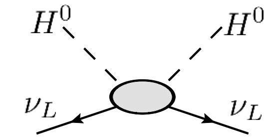
$$m_\nu < 10^{-11} v$$

Upper limits of cca 0.2 eV comes from various (non)observations (beta-decay-spectrum endpoint, 0nbb, cosmology).

SEESAW MECHANISM

- New physics beyond Standard Model enters effective lagrangian by operators of dim>4 suppressed by its energy scale.

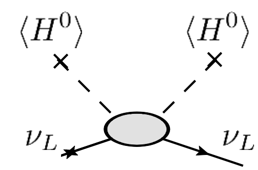
$$\mathcal{L}_{\rm SM}^{(\rm eff)} = \mathcal{L}_{\rm SM} - \frac{G_\nu}{\Lambda}(\bar{\ell}_L^c \tilde{H}^*)(\tilde{H}^\dagger \ell_L) + \text{h.c.} + \mathcal{O}(\Lambda^{-2})$$



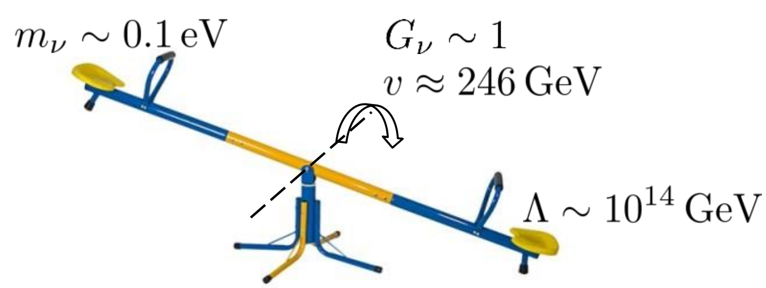
  - The Weinberg operator is the only one of dim=5 allowed by gauge symmetries in SM.
  - It violates the lepton number.
  - It **generates neutrino masses suppressed** by the ratio v/Λ.

$$\nu = \nu_L + \nu_L^c$$

$$\mathcal{L}_\nu = -\frac{G_\nu}{\Lambda}(\bar{\nu}_L^c \frac{v}{\sqrt{2}})(\frac{v}{\sqrt{2}}\nu_L) + \text{h.c.} = -\frac{1}{2} m_\nu \bar{\nu}^c \nu + \text{h.c.}$$



$$m_\nu \simeq G_\nu v \frac{v}{\Lambda}$$

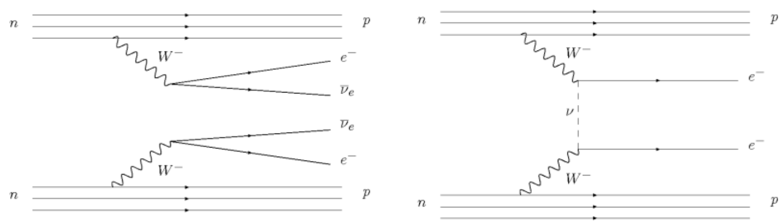


- Seesaw mechanism provides **Majorana neutrinos** which can be made **light naturally** by large enough Λ.

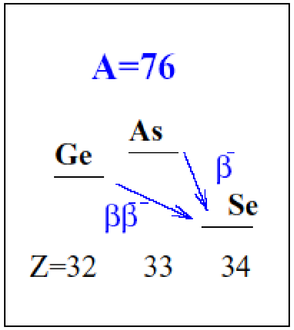
NEUTRINOLESS DOUBLE BETA DECAY

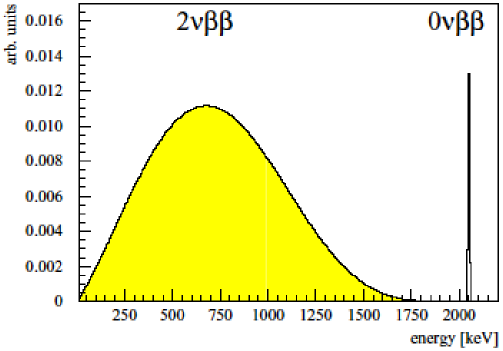
- Majorana nature of neutrinos and lepton number violation allows rare neutrinoless double beta decay (0nbb,ECEC).

