Beyond the Standard Model

2. Neutrino mass models

Neutrinos have `BSM' mass

- Neutrinos fit into SM very well, except they are observed to oscillate.

Solar, Atmospheric, Accelerator, Reactor

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{\delta m^2 L}{4E}\right)$$

 2002

 2015

Neutrinos ($\Gamma_{Z,\mathrm{inv.}}$: Nν =2.98, LEP, 1989) mix and carry mass (differences).

$$V = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\phi_2/2} & 0 \\ 0 & 0 & e^{i\phi_3/2} \end{bmatrix}$$

Neutrino mixing
`PMNS matrix'

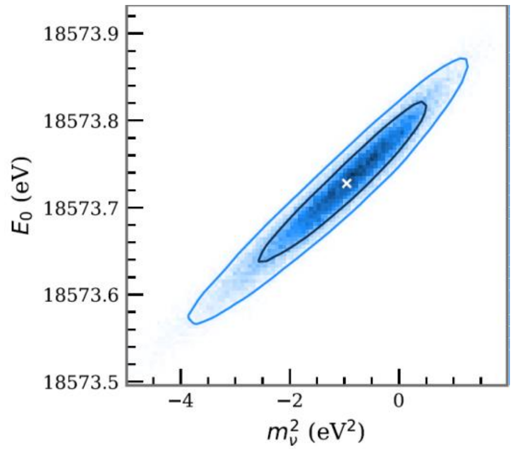
$$\nu_\alpha = \sum V^*_{\alpha i} \nu_i$$

Z. Maki, M. Nakagawa, S. Sakata 62'
B. Pontecorvo 57'

Current PDG on Δmass^2 :

$\sin^2(\theta_{12})$	0.307 ± 0.013
Δm^2_{21}	$(7.53 \pm 0.18) \times 10^{-5}$ eV^2
$\sin^2(\theta_{23})$	0.546 ± 0.021 ...
Δm^2_{32}	0.002453 ± 0.000033 eV^2
$\sin^2(\theta_{13})$	0.0220 ± 0.0007

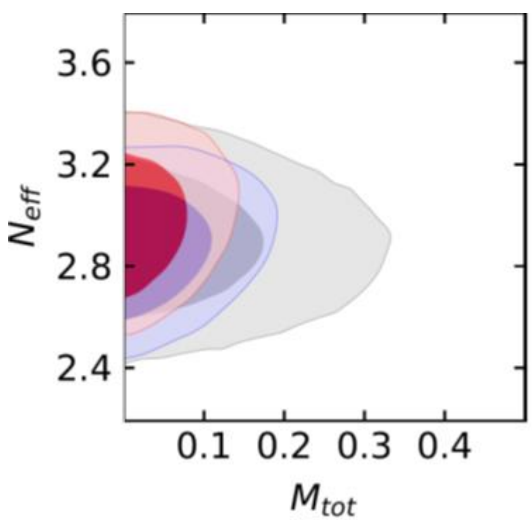
Neutrino mass-scale is quite light



3H beta decay, $^3\mathrm{H} \rightarrow {}^3\mathrm{He}^+ + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$

m_ν< 1.1 eV, KATRIN, 2019

0νββ decay, upper limits
(ν Majorana mass)
< 0.075–0.350 eV, CUORE (2020)
< 0.2-0.433 eV, MAJORANA Demo (2019)



Cosmological (CMB & BAO),

$\sum m_\nu$ < 0.16 eV (95% C.L.).
PLANCK & BOSS (2019)

The Weinberg operator

- The SM only has a left-handed neutrino inside the lepton doublet.

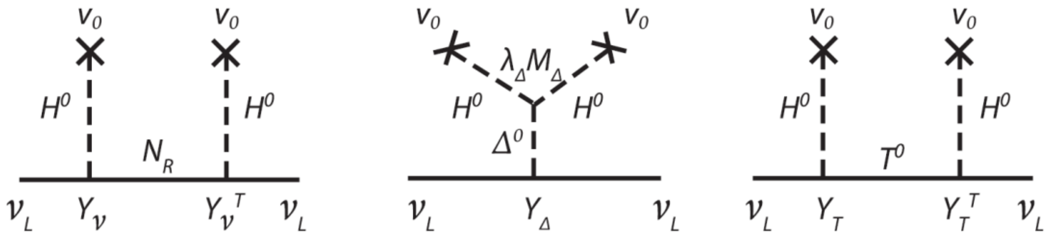
S. Weinberg, 79'

$$\left(\frac{\kappa}{\Lambda}\right) L_i L_j H H$$

A (effective) Majorana mass term, SM gauge invariant, with ΔL =2

$$m_\nu = \kappa v_0^2 / \Lambda$$

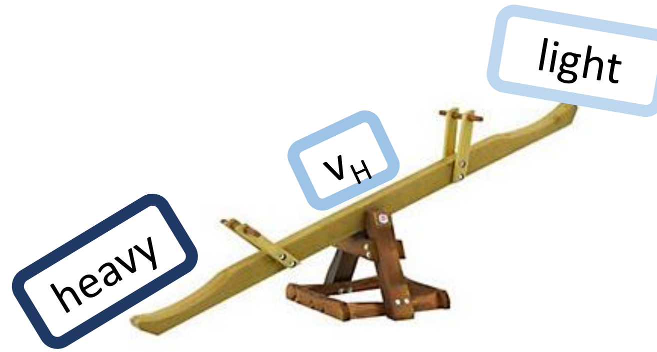
$$m_\nu \lesssim 1\,\text{eV implies that } \Lambda \gtrsim 10^{14-15}\,\text{GeV.}$$



Light Maj. mass generation in Type I, II, III seesaw

Z-Z.Xing, 0810.1421

`Seesaw' mechanism



A small `active neutrino' mass can derive from the mixing with some heavy scale.

$$\begin{array}{cc} \nu_L & \text{New state} \\ \end{array}$$

$$\begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \xrightarrow[m_R \gg m_D]{\text{Diagonalization}} \begin{array}{cc} \nu_1 & \nu_2 \\ \multicolumn{2}{c}{\begin{pmatrix} -\dfrac{m_D^2}{m_R} & 0 \\ 0 & m_R + O\left(\dfrac{m_D^2}{m_R^2}\right) \end{pmatrix}} \end{array}$$

rotational angle $\theta^2 \sim \dfrac{m_D^2}{m_R^2} \sim m_{\nu 1}/ m_{\nu 2}$

Type I: N_R extension to SM

P. Minkowski, 77; T. Yanagida, 79;
M. Gell-Mann, P. Ramond, and
R. Slansky, 1979; S. L. Glashow, 1980.

ΔL=2

$$-\mathcal{L}_\nu^I = \bar{l}_L\, Y_\nu^D\, \tilde{H}\, \nu_R + \frac{1}{2}\overline{(\nu^c)}_L\, M_N\, \nu_R + \text{h.c.}$$

$$\tilde{H} = i\sigma_2 H^*$$

ν_R is SM singlet, Y^D, M_N are 3x3 matrices

after EWSB $m_D = Y_\nu^D\, v_0/\sqrt{2}$

$$-\mathcal{L}_\nu^m = \frac{1}{2}\left(\overline{\nu}_L\, m_D\, \nu_R + \overline{(\nu^c)}_L\, m_D^T\, (\nu^c)_R + \overline{(\nu^c)}_L\, M_N\, \nu_R\right) + \text{h.c.}$$

$$\begin{pmatrix} \nu_L \\ (\nu^c)_L \end{pmatrix} = \mathbb{N} \begin{pmatrix} \nu_L \\ (\nu^c)_L \end{pmatrix}_{mass}, \quad \mathbb{N} = \begin{pmatrix} U & V \\ V_C & U_C \end{pmatrix}.$$

6x6 mass matrix
($3\nu_L$ and $3\nu_R$)

$$\mathbb{N}^\dagger \begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix} \mathbb{N}^* = \begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix},$$

$$\mathbb{N} = \begin{pmatrix} U & V \\ V_C & U_C \end{pmatrix}$$

U and V blocks mix the light and heavy states into weak gauge eigenstates

Diagonalization (by 3x3 blocks)

$$V_C^\dagger m_D^T U^* + U^\dagger m_D V_C^* + V_C^\dagger M_N V_C^* = m,$$
$$U_C^\dagger m_D^T V^* + V^\dagger m_D U_C^* + U_C^\dagger M_N U_C^* = M,$$
$$V_C^\dagger m_D^T V^* + U^\dagger m_D U_C^* + V_C^\dagger M_N U_C^* = 0,$$

$$m \approx \frac{m_D^2}{M_N}, \quad M \approx M_N$$
$$U^2 \approx \mathcal{O}(1), \quad V^2 \approx \frac{m}{M}$$

Unitarity condition

$$UU^\dagger + VV^\dagger = U^\dagger U + V_C^\dagger V_C = V_C V_C^\dagger + U_C U_C^\dagger = V^\dagger V + U_C^\dagger U_C = I,$$
$$UV_C^\dagger + VU_C^\dagger = U^\dagger V + V_C^\dagger U_C = 0.$$

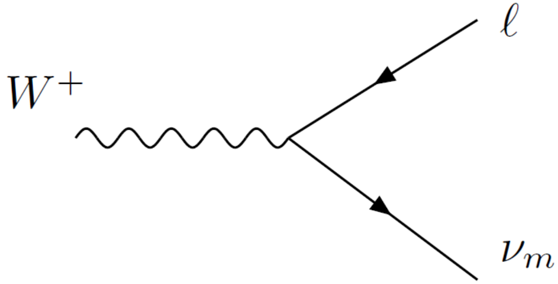
see: Atre, Han, Pascoli, Zhang, 0901.3589

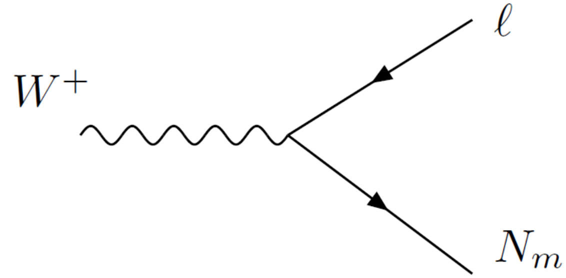
Neutrino to lepton transition via weak charged current interaction (Wlν)

(*E* diagonalizes the charged lepton mass)

$$E^\dagger U \equiv V_{PMNS}, \quad E^\dagger V \equiv V_{\ell N},$$
$$V_{PMNS} V_{PMNS}^\dagger + V_{\ell N} V_{\ell N}^\dagger = I,$$
$$V_{\ell N}^* \, M \, V_{\ell N}^\dagger = -V_{PMNS}^* \, m \, V_{PMNS}^\dagger$$

Weak charged current vertices:





$-i\frac{g}{\sqrt{2}}U^*_{\ell m}\gamma^\mu P_L$ $\qquad$ $-i\frac{g}{\sqrt{2}}V^*_{\ell m}\gamma^\mu P_L$

Heavy neutrino (mass eigenstate) talks weakly via its ν_L component

`Casas-Ibarra ansatz', hep-ph/0103065 $\qquad V_{\ell N} = V_{PMNS}\, m^{1/2}\, \Omega\, M^{-1/2}$, $\quad \Omega^T\Omega=1$

$$\Omega(w_{21}, w_{31}, w_{32}) = R_{12}(w_{21})\, R_{13}(w_{31})\, R_{23}(w_{32})$$

$$R_{12} = \begin{pmatrix} u_{21} & -w_{21} & 0 \\ w_{21} & u_{21} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad R_{13} = \begin{pmatrix} u_{31} & 0 & -w_{31} \\ 0 & 1 & 0 \\ w_{31} & 0 & u_{31} \end{pmatrix}, \quad R_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & u_{32} & -w_{32} \\ 0 & w_{32} & u_{32} \end{pmatrix}$$

Type II: triplet scalar extension

W. Konetschny, W. Kummer, 77'; T. P. Cheng, L. F. Li, 80'; G. Lazarides, Q. Shafi, C. Wetterich, 81'; J. Schechter, J. Valle, 80'; R. N. Mohapatra and G. Senjanovic, 81'

Type II seesaw Lagrangian

$$\mathcal{L}_{\rm TypeII} = (D_\mu H)^\dagger (D^\mu H) + {\rm Tr}(D_\mu \Delta)^\dagger (D^\mu \Delta) - V(H, \Delta)$$

$$-Y_\nu \, l_L^T \, C \, i\sigma_2 \, \Delta \, l_L + \text{h.c.}$$

$$\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}$$

Δ: in adjoint rep. of $SU(2)_L$
(1, 3, 1) under $SU(3) \times SU(2)_L \times U(1)_Y$

The scalar potential

$$V(H,\Delta) = -m_H^2 \, H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + M_\Delta^2 \, Tr \Delta^\dagger \Delta + \left(\mu \, H^T \, i\sigma_2 \, \Delta^\dagger H + h.c.\right) +$$
$$+ \lambda_1 \, (H^\dagger H) Tr \Delta^\dagger \Delta + \lambda_2 \left(Tr \Delta^\dagger \Delta\right)^2 + \lambda_3 \, Tr \left(\Delta^\dagger \Delta\right)^2 + \lambda_4 \, H^\dagger \Delta \Delta^\dagger H.$$

$$V(H,\Delta) = -m_H^2\, H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + M_\Delta^2\, Tr\Delta^\dagger\Delta + \left(\mu\, H^T\, i\sigma_2\, \Delta^\dagger H + h.c.\right) +$$

$$\cancel{+\ \lambda_1\, (H^\dagger H) Tr\Delta^\dagger\Delta + \lambda_2 \left(Tr\Delta^\dagger\Delta\right)^2 + \lambda_3\, Tr\left(\Delta^\dagger\Delta\right)^2 + \lambda_4\, H^\dagger\Delta\Delta^\dagger H.}$$

assuming Δ heavy $M_\Delta > v_H$ and ignore λ terms, minimization (from 1st line) gives

$$-m_H^2 + \frac{\lambda}{4}v_0^2 - \sqrt{2}\,\mu\, v_\Delta = 0,$$

$$v_\Delta = \frac{\mu\, v_0^2}{\sqrt{2}\, M_\Delta^2} \qquad v_0^2 + v_\Delta^2 \approx (246\ \mathrm{GeV})^2$$

The neutrino gets a Maj. mass with Δ vev,

$$M_\nu = \sqrt{2}\, Y_\nu\, v_\Delta = Y_\nu\, \frac{\mu\, v_0^2}{M_\Delta^2}$$

proportional to μ
(which breaks L#)

In type II seesaw: no heavy neutrino. 7 scalars after EWSB, 6 are heavy

$$H_1 = \cos\theta_0\, h^0 + \sin\theta_0\, \Delta^0, \quad H_2 = -\sin\theta_0\, h^0 + \cos\theta_0 \Delta^0,$$
$$A = -\sin\alpha\, \xi^0 + \cos\alpha\, \eta^0,$$
$$H^\pm = -\sin\theta_\pm\, \phi^\pm + \cos\theta_\pm\, \delta^\pm$$
$$H^{\pm\pm} = \delta^{\pm\pm}$$

$$\theta_0 \approx \frac{2v_\Delta}{v_0} \qquad \alpha \approx \frac{2v_\Delta}{v_0} \qquad \theta_+ \approx \frac{\sqrt{2}v_\Delta}{v_0}$$

`seesaw':
scale suppression
among scalar
mixings

$$M_{H_2} \simeq M_A \simeq M_{H^\pm} \simeq M_{H^{++}} = M_\Delta$$

Type III: triplet fermion extension

Σ: triplet fermion, (3, 0) under SM $SU(2)_L \times U(1)_Y$.

R. Foot, H. Lew, X. G. He and G. C. Joshi, 89'

$$\Sigma_L = \Sigma_L^a \sigma^a = \begin{pmatrix} \Sigma_L^0/\sqrt{2} & \Sigma_L^+ \\ \Sigma_L^- & -\Sigma_L^0/\sqrt{2} \end{pmatrix}, \quad \Sigma_L^\pm \equiv \frac{\Sigma_L^1 \mp i\Sigma_L^2}{\sqrt{2}}, \quad \Sigma_L^0 = \Sigma_L^3,$$

(RH) charge conjugate form

$$\Sigma_R^c = \begin{pmatrix} \Sigma_R^{0c}/\sqrt{2} & \Sigma_R^{-c} \\ \Sigma^{+c} & -\Sigma_R^{0c}/\sqrt{2} \end{pmatrix} \qquad \psi_R^c \equiv (\psi^c)_R = (\psi_L)^c$$

The type-III Lagrangian

$$\mathcal{L}_T = \frac{1}{2}\,\mathrm{Tr}\left[\overline{\Sigma_L} i \not{D} \Sigma_L\right] - \left(\frac{M_\Sigma}{2}\overline{\Sigma_L^0}\Sigma_R^{0c} + M_\Sigma \overline{\Sigma_L^-}\Sigma_R^{+c} + \mathrm{H.c.}\right)$$

$$-Y_\Sigma \overline{L}\, \Sigma_R^c\, i\sigma^2 H^* + \mathrm{H.c.}$$

mass terms (v_0 as Higgs vev)

$$\mathcal{L}^m_{\mathrm{III}} = -\begin{pmatrix}\overline{l_R} & \overline{\Psi_R}\end{pmatrix}\begin{pmatrix} m_l & 0 \\ Y_\Sigma v_0 & M_\Sigma \end{pmatrix}\begin{pmatrix} l_L \\ \Psi_L \end{pmatrix}$$

$$\Psi_L \equiv \Sigma_L^-,\ \Psi_R \equiv \Sigma_L^{+c}$$

$$-\begin{pmatrix}\overline{\nu_L^c} & \overline{\Sigma_L^{0c}}\end{pmatrix}\begin{pmatrix} 0 & Y_\Sigma^T v_0/2\sqrt{2} \\ Y_\Sigma v_0/2\sqrt{2} & M_\Sigma/2 \end{pmatrix}\begin{pmatrix} \nu_L \\ \Sigma_L^0 \end{pmatrix} + \mathrm{H.c.}$$

diagonalize neutral & charged mass matrix

$$U_0^\dagger \begin{pmatrix} 0 & Y_\Sigma^\dagger v_0/\sqrt{2} \\ Y_\Sigma^* v_0/\sqrt{2} & M_\Sigma^* \end{pmatrix} U_0^* = \begin{pmatrix} m_\nu^{diag} & 0 \\ 0 & M_N^{diag} \end{pmatrix}$$

$$U_L^\dagger \begin{pmatrix} m_l^\dagger & Y_\Sigma^\dagger v_0 \\ 0 & M_\Sigma^\dagger \end{pmatrix} U_R = \begin{pmatrix} m_l^{diag} & 0 \\ 0 & M_E^{diag} \end{pmatrix}$$

seesaw occurs between Y_Σ v_0 and M_Σ

via mixing matrices

$$\begin{pmatrix} l_{L,R} \\ \Psi_{L,R} \end{pmatrix} = U_{L,R}\begin{pmatrix} l_{mL,R} \\ \Psi_{mL,R} \end{pmatrix}, \quad \begin{pmatrix} \nu_L \\ \Sigma_L^0 \end{pmatrix} = U_0 \begin{pmatrix} \nu_{mL} \\ \Sigma_{mL}^0 \end{pmatrix},$$

$$U_L \equiv \begin{pmatrix} U_{Lll} & U_{Ll\Psi} \\ U_{L\Psi l} & U_{L\Psi\Psi} \end{pmatrix}, \quad U_R \equiv \begin{pmatrix} U_{Rll} & U_{Rl\Psi} \\ U_{R\Psi l} & U_{R\Psi\Psi} \end{pmatrix}, \quad U_0 \equiv \begin{pmatrix} U_{0\nu\nu} & U_{0\nu\Sigma} \\ U_{0\Sigma\nu} & U_{0\Sigma\Sigma} \end{pmatrix},$$

light and heavy neutrino masses:

$$m_\nu \approx \frac{Y_\Sigma^2 v_0^2}{2M_\Sigma}, \quad M_N \approx M_\Sigma$$

+ heavy charged leptons (mix with SM leptons)

light leptons gets mass correction ~$O\left(\frac{Y_\Sigma^2 v_0^2}{2M_\Sigma^2}\right)$, heavy leptons $\mathrm{M_E} \approx \mathrm{M_\Sigma}$

Heavy neutrino obtain an effective coupling to W (and Z, h by equivalence th.)

$$V_{\ell N} = -Y_\Sigma^\dagger v_0 M_\Sigma^{-1}/\sqrt{2}.$$

Heavy neutrino decay width

$$\Gamma(N \to lW) = \frac{G_F}{4\sqrt{2}\pi} \sum_l |V_{lN}|^2 M_\Sigma^3$$

+ $N \to \nu Z/h$ decays

Hybrid models

- Type I + II

$$M_\nu^{light} = M_L - M_D M_R^{-1} M_D^T.$$

negative sign between type II (M_L) and type I contribution

Phenomenology studies, see hep-ph/0504181, hep-ph/0609046, 0709.1069, 0907.0935

- Left-right symmetric model (LRSM)

Pati, Salam, 74'; Mohapatra, Pati,75'

An $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ model, features LR symmetry

One bi-doublet $(2_L,2_R,0)$
Two triplet scalars $(3_L,1,2)$, $(1,3_R,2)$

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}, \quad \Delta_{L,R} = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}_{L,R}$$

$$\langle \Delta_R \rangle = \sqrt{1/2} \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix} \qquad \langle \phi \rangle = \sqrt{1/2} \begin{pmatrix} \kappa & 0 \\ 0 & \kappa' e^{i\alpha} \end{pmatrix} \qquad \langle \Delta_L \rangle = \sqrt{1/2} \begin{pmatrix} 0 & 0 \\ v_L e^{i\theta_L} & 0 \end{pmatrix}$$

v_R breaks $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ to $SU(2)_L \times U(1)_Y$

v_ϕ for EWSB $\rightarrow U(1)_{EM}$

$v_L \leq O(eV)$

Inverse seesaw

Mohapatra, Valle 86';
Gonzalez-Garcia, Valle 89'

"Majorana ISS", a $U(1)_{B\text{-}L}$ conserving Lagrangian

$$\mathcal{L}_{\rm Maj} = Y\,\bar{L}^c\,\widetilde{H}\,N + \lambda\,\bar{S}^c\,\chi\,S + M\,\bar{S}^c\,N + \text{h.c.}$$
$$+\ \lambda'\,\bar{N}^c\,\chi^*\,N + \text{h.c}$$

New singlet fermions N, S and scalar χ, B-L = (1, -1, 2)

U(1) breaks into Z2 after χ gets a vev v_χ = u, Higgs vev = v

Fields	$SU(2)_L \otimes U(1)_Y$	$U(1)_{B-L} \to \mathbb{Z}_2$	Fields	$SU(2)_L \otimes U(1)_Y$	$U(1)_{B-L} \to \mathbb{Z}_2$
L	$(\mathbf{2}, -1/2)$	$-1 \to -1$			
N	$(\mathbf{1}, 0)$	$1 \to -1$	S	$(\mathbf{1}, 0)$	$-1 \to -1$
H	$(\mathbf{2}, 1/2)$	$0 \to 1$	χ	$(\mathbf{1}, 0)$	$2 \to 1$

The ISS mass terms

$$\mathcal{L}_m = \begin{pmatrix} \bar{\nu}^c & \bar{N}^c & \bar{S}^c \end{pmatrix} \begin{pmatrix} 0 & Y\,v & 0 \\ Y^T\,v & \mu' & M^T \\ 0 & M & \mu \end{pmatrix} \begin{pmatrix} \nu \\ N \\ S \end{pmatrix}$$

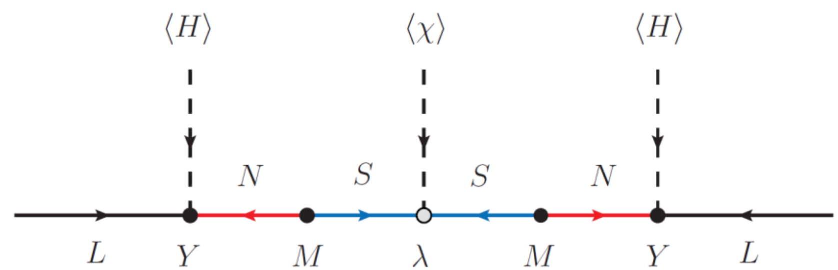
$$\mu = \lambda\, u$$
$$\mu' = \lambda'\, u$$

with ISS hierarchy condition $\mu, \mu' \ll Y\,v \ll M$

the lightest masses are approx.