$$(A,Z) \longrightarrow (A,Z+2) + e^- + e^- (+\bar{\nu}_e + \bar{\nu}_e)$$



  - kinematically allowed only for few nuclei



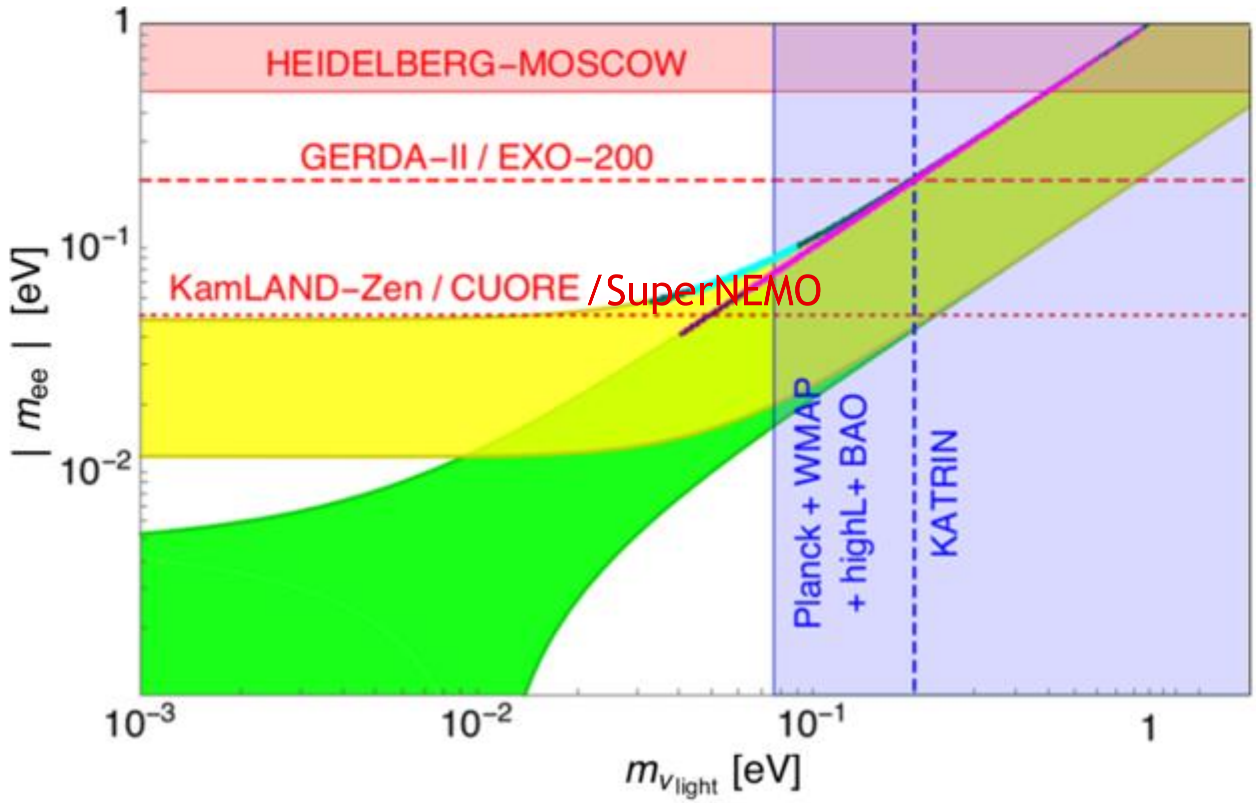


  - ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{150}Nd, ^{238}U
  - 2nbb: $T_{1/2} \approx (10^{18} - 10^{24})\,\mathrm{y}$
  - 0nbb: $T_{1/2} > 10^{26}\,\mathrm{y}$

NEUTRINOLESS DOUBLE BETA DECAY

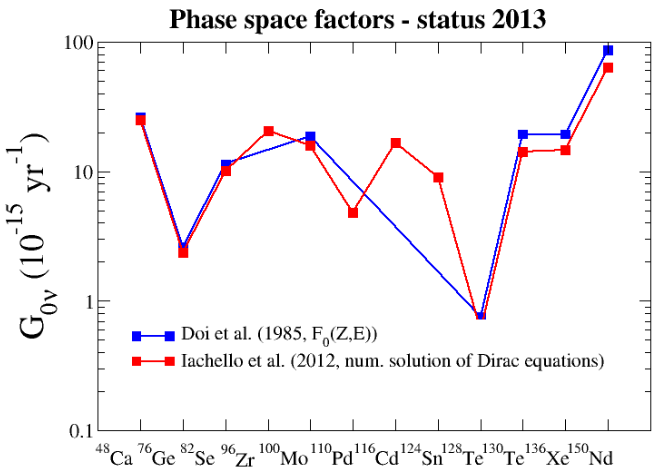
$$\left(T_{1/2}^{0\nu}\right)^{-1} = \left|\frac{m_{\beta\beta}}{m_e}\right|^2 g_A^4 \left|M_\nu^{0\nu}\right|^2 G^{0\nu}$$

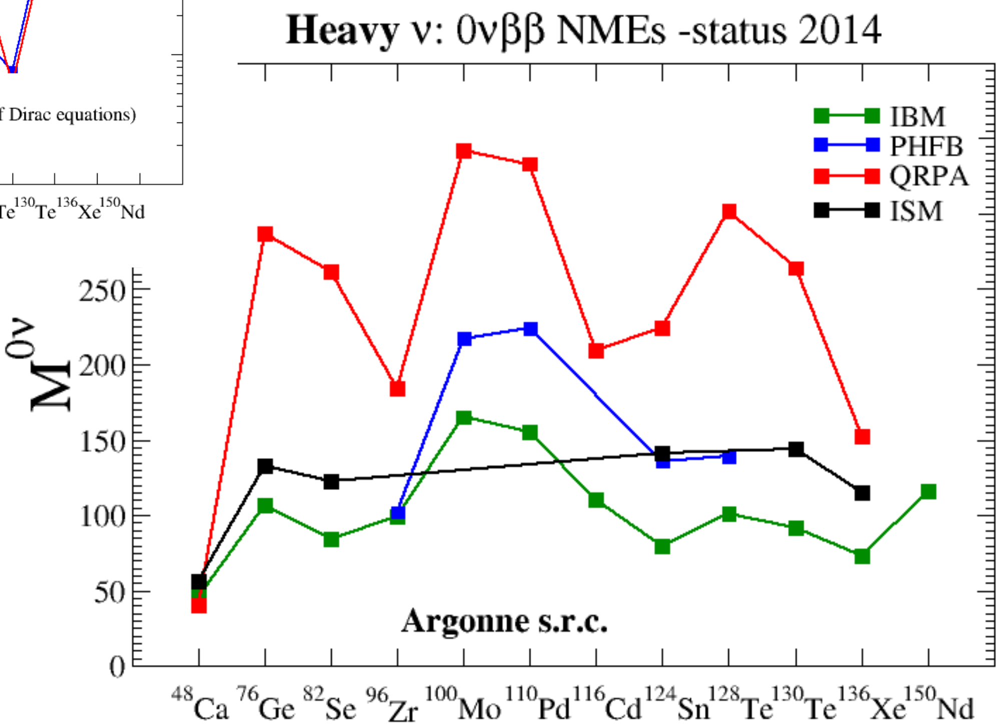
$$|m_{\beta\beta}| \;=\; |c_{12}^2 c_{13}^2 e^{i\alpha_1} m_1 + s_{12}^2 c_{13}^2 e^{i\alpha_2} m_2 + s_{13}^2 m_3|$$