$$m_\nu = \begin{pmatrix} Y v & 0 \end{pmatrix} \begin{pmatrix} \mu' & M^T \\ M & \mu \end{pmatrix}^{-1} \begin{pmatrix} Y^T v \\ 0 \end{pmatrix}$$

$$m_\nu = Y^2 \frac{v^2 \mu}{\mu\,\mu' - M^2} \quad \to \quad -Y^2\, \frac{v^2\,\mu}{M^2}$$



Alternative ISS model:
(w Dirac term)

$$-\mathcal{L}_\nu = \overline{\ell_{\rm L}} Y_\nu \widetilde{H} N_{\rm R} + \overline{S_{\rm L}} Y_{\rm S} N_{\rm R} \Phi + \frac{1}{2} \overline{S_{\rm L}} \mu S_{\rm L}^{\rm C} + {\rm h.c.}$$

$$M_\nu \approx -M_{\rm D} M_{\rm S}^{-1} \mu \left(M_{\rm D} M_{\rm S}^{-1}\right)^{\rm T}$$

Radiative m_ν

For review, see 1706.08524

A. Zee, 86'; K. S. Babu, 88'

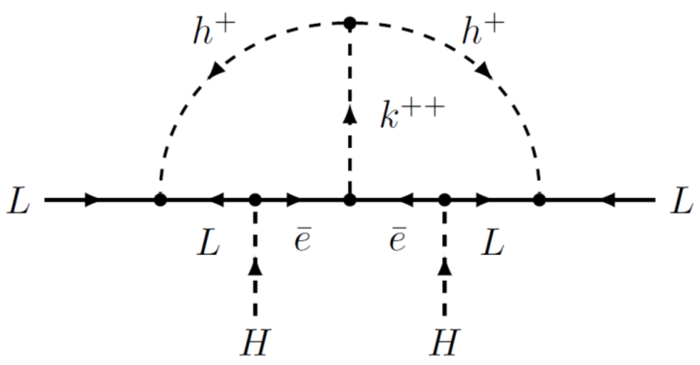
Zee-Babu Model

$$\Delta\mathcal{L} = \bar{L}Y^\dagger e_R H + \tilde{L} f L h^+ + \overline{e_R^c} g e_R k^{++} + \mu_{ZB} h^+ h^+ k^{--} + \mathrm{H.c.}$$

$$\tilde{L} \equiv i\tau_2 L^c = i\tau_2 C\overline{L}^T$$

$$|\mu_{ZB}| \ll 4\pi \, \min(m_h, m_k)$$

Field	Spin	$G_{\rm SM}$
h^+	0	$(1, 1, 1)$
k^{++}	0	$(1, 1, 2)$



neutrino mass generation at two loop

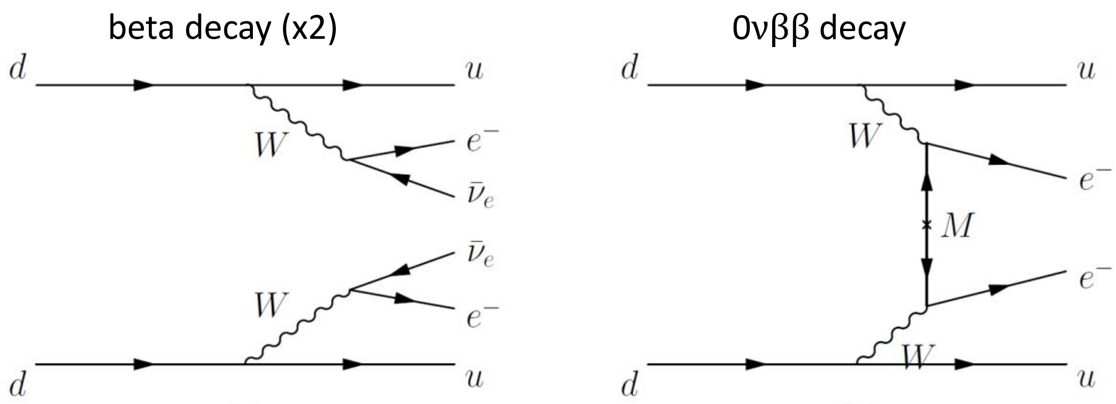
$$\mathcal{M}_\nu \simeq \frac{v^2 \mu_{\rm ZB}}{96\pi^2 M^2} f\, Y\, g^\dagger Y^T f^T$$

Test of seesaw

- (Active) neutrino has Majorana mass?
- Search for BSM fields: massive neutrinos, scalars
- Others?

Neutrinoless double β-decay (0νββ)

- Require Majorana mass



(a)

(b)

$$\Gamma_{0\nu 2\beta} \propto G_F^4 |\tilde{M}_{0\nu 2\beta}|^2 \Big| \sum_j U_{ej}^2 m_j \Big|^2 p_e^2$$

$\widetilde{M}$:nuclear form factor; p_e: energy scale

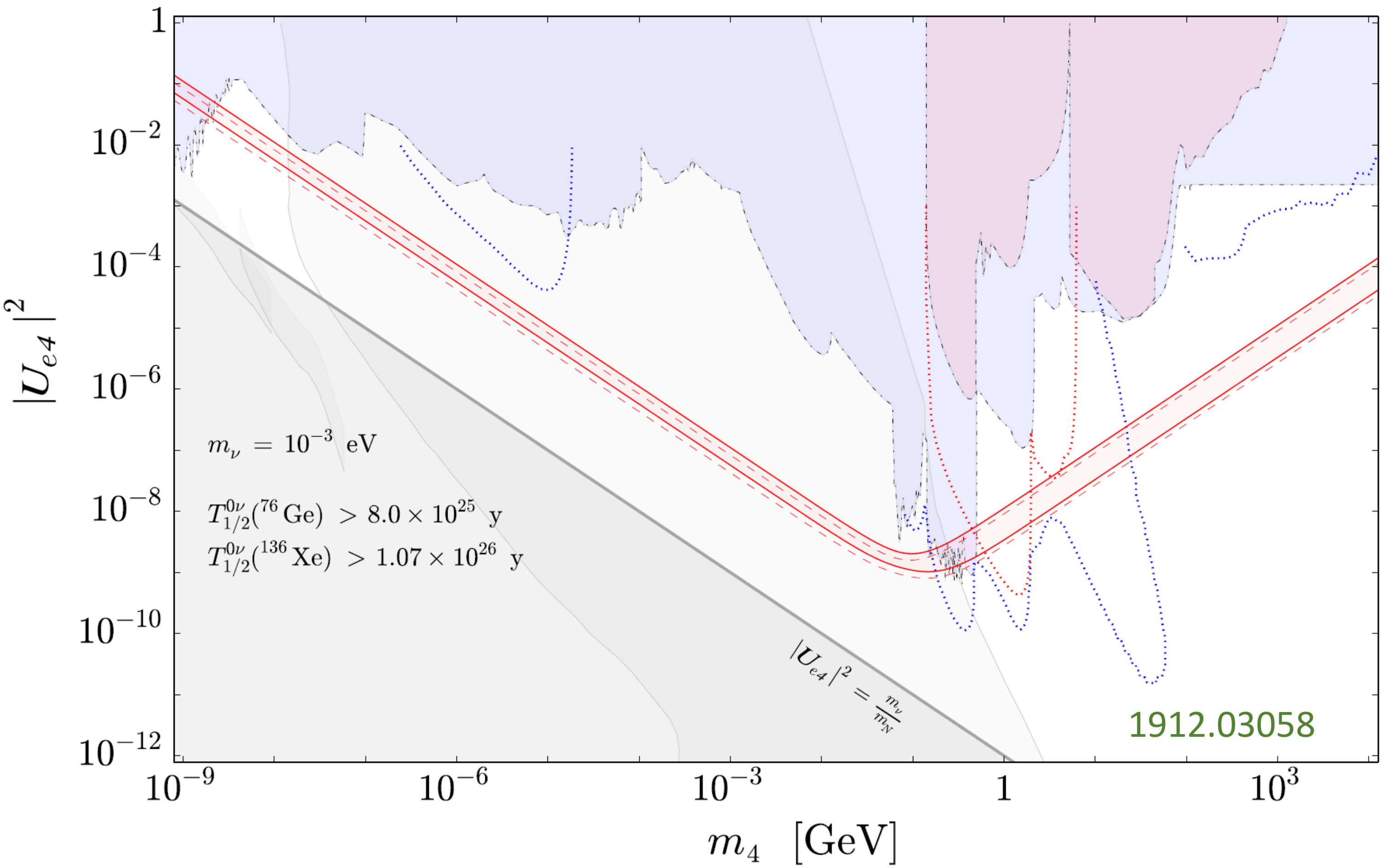
Give limits on the effective mass

$$m_{0\nu 2\beta}^{\text{eff}} \equiv \sum_j U_{ej}^2 m_j$$

GERDA, Kamland,
CUORE, MAJORANA,PANDAX, etc.

0νββ also probes a fourth ν

(if ν_4 has a ν_e component, e.g. to explain LSND anomaly, etc.)



GERDA (dashed)
Kamland-Zen (solid)

LBL osc.

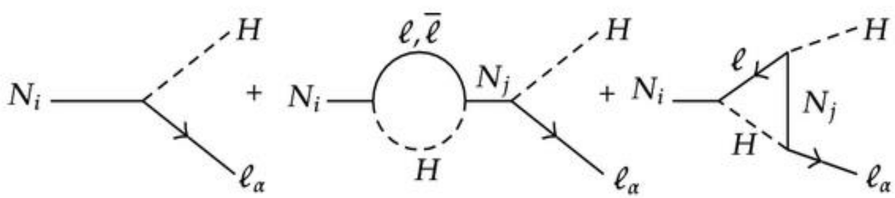
Indirect searches

collider searches

"Leptogenesis"

- If a heavy seesaw neutrino exists, it may satisfy Sakharov conditions

  * Nonthermal: massive thus decouple;
  * CP violating phases exist in Yukawas & mass matrices;
    N decay and its CP-conjugate process has slightly different partial width;
  * Sphalerons communicate L# into B# (while conserving B-L)



CP asymmetry from interference
between tree & loop diagrams
(CPV requires more than one species)

$$\epsilon_i = \frac{\Gamma(N_i \to l\,H) - \Gamma(N_i \to \bar{l}\,H^*)}{\Gamma(N_i \to l\,H) + \Gamma(N_i \to \bar{l}\,H^*)}$$

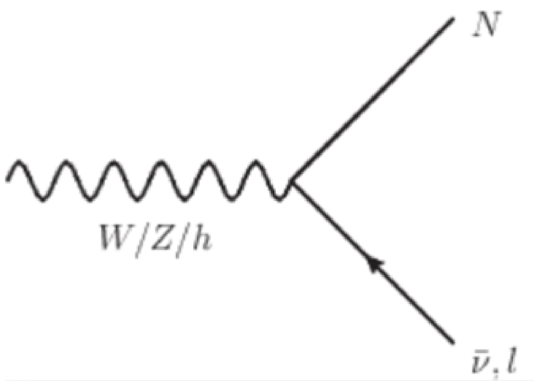
$$\epsilon_i = \frac{1}{8\pi} \sum_{k \neq i} f\left(\frac{|M_k|^2}{|M_i|^2}\right) \frac{\mathrm{Im}[(h^\dagger h)^2_{ik}]}{(h^\dagger h)_{ii}}$$

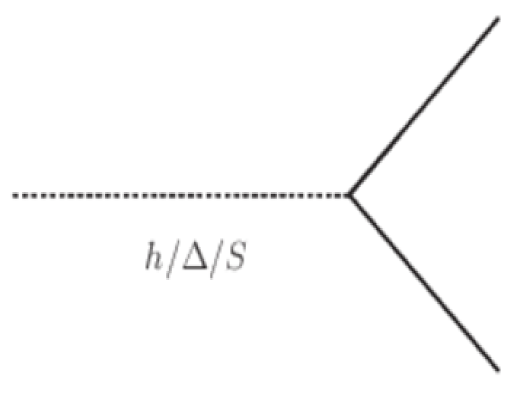
$$h^\dagger h = \frac{1}{v^2} U_R^\dagger (m_D^{diag})^2 U_R$$

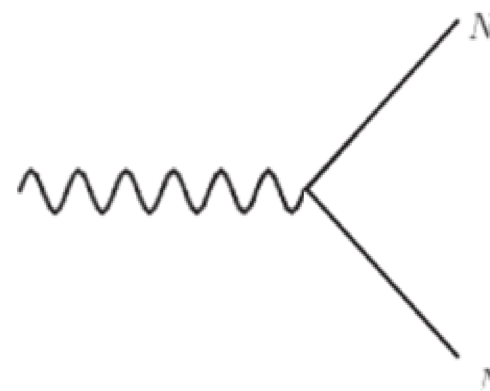
see hep-ph/0305322, hep-ph/9710460

Collider search for seesaw (N_R)

- Heavy neutrino search







Weak production
(via ν_L mixing)
effective couplings $\propto |V_{lN}|^2$

pair prod. $\propto |V_{lN}|^4$

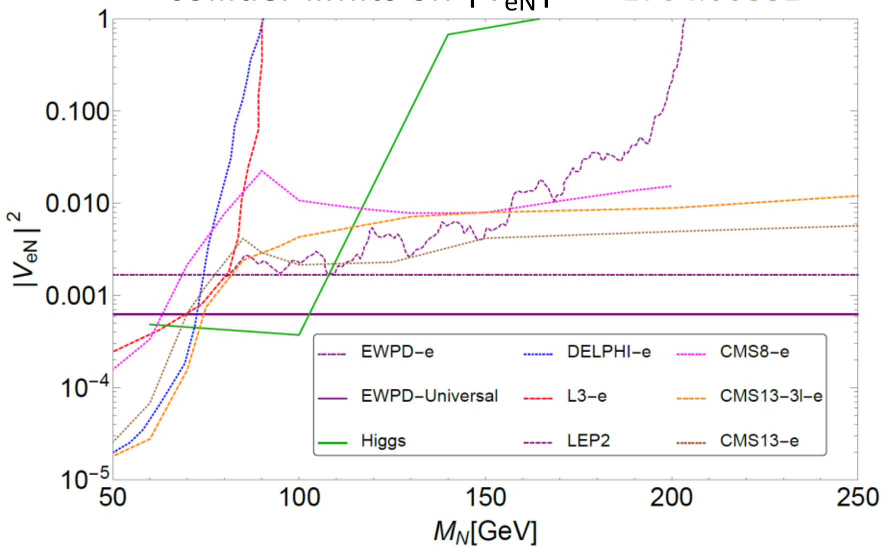
Scalar mediated production
(extra scalar)
scalar couplings $\propto |\sin\alpha|^2$

relatively large scalar mixing
is allowed. Wait for Higgs precision.

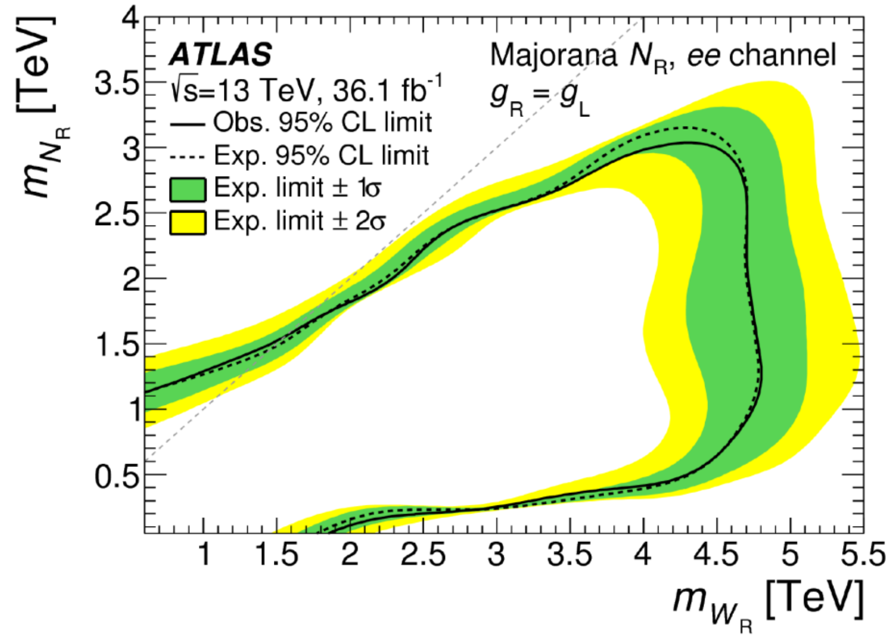
Extra gauge production
(BSM gauge group for N_R)
$\propto g^2$

extra gauge bosons
are likely heavy

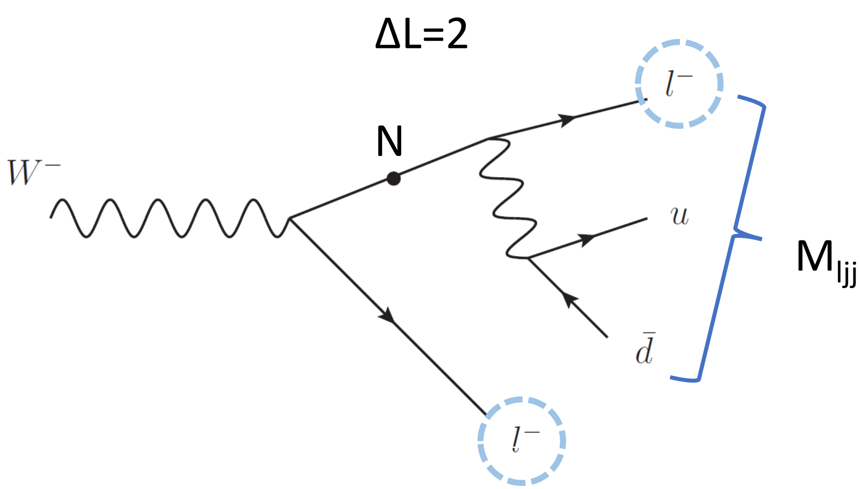
collider limits on $|V_{eN}|^2$ 1704.00881



pp→ $W_R \to N_R + X$, ATLAS (2020)

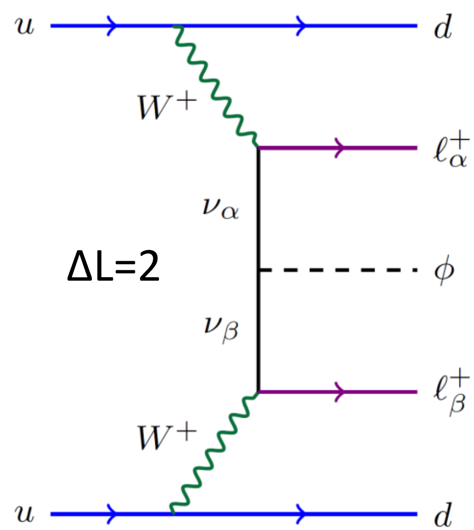


Collider search for ΔL≠0



Same-sign (SS) dilepton with M_{ljj} peaking at M_N

for review, see 1711.02180



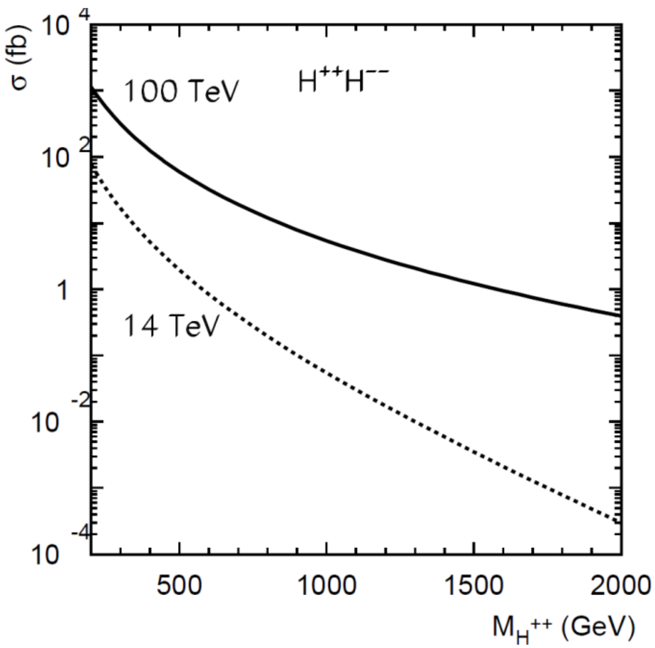
Production via Higgs, 1503.06834, 1904.12325

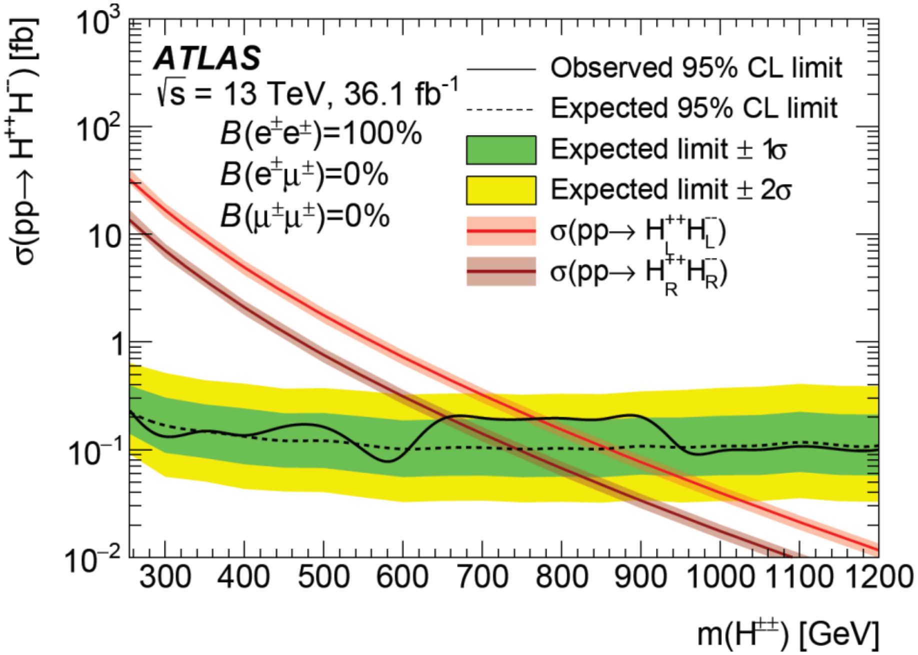
neutrino Maj. mass is small; its coupling may be not.

Same-sign (SS) dilepton+VBF+?

1910.01132

Collider search for seesaw (Δ)





δ^+ and δ^{++} can be easily produced via Drell-Yan, VBF, etc.

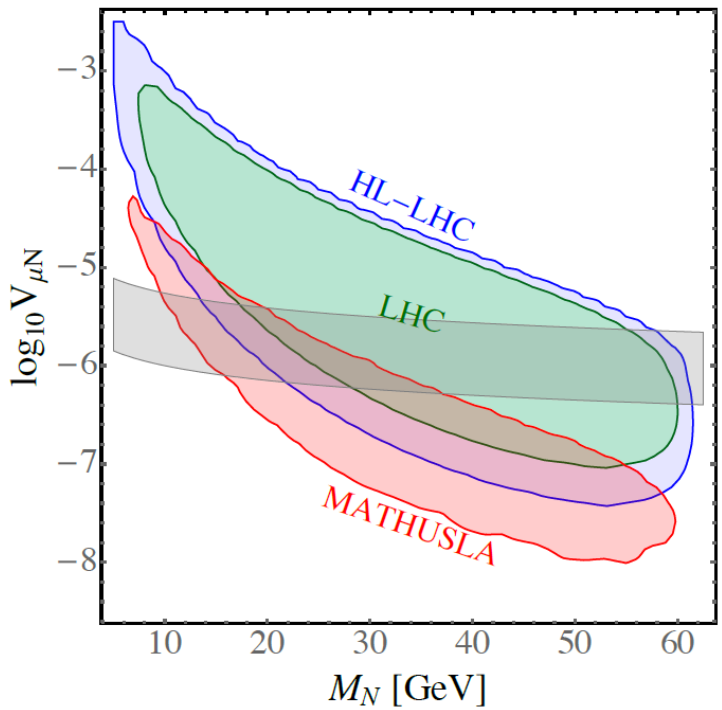
1710.09748

N_R `displaced vertex’

In some (Type I & alikes) models
N_R decay width is suppressed,
esp. for $m_{NR} < m_W$

$$L_N \approx 0.025\ \mathrm{m} \cdot \left(\frac{10^{-6}}{V_{\mu N}}\right)^2 \cdot \left(\frac{100\ \mathrm{GeV}}{M_N}\right)^5$$

1804.04075



$0.01 < m_\nu < 0.3$ eV

Beyond the Standard Model

3. Strong CP & Axions

CP in strong interaction?