NEUTRINOLESS DOUBLE BETA DECAY

- The predicted values of half-lifes have big uncertainties mainly from nuclear matrix elements.





searching for

AXION(S)

ANOMALOUS GLOBAL SYMMETRIES

- QCD in the chiral limit $m_q \to 0$

$$\mathcal{L}_{\rm QCD} = \bar{q}\mathrm{i}\not{D}q - \frac{1}{4}G_a^{\mu\nu}G_{a\mu\nu}$$

$$q = q_L + q_R = \left(\begin{array}{c} u \\ d \\ \vdots \end{array}\right)\Bigg\} n_f$$

- global symmetries

$$G_{\rm class.} = \mathrm{U}(n_f)_L \times \mathrm{U}(n_f)_R \qquad q' = \mathrm{e}^{\mathrm{i}\varepsilon_a^L T_a} q_L + \mathrm{e}^{\mathrm{i}\varepsilon_a^R T_a} q_R$$

$$G_{\rm quant.} = \mathrm{SU}(n_f)_L \times \mathrm{SU}(n_f)_R \times \mathrm{U}(1)_B \qquad q' = \mathrm{e}^{\mathrm{i}\varepsilon/3} q$$

$$\partial_\mu J^\mu = 0$$

- axial symmetry is anomalous

$$G_{\rm class.}/G_{\rm quant.} = \mathrm{U}(1)_A \qquad q' = \mathrm{e}^{\mathrm{i}\varepsilon^A \gamma_5} q$$

$$\partial_\mu J_A^\mu = \frac{\alpha_3}{4\pi} G_a^{\mu\nu}\tilde{G}_{a\mu\nu} + 2m\bar{q}\mathrm{i}\gamma_5 q$$

- global symmetries are spontaneously broken by chiral codensate

$$\langle 0|\,\bar{q}q\,|0\rangle = \langle 0|\,\bar{q}_R q_L + \mathrm{h.c.}\,|0\rangle \quad \to \quad \langle 0|\,\bar{q}_R \mathrm{e}^{-\mathrm{i}\varepsilon_a^R T_a}\mathrm{e}^{\mathrm{i}\varepsilon_a^L T_a} q_L + \mathrm{h.c.}\,|0\rangle$$

$$G_{\rm quant.} \quad \to \quad \mathrm{SU}(n_f)_V \times \mathrm{U}(1)_B \qquad \varepsilon_a^V = \varepsilon_a^L = \varepsilon_a^R$$

$$\Rightarrow \quad n_f = 2: \qquad \pi^+, \pi^0, \pi^-, \quad m_\pi = 0$$
$$\eta^0, \quad m_\eta \neq 0$$

VACUUM OF GAUGE THEORY

- usually vacuum is empty of fields

$$\psi = 0$$

- gauge fields have however redundant degrees of freedom, which can make nontrivial vacuum field configuration

$$A_n = \frac{\mathrm{i}}{g}\Omega_n \nabla \Omega_n^{-1}$$

gauge transformation of $A = 0$

classes of vacuum configurations (pure gauge fields) $\Omega_n \overset{r\to\infty}{\longrightarrow} \mathrm{e}^{2\pi \mathrm{i} n}; \quad |n\rangle$

$$|\theta\rangle = \sum_{n=0}^{\infty} \mathrm{e}^{-\mathrm{i}n\theta}\,|n\rangle$$

gauge invariant vacuum

- ‘t Hooft – tunelling transition between two vacua

due to the growth of QCD strengthat large distances

$$A[\nu \neq 0] \sim A[\nu = 0]$$

$$_+\langle\theta|\theta\rangle_- = \sum_\nu \mathrm{e}^{\mathrm{i}\theta\nu}\Big(\sum_n {}_+\langle n+\nu|n\rangle_-\Big) = \int_{\mathrm{paths}} \delta A_\mu \mathrm{e}^{\mathrm{i}S_{\mathrm{eff}}[A]}$$

what should be the action to incorporate such transitions?

$$\nu = n_+ - n_- = \int \mathrm{d}^4x\, \frac{\alpha_3}{8\pi} G_a^{\mu\nu}\tilde{G}_{a\mu\nu}$$

$$\rightarrow S_{\mathrm{eff}} = S + \theta \int \mathrm{d}^4x\, \frac{\alpha_3}{8\pi} G_a^{\mu\nu}\tilde{G}_{a\mu\nu} \rightarrow$$

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L} + \theta \frac{\alpha_3}{8\pi} G_a^{\mu\nu}\tilde{G}_{a\mu\nu}$$