- We know: weak interaction violates both *P* and *CP*.

Yang, Li, 56'; Wu, 57'
Cronin, Fitch, 64'

- *CP* in strong interaction?

$$\mathcal{L} \supset -\frac{1}{4}G^2 + \frac{\theta g_s^2}{32\pi^2}G\tilde{G}$$

The θ term is CP-violating, yet it is a total derivative:

$$G\tilde{G} = \partial_\mu K^\mu$$
$$K^\mu = \epsilon^{\mu\nu\rho\sigma} A^a_\nu \left[F^a_{\rho\sigma} - \frac{g}{3} f^{abc} A^b_\rho A^c_\sigma \right]$$

Naively it won't have an effect if *K* vanishes at infinity.

$$S = \int d^4x \mathcal{L} \supset \int d^4x \frac{\theta g_s^2}{32\pi^2} G\tilde{G} = \int d^3x \frac{\theta g_s^2}{32\pi^2} K^{\hat{r}} \mid_{r\to\infty}$$

Classical vacuum energy minimized by pure-gauge configurations $G^{(n)}$ fall into homotopy classes, categorized by $\pi_3(SU(3)) = Z$, or `winding number' n:
(class noted as $|n\rangle$)

$$\int d^4x \frac{1}{32\pi^2} G\tilde{G} = n_1 - n_2$$

for review, see
hep-ph/0009136

Configurations $G^{(n)}$ are `pure-gauge' and separated by finite ΔS barriers.

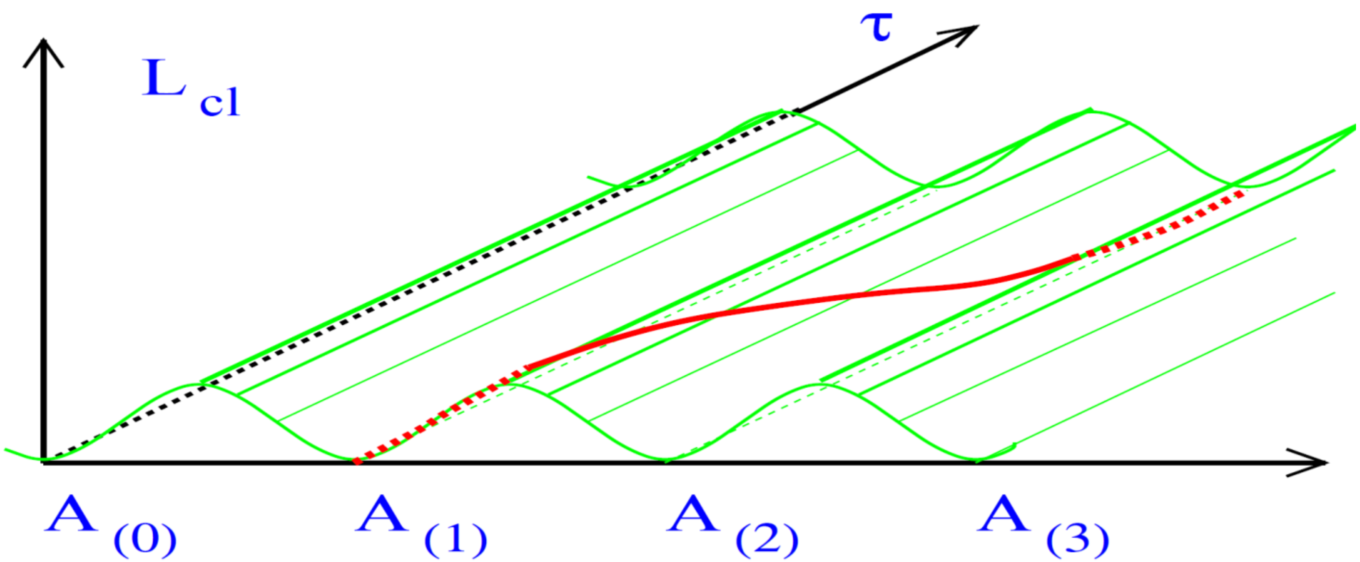
Instantons are found to flip $G^{(n)} \to G^{(m \neq n)}$, breaking their degeneracy.

Mixed (by instantons) $G^{(n)}$ states form new eigenstates of the Hamiltonian.

$$|\,\theta\rangle = N \sum e^{i\theta n} \,|\, n\rangle$$ `θ vacua'

as `true' eigenstates of *H* and their energy ∝ –cos(θ) (a.k.a. Instanton potential)
the value of θ must be pre-set as super-selection rule.

➡ our SU(3) vacuum should have a θ-term with θ ~ O(1)



mixed |n> illustrated in a form of circulant matrix.

$$\begin{pmatrix} 1 & 2 & 3 & \cdots & D-1 \end{pmatrix} \cdot \begin{pmatrix} E & \epsilon_1 & \epsilon_2 & \cdots & \epsilon_{D-1} & \\ \epsilon_{D-1} & E & \epsilon_1 & \epsilon_2 & \cdots & \\ . & . & . & . & . & \\ \epsilon_1 & & \epsilon_2 & \cdots & \epsilon_{D-1} & E \end{pmatrix} \cdot \begin{pmatrix} 1 \\ 2 \\ 3 \\ \cdots \\ D-1 \end{pmatrix}$$

jth eigenvector:

$$\begin{pmatrix} 1 & w_j & w_j^2 & \cdots & w_j^{D-1} \end{pmatrix}, \qquad w_j = e^{2\pi i j/D} \quad \xrightarrow{D\to\infty} \quad |\,\theta\rangle = N \sum e^{i\theta n}\,|\,n\rangle$$

$$b = |b| e^{i\theta}$$

$$U = e^{i \frac{\Pi^a}{\sqrt{2} f_\pi} \sigma^a}$$

θ-term identifies with the chiral current anomaly.

$$M = \begin{pmatrix} m_u e^{i\theta_u} & 0 \\ 0 & m_d e^{i\theta_d} \end{pmatrix}$$

Minimization of effective strong interaction potential

breaks $U(1)_A$

$$\mathcal{L} = f_\pi^2 \,\mathrm{Tr}\, \partial_\mu U \partial^\mu U^\dagger + \underline{a f_\pi^3 \,\mathrm{Tr}\, MU + b f_\pi^4 \det U} + h.c.$$

Yields the minimum at $V = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2 \frac{\bar{\theta}}{2}}$

$\bar{\theta} = \theta + \theta_u + \theta_d$ is invariant under the anomalous symmetry:

$$U \to e^{i\alpha} U, \qquad \theta \to \theta - 2\alpha, \qquad M \to e^{-i\alpha} M$$

`Naturally' the combined $\bar{\theta}$ should take O(1) values.

The strong CP problem

$\bar{\theta}$ causes CP-violating effect and appears in baryon EDM:

$$\mathcal{L} = -\bar{\theta}\frac{c_+\mu}{f_\pi}\pi^a N\tau^a N^c - i\frac{g_A m_N}{f_\pi}\pi^a N\tau^a N^c, \qquad \mu = \frac{m_u m_d}{m_u + m_d}$$

$$g_A \approx 1.27 \qquad c_+ \approx 1.7$$

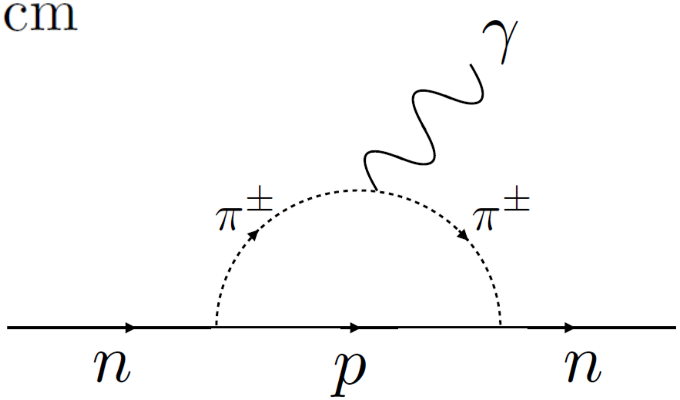
$$\bar{\theta} = \theta + \theta_u + \theta_d$$

$$d_n = \frac{e\bar{\theta} g_A c_+ \mu}{8\pi^2 f_\pi^2}\log\frac{\Lambda^2}{m_\pi^2} \sim 3\times 10^{16}\,\bar{\theta}\,\mathrm{e\ cm}$$

see 1509.04411

Experiment: $\bar{\theta} \lesssim 10^{-10}$

→ 10 orders of fine-tuning.



Feynman diagram for neutron EDM

Non-axion solutions

1. zero u-quark mass: $m_u < 10^{-10} m_d$

G't Hooft, 76'

$$\mathcal{L} \supset m_u e^{i\theta_u} u u^c + m_d e^{i\theta_d} d d^c + \frac{\theta g_s^2}{32\pi^2} G\tilde{G}$$

$$u \to e^{i\alpha} u,\ \ \cancel{\theta_u \to \theta_u} - \alpha,\ \theta \to \theta + \alpha$$
$$d \to e^{i\alpha} d,\ \ \theta_d \to \theta_d - \alpha,\ \theta \to \theta + \alpha.$$

$$u \to e^{i\alpha} u, \quad\ \theta \to \theta + \alpha$$
$$d \to e^{i\alpha} d,\ \ \theta_d \to \theta_d - \alpha,\ \theta \to \theta + \alpha.$$

After m_u ->0, θ and θ_d may vanish by field redef. Restores CP.

Tension with lattice QCD results ☹

- 2. Parity

Babu, Mohapatra, 90'

In a L-R model with $SU(2)_L$ x $SU(2)_R$, symmetric under parity:

$$SU(2)_L \leftrightarrow SU(2)_R, \qquad Q_L \leftrightarrow Q_R^\dagger, \qquad H_L \leftrightarrow H_R^\dagger, \qquad L_L \leftrightarrow L_R^\dagger,$$

θ term violates P and is forbidden. Yukawa takes the form:

$$\mathcal{L} \supset \frac{y_u Q_L H_L Q_R H_R}{\Lambda_u} + \frac{y_d Q_L H_L^\dagger Q_R H_R^\dagger}{\Lambda_d} + h.c.$$

After $SU(2)_R$ breaking, the Yukawas required by parity

$$Y_u = \frac{y_u v_R}{\Lambda_u} = Y_u^\dagger, \qquad Y_d = \frac{y_d v_R}{\Lambda_d} = Y_d^\dagger$$

Hermitian matrix: arg det(Y) = 0. so that combined $\bar{\theta}$ =0

Good at tree level, compilations arises at loop level.