STRONG CP PROBLEM IN QCD

- CP violation has two sources in QCD

$$\theta\frac{\alpha_3}{8\pi}G_a^{\mu\nu}\tilde{G}_{a\mu\nu} - \bar{q}_{Li}M_{ij}q_{Rj} + \text{h.c.}$$

vacuum structure — quark mass matrix

- quark mass matrix should be diagonalized by: $q_R \to U_R q_R$, $q_L \to U_L q_L$ ⟶ $m_\text{d} = U_L^\dagger M U_R$

  part of which is axial symmetry $\mathrm{U}(1)_A$

- due to anomaly, **proper** axial transformation is **not** that with $\partial_\mu J_A^\mu = \frac{\alpha_3}{4\pi}G_a^{\mu\nu}\tilde{G}_{a\mu\nu} \stackrel{\text{def}}{=} \partial_\mu K^\mu$

  but rather that with $\partial_\mu \tilde{J}_A^\mu \stackrel{\text{def}}{=} \partial_\mu(J_A^\mu + K^\mu) = 0$

  which has time-independent eventhough gauge dependent charge $\tilde{Q}_A$

- the proper axial transformation changes vacuum $\mathrm{e}^{\mathrm{i}\alpha\tilde{Q}_A}|\theta\rangle = |\theta+\alpha\rangle$

$\xrightarrow{\mathrm{e}^{\mathrm{i}\alpha\tilde{Q}_A}}$ $\bar{\theta}\frac{\alpha_3}{8\pi}G_a^{\mu\nu}\tilde{G}_{a\mu\nu} - m\bar{q}q$ — diagonal masses and $\bar{\theta} \stackrel{\text{def}}{=} \theta + \alpha$

$\xrightarrow{\mathrm{e}^{\mathrm{i}\bar{\theta}\gamma_5/4}}$ $0 - m(\bar{q}q + \mathrm{i}\bar{\theta}\bar{q}\frac{\gamma_5}{2}q)$ — electric dipole moment of neutron

$\bar{\theta} < 2\times 10^{-10}$ ⟵ $d_n \sim \frac{em}{M_n^2}\bar{\theta} \sim 5\times 10^{-16}\,\text{ecm}$ — experiment: $d_n^\text{exp} < 10^{-25}\,\text{ecm}$

PECCEI-QUINN SOLUTION

- new symmetry $\mathrm{U}(1)_{\mathrm{PQ}}$ with the same anomaly $\partial_\mu J^\mu_{\mathrm{PQ}} \propto G\tilde{G}$
  - if Wigner-Weyl realization → at least one massless quark

$$\mathrm{e}^{-\mathrm{i}\bar{\theta}\tilde{Q}_{\mathrm{PQ}}}\,|\theta\rangle = |0\rangle$$

  - but it **must** be broken in SM → Nambu-Goldstone realization

NG boson = Winberg-Wilczek axion (1978)

$$m_a \sim \frac{\Lambda^2_{\mathrm{QCD}}}{f}, \qquad f \quad \text{scale of symmetry breaking}$$

  - effective lagrangian for the axion

$$\mathcal{L}^{\mathrm{eff}}_{\mathrm{SM}} = \mathcal{L}_{\mathrm{SM}} + \underbrace{\bar{\theta}\frac{\alpha_3}{8\pi}G^{\mu\nu}_a\tilde{G}_{a\mu\nu}}_{\text{axial anomaly}} - \frac{1}{2}\partial_\mu a\partial^\mu a + \underbrace{\frac{a}{f}\xi\frac{\alpha_3}{8\pi}G^{\mu\nu}_a\tilde{G}_{a\mu\nu}}_{\text{Peccei-Quinn anomaly}} + \mathcal{L}^{\mathrm{int}}_{\mathrm{axion}}\left[\frac{\partial_\mu a}{f};\psi\right]$$

  - the axion has periodic potential which is minimized by

$$\boxed{\theta_{\mathrm{eff}} = \bar{\theta} + \frac{\xi}{f}\langle a(x)\rangle = 0}$$

ANOMALIES IN STANDARD MODEL

- all the gauge symmetry currents are anomaly free $\partial_\mu j^\mu_{c,L,Y} = 0$
  nice consistency check

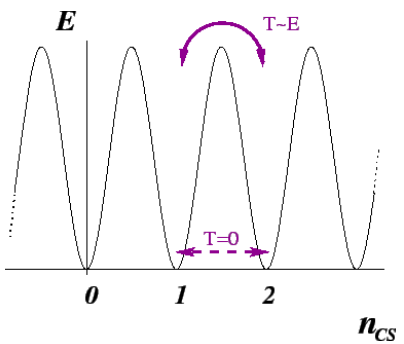
- lepton and baryon number symmetries are anomalous!

$$\partial_\mu J^\mu_{\rm B} = 3\frac{g_1^2}{8\pi^2} Y_{\mu\nu}\tilde{Y}^{\mu\nu} - 3\frac{g_2^2}{32\pi^2} W_{\mu\nu a}\tilde{W}^{\mu\nu}_a$$
$$\partial_\mu J^\mu_{\rm L} = 3\frac{g_1^2}{8\pi^2} Y_{\mu\nu}\tilde{Y}^{\mu\nu} - 3\frac{g_2^2}{32\pi^2} W_{\mu\nu a}\tilde{W}^{\mu\nu}_a$$

- but their combination…

$\partial_\mu J^\mu_{\rm B-L} = 0$ → symmetry which might be gauged in SM (L-R models, GUT)

$\partial_\mu J^\mu_{\rm B+L} \neq 0$ → symmetry which might be gauged in SM (L-R models, GUT)