A. Nelson,84'
S. Barr, 84'

- Nelson-Barr (spontaneously broken CP)

In a minimal Bento, Branco, Parada setup (Phys.Lett. B267 (1991) 95–99)

$$\mathcal{L} = \mu \bar{q} q + a_{af} \eta_a \bar{d}_{\bar{f}} q + y_{f\bar{f}} H Q_f \bar{d}_{\bar{f}} + \ldots \ .$$

q are new vector-like quarks,
η_a develop vevs with relative phases, breaking CP

$$\mathcal{M} = \begin{pmatrix} \mu & B \\ 0 & m_d \end{pmatrix}; \ m_d \equiv yv; \ B_f = a_{af}\eta_a$$

After diag., the SM 3x3:

assuming $\mu^2 + |B_f|^2 \gg m_d^2$

$$\left((m_d m_d^T)_{ij} - \frac{(m_d)_{ik} B_k^\dagger B_\ell (m_d^T)_{\ell j}}{\mu^2 + B_f B_f^\dagger} \right)$$

@ Tree level, arg det (M) = 0.
Diagonalizing matrix (CKM) carry CP phase

Likely tuned to have large CKM phase.
For many model variants,
see review: 1506.05433

Peccei, Quinn, 77'

Peccei-Quinn (axion)

Assume a global $U(1)_{PQ}$ as good UV symmetry

(as in PQWW)

$$Q_i/U_i^c/D_i^c/L_i/E_i^c \longrightarrow e^{i\alpha} Q_i/U_i^c/D_i^c/L_i/E_i^c \ ,$$
$$H_d/H_u \longrightarrow e^{-i2\alpha} H_d/H_u \ .$$

$U(1)_{PQ}$ breaks after a (charged) scalar gets vev ~ $O(f_a)$, leaving out a goldstone field (a). The goldstone can acquire an effective coupling term:

$$\frac{a}{f_a} G\tilde{G}$$

so that `extends' the QCD theta into a dynamic field:

$$\mathcal{L} \supset \left(\frac{a}{f_a} + \theta\right) \frac{1}{32\pi^2} G\tilde{G}.$$

$$\overline{\theta} \ \rightarrow \ \overline{\theta} = \theta + \theta_u + \theta_d + \frac{a}{f_a}$$

Not an exact Goldstone. QCD vacuum has V_{inst}. The pNGB has a mass

$$m_a = \frac{m_\pi f_\pi}{f_a} \frac{\sqrt{m_u m_d}}{m_u + m_d} \approx \frac{\Lambda_{QCD}^2}{f_a}$$

At low energy, *a* makes V_{QCD} go to its minimum at $\bar{\theta} + \frac{a}{f_a} = 0$.

⇨ Strong CP solved by ***relaxation***.

New pNGB is the \`axion’

composed of imaginary part(s) of scalars that transform under $U(1)_{PQ}$

Low-E effective Lagrangian:

$$\mathcal{L}_{\rm int} = -\frac{g_{\phi\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{g_{\phi N}}{2m_N}\partial_\mu\phi(\bar{N}\gamma^\mu\gamma_5 N) + \frac{g_{\phi e}}{2m_e}\partial_\mu\phi(\bar{e}\gamma^\mu\gamma_5 e) - \frac{i}{2}g_d\phi\bar{N}\sigma_{\mu\nu}\gamma_5 N F^{\mu\nu}$$

(Peccei, Quinn, Weinberg, Wilczek)

The PQWW model

$$
\begin{aligned}
-\mathcal{L} \quad = \quad & y^u_{ij} Q_i U^c_i H_u + y^d_{ij} Q_i D^c_i H_d + y^e_{ij} L_i E^c_i H_d \\
& + V\left(H^\dagger_u H_u,\ H^\dagger_d H_d,\ (H^\dagger_d H_u)(H^\dagger_u H_d) \right) \ .
\end{aligned}
$$

Two Higgs doublets (H_u & H_d). The PQ transformation:

$$
\begin{aligned}
& Q_i / U^c_i / D^c_i / L_i / E^c_i \longrightarrow e^{i\alpha} Q_i / U^c_i / D^c_i / L_i / E^c_i \ , \\
& H_d / H_u \longrightarrow e^{-i2\alpha} H_d / H_u \ .
\end{aligned}
$$

axion is a mixture of neutral scalar components.

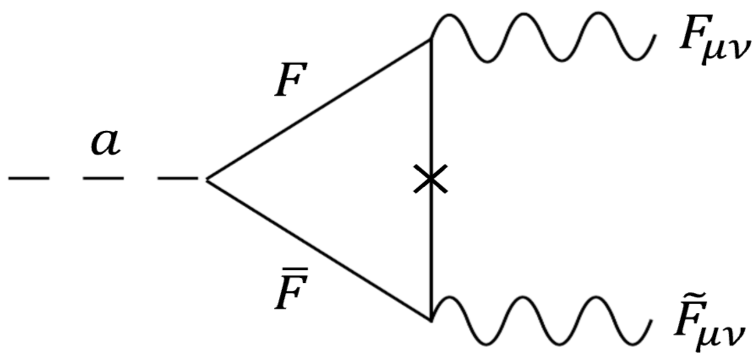
$$
a \equiv \sin\beta \mathrm{Im} H^0_d + \cos\beta \mathrm{Im} H^0_u \ , \quad \text{where} \tan\beta \equiv \frac{\langle H^0_u \rangle}{\langle H^0_d \rangle} \ .
$$

Axion is CP odd and can mix with a pion.
In PQWW, $f_a \sim O(v_H)$ ruled out by meson decays.

$f_a < 10^4$ GeV, $m_a < 10^2$ MeV constrained by rare decay of mesons.

`Invisible' axion models

Need a large f_a to avoid beam dump, astrophysical constraints ($f_a > 10^9$ GeV)



aGG~ generated
at loop level.

KSVZ model : heavy vector-like quarks, with coupling $\lambda_Q Q^c Q S$

The PQ U(1): $Q^c/Q \rightarrow e^{i\alpha} Q^c/Q$, $S \rightarrow e^{-i2\alpha}\, S$

a =Im(S) , $f_a \sim v_S$

Kim,79;
Shifman, Vainshtein, Zakharov, 80'

- The DSVZ model

Zhitnitsky, 80'
Dine, Fischler, and Srednicki, 81'

$$\lambda H_u H_d S^2$$

H_u, H_d, S charged as -1, -1, +1 under $U(1)_{PQ}$

$$f_a = \sqrt{v_u^2 + v_d^2 + v_S^2}$$ raised by S vev.

The axion is dominated by Im*S.*

$$a = \frac{1}{\sqrt{v_u^2 + v_d^2 + v_S^2}} (v_u \mathrm{Im} H_d + v_u \mathrm{Im} H_d + v_s \, \mathrm{Im} S)$$

SM quarks runs the fermion loop to generate effective aGG~.

For review, see
0807.3125, 1510.07633

Quality problem

EFT: $\epsilon^2 \Phi^2$

Gravity: $V \sim \frac{\Phi^n}{M_p^{n-4}}$

$$V \sim \epsilon^2 f_a^2 \cos\left(\frac{a}{f_a} + \phi\right)$$

$$V \sim \frac{f_a^n}{M_p^{n-4}} \cos\left(\frac{a}{f_a} + \phi_n\right)$$

n > 14 not to spoil strong CP.

`Axion like' particle (ALP)

Any pseudoscalar with $\frac{a}{\Lambda}F\tilde{F}$ coupling w/o solving the strong CP problem.

$$\mathcal{L} = \frac{1}{2}m_a^2 a^2 + \frac{g_{a\gamma\gamma}a}{4f}F\tilde{F}$$

Copious candidates from BSM UV theories, string theory, etc.

For EM couplings, axion mixes the E and B fields:

$$\mathcal{L}_{a\gamma\gamma} = \frac{a}{f}\vec{E}\cdot\vec{B} = -\frac{1}{4f}aF\tilde{F}$$

Axion as cold dark matter

For review, see 1510.07633

A fast oscillating field at the bottom of a $V(\phi) \sim (\phi - \phi_0)^2$ potential behaves as matter-like: $\rho(z) \sim (1+z)^3$ M.Turner, 83'

axion starts to oscillate after strong PT.

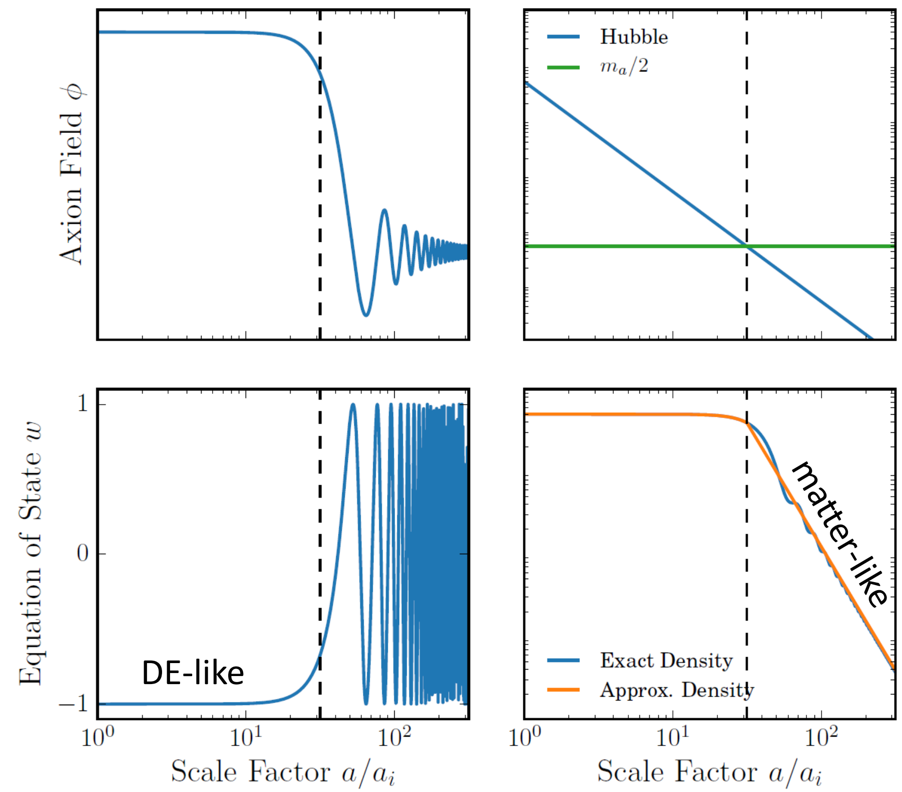
$$a(t) = a_0 \left(\frac{R_{m\sim H}}{R(t)}\right)^{2/3} \cos(m_a t)$$

Misalignment Mechanism:

axion gets a homogeneous initial value a_0 via inflation. Gives the DM abundance:

$$\Omega_a h^2 \sim 2 \times 10^4 \left(\frac{f_a}{10^{16}\ \mathrm{GeV}}\right)^{7/6} \langle \theta_{a,i}^2 \rangle$$

(topological defect corrections apply if f_a is lower than inflation scale)



axion dark matter requires $f_a \sim 10^{11}$ GeV, $m_a \approx 50$ μeV

Recent calculations:

$$m_a = 5.70(7)\mu eV \left(\frac{10^{12}\ \mathrm{GeV}}{f_a}\right).$$

G. Grilli di Cortona, E. Hardy, J. Pardo Vega and G. Villadoro, JHEP 1601, 034 (2016)

m_a = 60−150 μeV

T. Hiramatsu, et.al., PRD 85, 105020 (2012)
M. Kawasaki, et.al. PRD 91, no. 6, 065014(2015)

m_a = 26.5±3.4 μeV

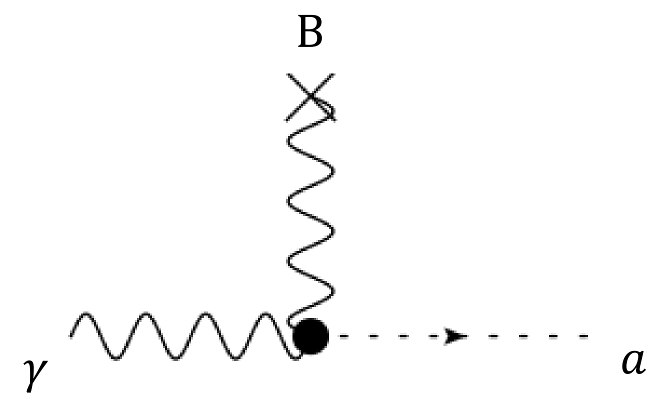
V.B.Klaer, G.D.Moore, JCAP 1711, no.11, 049 (2017)

DM axion has macroscopic de Broglie wave length: $\lambda \sim \beta^{-1}\, O(\mathrm{cm})$

DM axion soliton may form \`bosonic stars':
miniclusters with mass ~ 10^{-15} -10^{-9} M_{sun} 2006.08637

Searches for axion (ALP)

EM coupling allows axion – photon conversion in external field.



`Primakoff effect'

Photon- axion oscillation (in relativistic limit)

May imprint oscillation feature on photon spectrum: e.g. astrophysical sources

$$\left(\omega - i\frac{\mathrm{d}}{\mathrm{d}x} + \mathcal{M}\right)\begin{pmatrix} A_\perp \\ A_\parallel \\ a \end{pmatrix} = 0$$

$$\mathcal{M} \approx \begin{pmatrix} -\omega_{\mathrm{pl}}^2/2\omega & & \\ & -\omega_{\mathrm{pl}}^2/2\omega & g_{a\gamma\gamma}B_{\mathrm{T}}/2 \\ & g_{a\gamma\gamma}B_{\mathrm{T}}/2 & -m_a^2/2\omega \end{pmatrix}$$

$$P_{\gamma\to a}(E_\gamma) = \left(1 + \frac{E_c^2}{E_\gamma^2}\right)^{-1} \sin^2\left(\frac{g_{a\gamma\gamma}B_{\mathrm{T}}L}{2}\sqrt{1 + \frac{E_c^2}{E_\gamma^2}}\right)$$

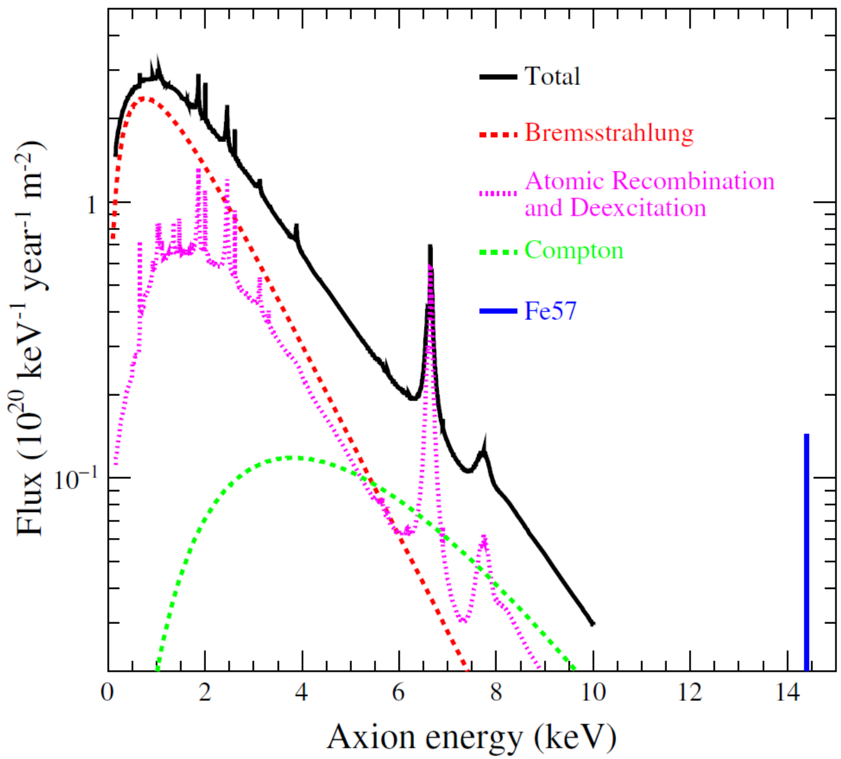
$$E_c = |m_a^2 - \omega_{pl}^2|/2g_{a\gamma\gamma}B_{\mathrm{T}}$$

Solar axions

axion couples to nucleus g_{aN}, electrons, g_{ae}, and photons $g_{a\gamma}$

axion emission via: fermion radiation, nuclear transitions, (Primakoff) conversion from photons, etc.

Experiments: CAST;
Direct detection Experiments



Armengaud, et al., J. Cosmol. Astropart. Phys. 2013, 067 (2013).

Stellar cooling exclusions

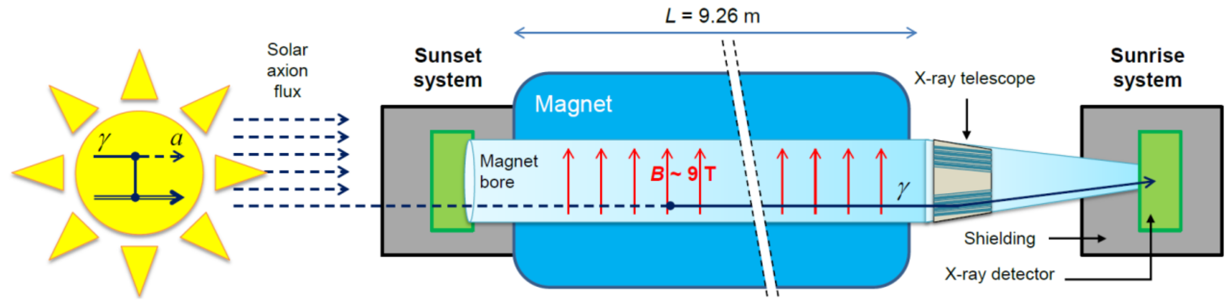
Axion emisssin via $e + \gamma \rightarrow e + a, N + e \rightarrow N + e + a$ cools stars if m_a is light.

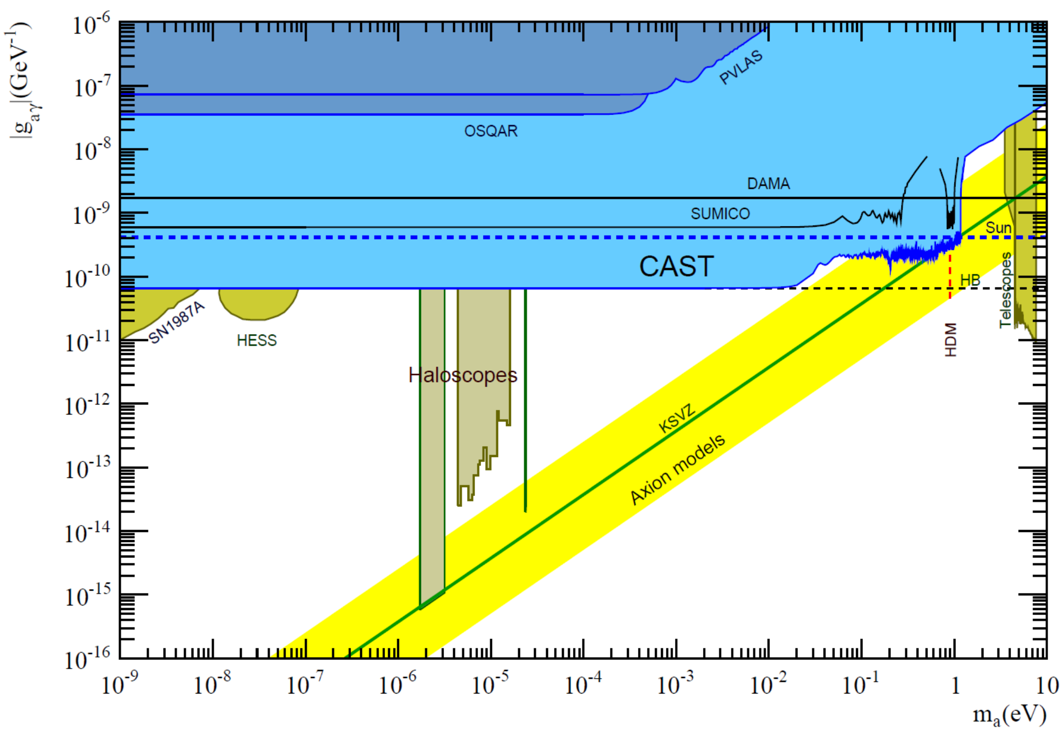
HB stars: $g_{ae} < 4*10^{-13}$ GeV^{-1} N. Viaux et.al. PRL 111, 231301 (2013).
Supernova 1987A: $g_{a\gamma} < 5.3 \times 10^{-12}$ GeV^{-1}, for $m_a < 4.4 \times 10^{-10}$ eV
Payez,et.al. JCAP 1502 (2015) 006

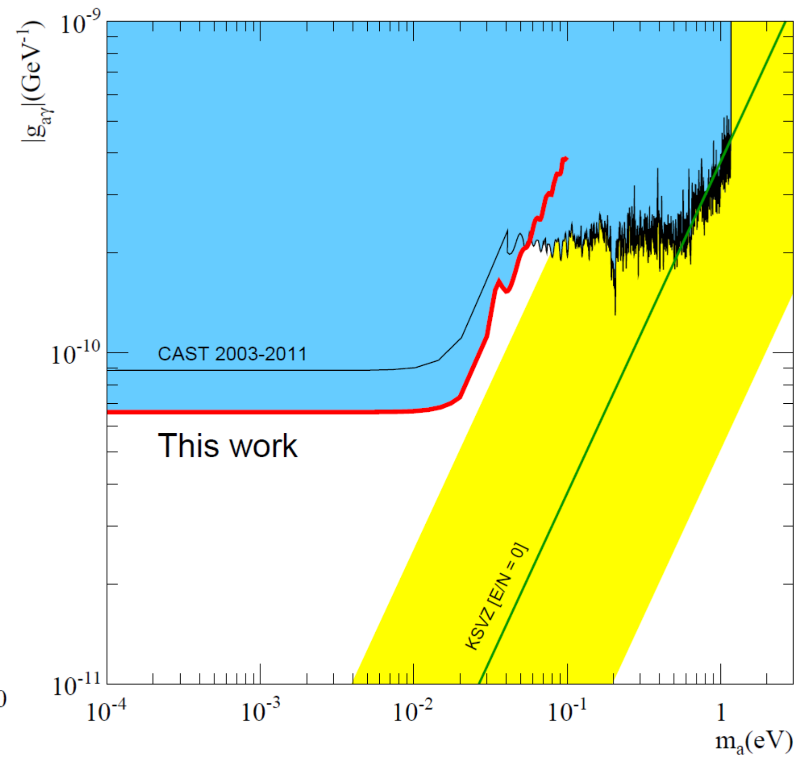
CAST

CAST (2017): 1705.02290

- Expected solar flux ~ KeV
- Accelerator magnets converts axions back to KeV photons



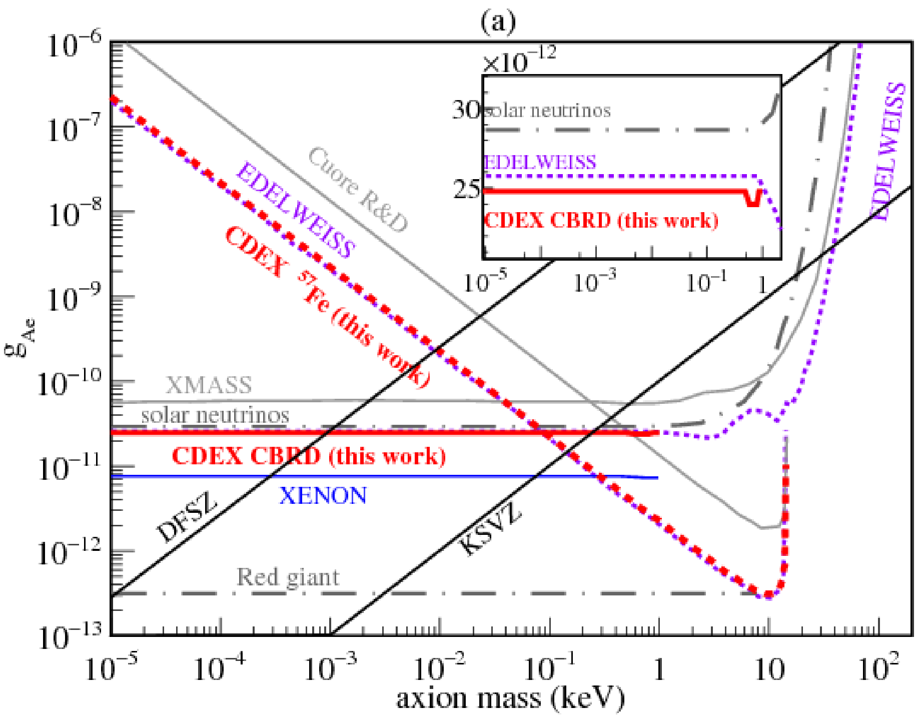




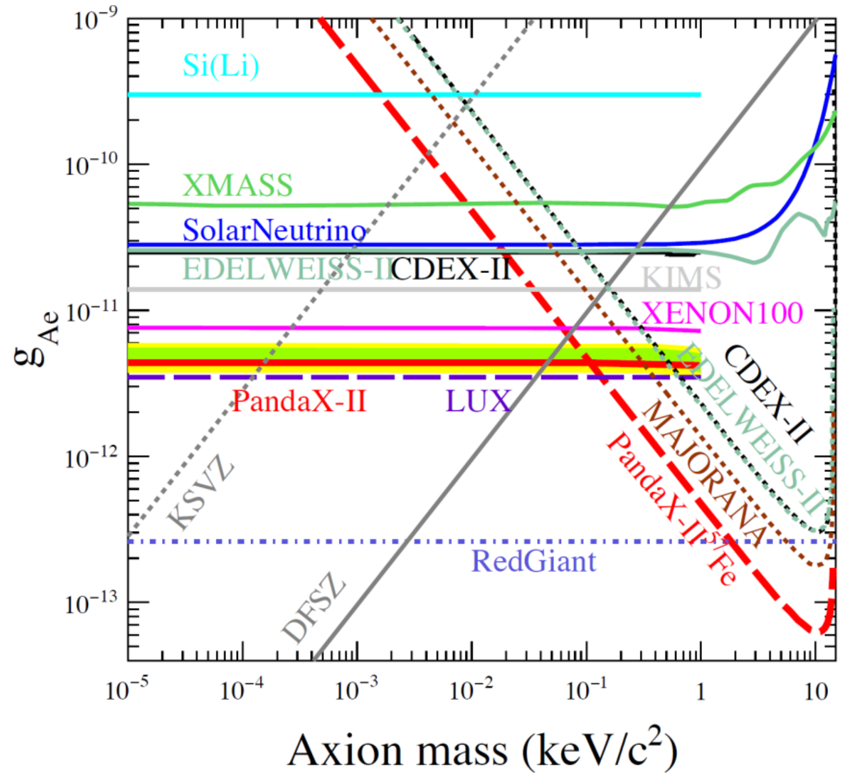
Recoil (underground exp.)