$\Delta(B+L) = 2N_g\nu \qquad \Delta(B+L)_{\rm min} = 6$

$\Delta(B+L) = 2$ process $p^+ \to e^+\pi^0$ is still forbidden in SM)

$$A[\nu]_{(B+L){\rm viol.}} \sim 10^{-80\nu}$$

in the early Universe due to thermal effects

$$A[\nu]_{(B+L){\rm viol.}} \sim 1$$

basis of baryogenesis via leptogenesis

INVISIBLE AXION AS DARK MATTER

- axion from singlet Higgs
  - KSVZ axion: singlet couples to new heavy quark only
  - DFSZ axion: singlet couples to Higgs doublet(s) only
  - LMN axion=majoron: singlet couples to neutrinos only

- cold dark matter does not need to consist of heavy particles >keV
- sub-eV particles work as well if
  - non-thermal (cold) production
  - non-fermionic particles

- axion window
  - to avoid axion emission by stars that would heat them up and accelerate their evolution
  - to avoid overclosing of the universe

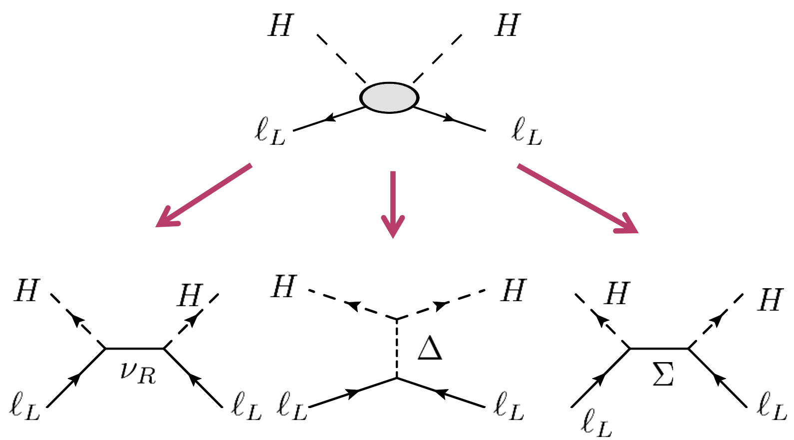
$$f \in (10^9, 10^{12})\,\mathrm{GeV}$$
$$m_a \in (10^{-6}, 10^{-3})\,\mathrm{eV}$$

consequences of

PHENOMENOLOGICAL EXTENSION OF STANDARD MODEL

LAGRANGIAN WITH OPERATORS UP TO DIM=5

- Weinberg operator originates in a new physics



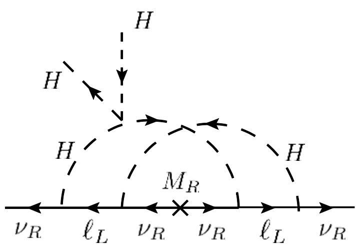
type I seesaw — type II — type III

keV sterile neutrinos are DM candidates

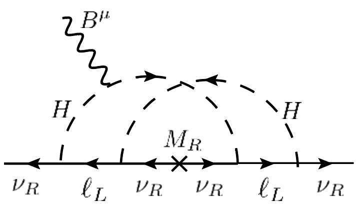
$$\mathcal{L}_5 = \mathcal{L}_{\rm SM} + \bar{\nu}_R i\partial\!\!\!/ \nu_R + \frac{1}{2}(\bar{\nu}_R M_R \nu_R^c + \text{h.c.}) + y_\nu(\bar{\ell}_L \tilde{H} \nu_R + \text{h.c.})$$
$$+ G_{hh\gamma\gamma} H^\dagger H (\bar{\nu}_R \nu_R^c) + G_{\gamma\nu\nu} Y^{\mu\nu} (\bar{\nu}_R \sigma^{\mu\nu} \nu_R^c)$$

only two additional dim=5 operators

no other new fields are necessary:



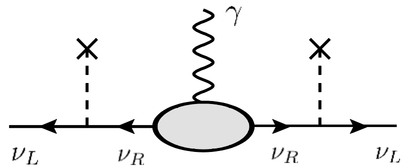
renormalizes M_R



magnetic moment of neutrino

MAGNETIC MOMENT OF NEUTRINO

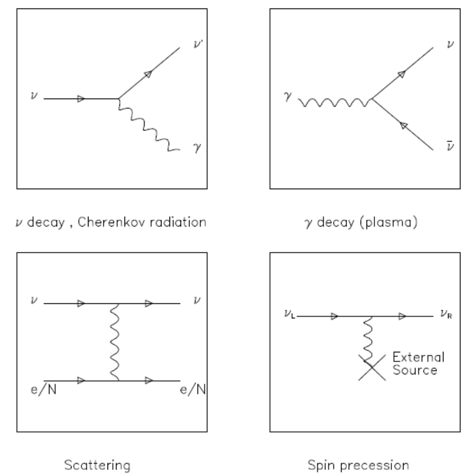
- for Majorana neutrinos



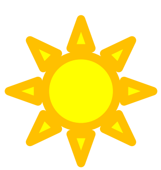
$$\mathcal{L}_\mu = \mu_{ij}\bar{\nu}_{Li}\sigma_{\mu\nu}\nu^c_{Lj}F^{\mu\nu}$$

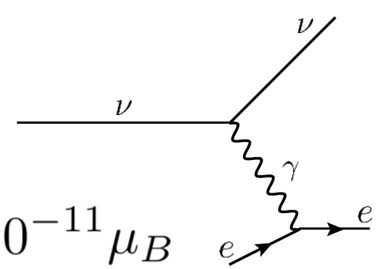
$$\mu^{\mathrm{T}} = -\mu$$

- the prediction (without exotics) is $\mu_\nu \sim 10^{-19}\mu_B$
  - connection with neutrino mass $m_\nu \sim \frac{\Lambda^2}{2m_e}\frac{\mu_\nu}{\mu_B}$
  - distinguishing between Dirac and Majorana nature of neutrinos
  - probe of new physics
  - CMB radiation distortions
  - changes in a color-magnitude diagram of globular clusters
  - neutrino spin-flavor precession in magnetic field



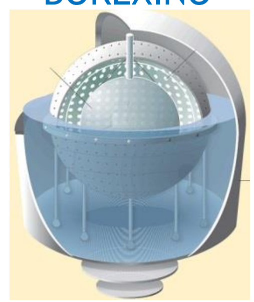
- directly, it can be observed in elastic scattering of neutrinos on electrons

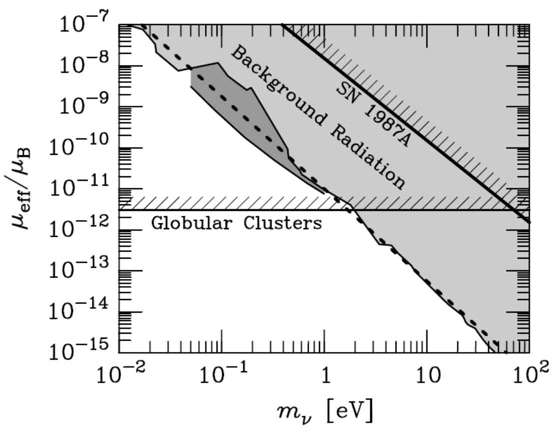




$\mu_\nu < 10^{-11}\mu_B$

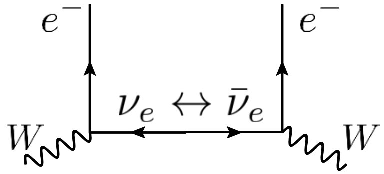
BOREXINO





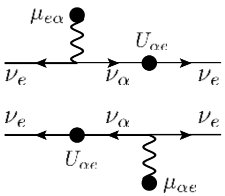
RESONANT ENHANCEMENT OF 0NBB

- 0nbb decay is driven by exchange of virtual neutrino changing as



  - such neutrino-antineutrino conversion may be driven not only by Majorana mass but also by magnetic moment

$$\nu_e \to \bar{\nu}_\alpha \to \bar{\nu}_e$$
$$\nu_e \to \nu_\alpha \to \bar{\nu}_e$$
$$\alpha = \mu, \tau$$



Gozdz, Kaminski

without time changing external magnetic field these two channels cancel due to

$$\mu_{e\alpha} = -\mu_{\alpha e}$$

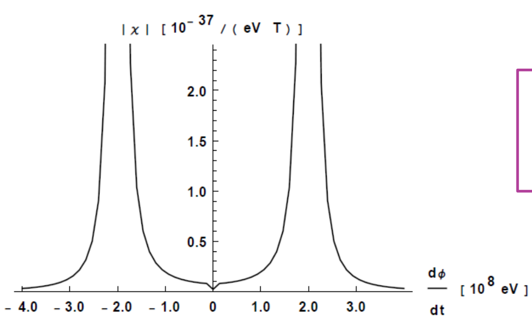
- rotating magnetic field $B,\ \omega$ lifts the degeneracy in H and avoids the cancelation

$$H = \begin{pmatrix} H_\nu + \omega/2 & B\mu \\ -B\mu & H_\nu - \omega/2 \end{pmatrix} \quad \text{in the basis} \begin{pmatrix} \nu \\ \bar{\nu} \end{pmatrix}$$

- it provides effective majorana mass which has resonant dependence on ω

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}|M^{0\nu}|^2|B\chi|^2$$

$$m^{\text{eff}}_{\beta\beta} = B\chi$$



resonance at

$B = 1\,\text{T}\,,\quad \omega = 10^{23}\,\text{Hz}$

LAGRANGIAN WITH OPERATORS UP TO DIM=5

- Peccei-Quinn solution of the strong CP problem has introduced axion

$$\mathcal{L}_5 = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial a)^2 - \frac{1}{2}m_a^2 a^2 + \frac{g_{agg}}{f} a G_a^{\mu\nu}\tilde{G}_{a\mu\nu}$$

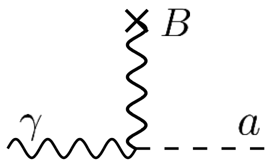
$$+ \frac{g_{a\gamma\gamma}}{f} a F^{\mu\nu}\tilde{F}_{\mu\nu} + \ldots$$

and other dim=5 operators

PHOTON-AXION CONVERSION

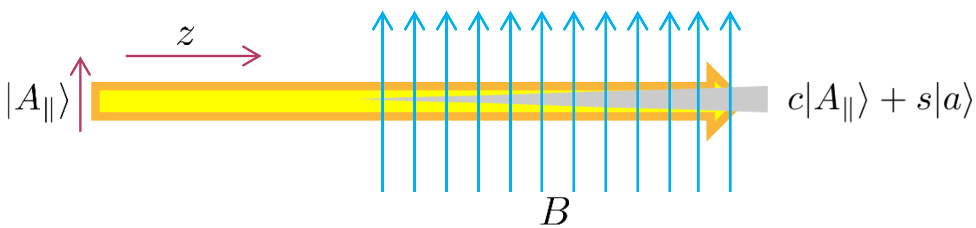
- the axion-photon interaction

$$\frac{g_{a\gamma\gamma}}{f} a\,\mathbf{E}\cdot\mathbf{B}$$



causes the axion-photon mixing in external magnetic field

$$\left(\omega^2 + \partial_z^2 + \begin{bmatrix} Q_{\parallel} & B\omega/f \\ B\omega/f & -m_a^2 \end{bmatrix}\right)\begin{bmatrix} A_{\parallel} \\ a \end{bmatrix} = 0$$



Maiani,Zavattini,Petronzio
Kayser

- vacuum magnetic birefringence
- photon-axion conversion in magnetic fields (terrestrial, intergalactic)

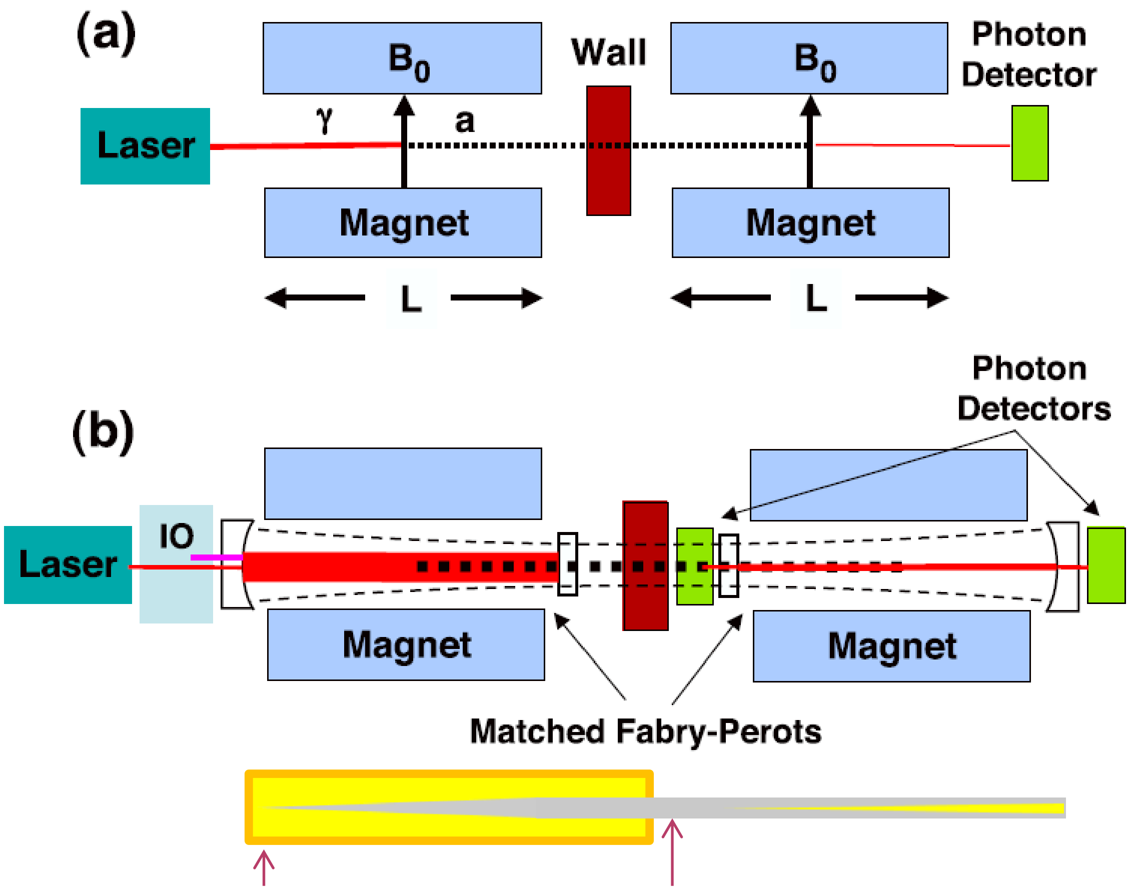
conversion probability

$$P = \frac{1}{4}\frac{1}{\beta_a\sqrt{\epsilon}}(g_{a\gamma\gamma}B_0L)^2\left(\frac{2}{qL}\sin\frac{qL}{2}\right)^2$$

in analogy with neutrino oscillations

$$P = \sin^2 2\theta_{ij}\cdot\sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right)$$

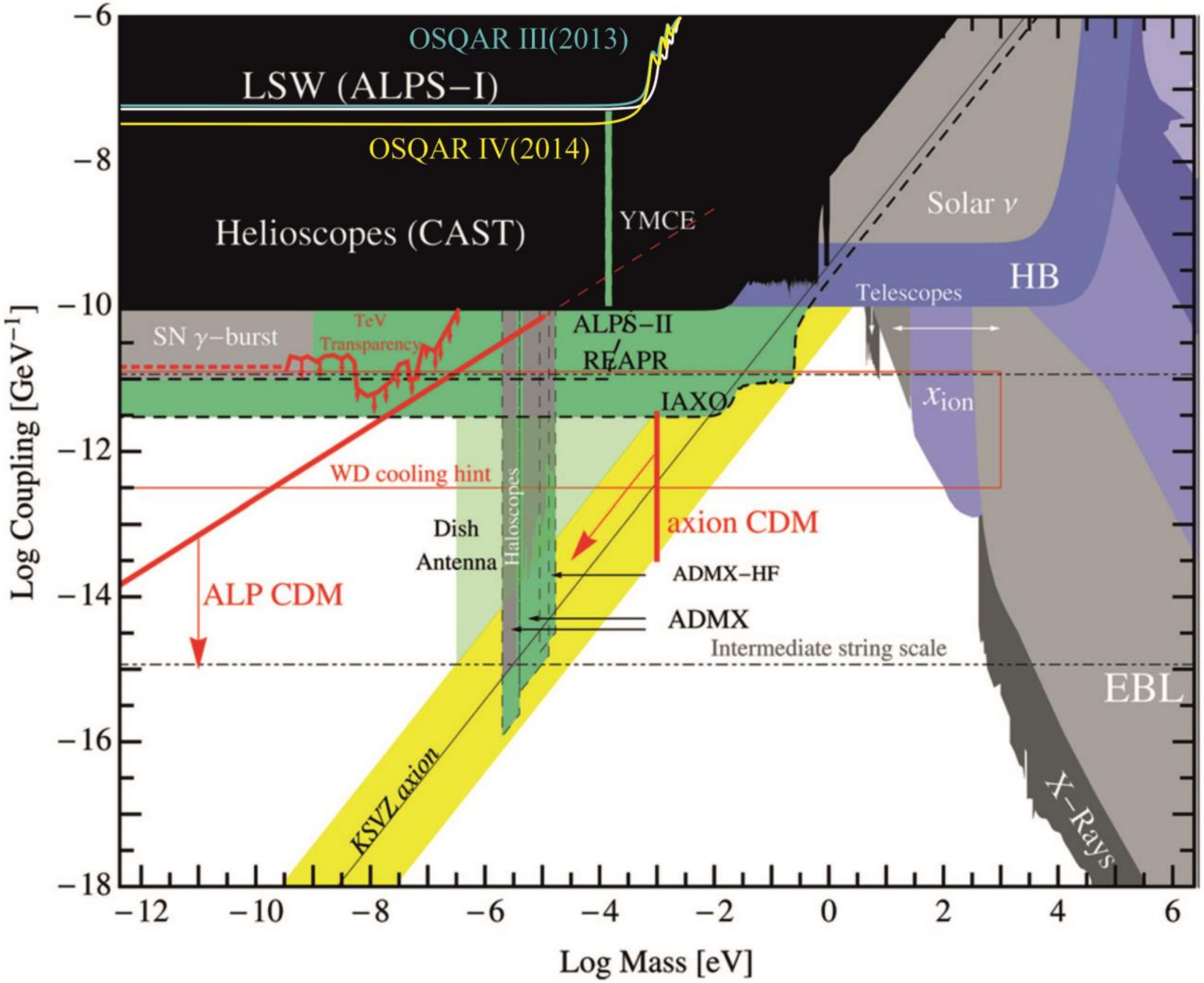
SHINING LIGHT THROUGH WALL



$|\gamma\rangle = c|A_{\|}\rangle + s|a\rangle$ $|a'\rangle = c'|A_{\|}\rangle + s'|a\rangle$

Sikivie
Tanner
Bibber

AXION SEARCH STATUS



Raffelt

CONCLUSIONS

- we presented a humble review of a wast topics (neutrinos and axions)
- we tried to track some of common features of both
- we have selected several observational techniques requiring extreme magnetic field

- some of the most urgent problems of current particle physics may be solved without TeV scale new physics (neutrino properties, dark matter)
- suitable discovery tools are then low-intensity-frontier experiments and cosmology observations

- even non-observation of new particles at LHC is great piece of information

MORE AXIONS

- imagine a Higgs doublet for every type of fermion H_d, H_u, H_e, H_ν

$$\mathrm{U}(1)_\mathrm{B} \times \mathrm{U}(1)_\mathrm{L} \times \mathrm{U}(1)_{\mathrm{B}_5} \times \mathrm{U}(1)_{\mathrm{L}_5} \xrightarrow{m_u, m_d, m_e, m_\nu^{\mathrm{Majorana}}} \mathrm{U}(1)_\mathrm{B}$$

$$\begin{aligned}
\partial_\mu J^\mu_\mathrm{B} &= 3\mathcal{Y} - 3\mathcal{W} \\
\partial_\mu J^\mu_\mathrm{L} &= 3\mathcal{Y} - 3\mathcal{W} \\
\partial_\mu J^\mu_{\mathrm{B}_5} &= \tfrac{11}{3}\mathcal{Y} + 3\mathcal{W} + 4\mathcal{G} \\
\partial_\mu J^\mu_{\mathrm{L}_5} &= 9\mathcal{Y} + 3\mathcal{W}
\end{aligned}$$

$$\begin{aligned}
\mathcal{Y} &= \frac{g_1^2}{8\pi^2} Y_{\mu\nu}\tilde{Y}^{\mu\nu} \\
\mathcal{W} &= \frac{g_2^2}{32\pi^2} W_{\mu\nu a}\tilde{W}_a^{\mu\nu} \\
\mathcal{G} &= \frac{g_3^2}{32\pi^2} G_{\mu\nu i}\tilde{G}_i^{\mu\nu}
\end{aligned}$$

- Weinberg-Wilczek axion $m_a \approx \frac{m_\pi f_\pi}{\Lambda_\mathrm{F}} \approx (10^{-3} - 10^{-7})\,\mathrm{eV}$
- Anselm-Uraltsev arion $m_{a'} \approx M_W \left(\frac{8\pi^2}{g^2}\right)^2 \mathrm{e}^{-\frac{4\pi^2}{g^2}} \approx 10^{-36} M_W$
- Chikashige-Mohapatra-Peccei majoron $m_J \stackrel{?}{=} 0$