Recent KeV `bump'
see XENON1T 2020
& PANDAX 2020 results

Electron recoils (axio-electric absorptions) test axion-electron coupling g_{ae}



CDEX, Phys.Rev. D95 (2017) no.5, 052006



PANDAX, PRL 119 (2017)

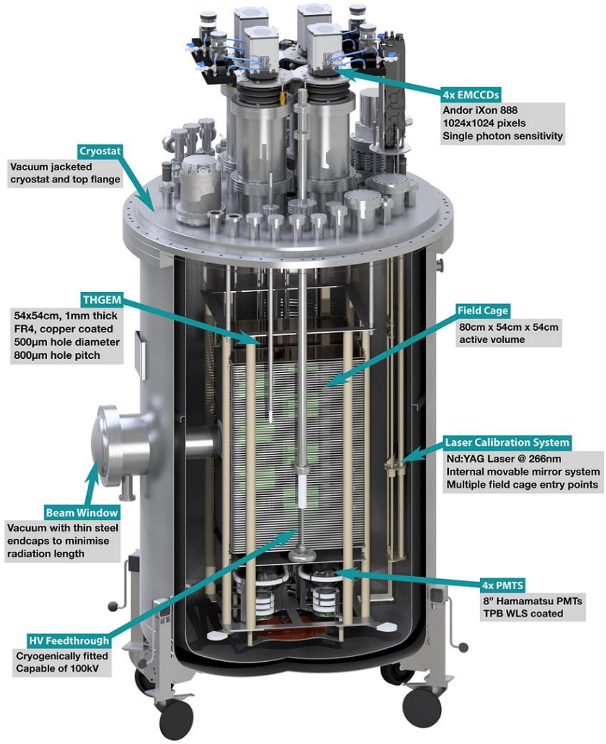
Fifth force?

$\partial_\mu (a/f_a) \bar{\Psi} \gamma^\mu \gamma^5 \Psi$ axion-fermion coupling leads to spin-dependent interactions

Effective interaction potential btw test objects

1910.05406

$$U_{pp}(r) = \frac{\hbar^3 c}{16\pi} \frac{g_{p_1} g_{p_2}}{m_{f_1} m_{f_2}} \left((\hat{\sigma}_1 \cdot \hat{\sigma}_2) \left(\frac{1}{r^2 \lambda_a} + \frac{1}{r^3} \right) e^{-\frac{r}{\lambda_a}} \right.$$
$$\left. - (\hat{\sigma}_1 \cdot \hat{r})(\hat{\sigma}_2 \cdot \hat{r}) \left(\frac{1}{r \lambda_a^2} + \frac{3}{r^2 \lambda_a} + \frac{3}{r^3} \right) e^{-\frac{r}{\lambda_a}} \right)$$
$$U_{sp}(r) = \frac{\hbar^2 g_s g_p}{8\pi m_f} \left(\frac{1}{r \lambda_a} + \frac{1}{r^2} \right) e^{-\frac{r}{\lambda_a}} (\hat{\sigma} \cdot \hat{r})$$



Can be tested by precision measurement.
MNR proposal: ARIADNE PRL. 113 (2014) no.16, 161801

Developments at UTSC: 2009.09257, 2010.14199

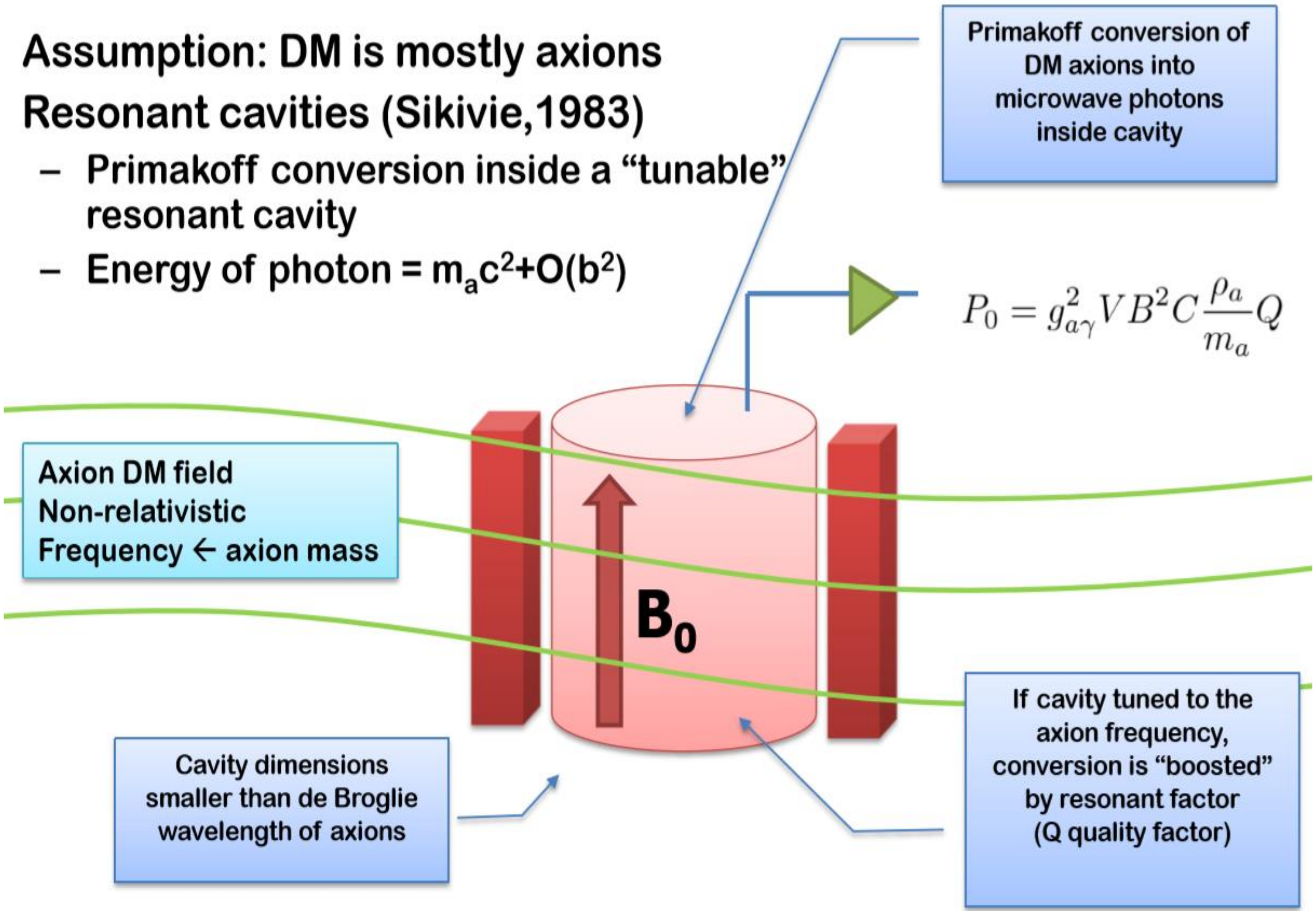
Axion DM - `haloscope'

DM axion has a *preferred* parameter range.

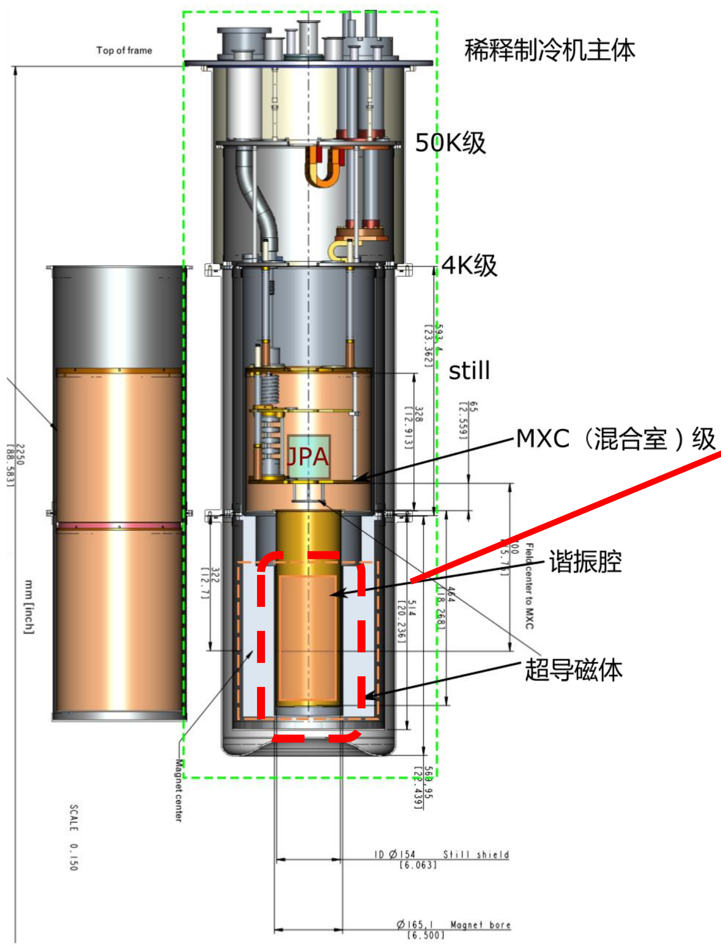
Assumption: DM is mostly axions

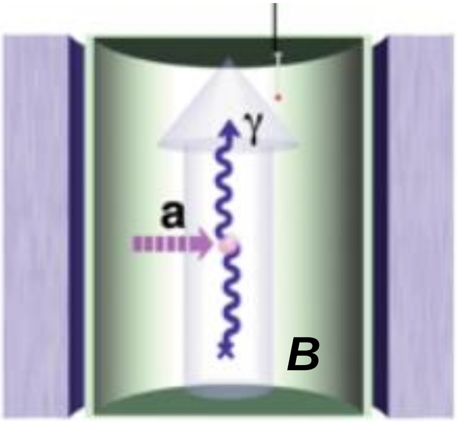
Resonant cavities (Sikivie,1983)

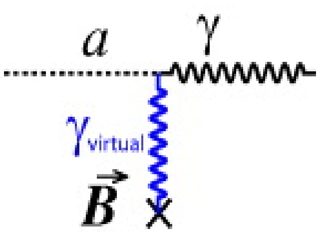
- **Primakoff conversion inside a "tunable" resonant cavity**
- **Energy of photon = $m_a c^2 + O(b^2)$**



Cryogenic resonance cavity







Cavity frequency tuned to expected axion decay signal frequency

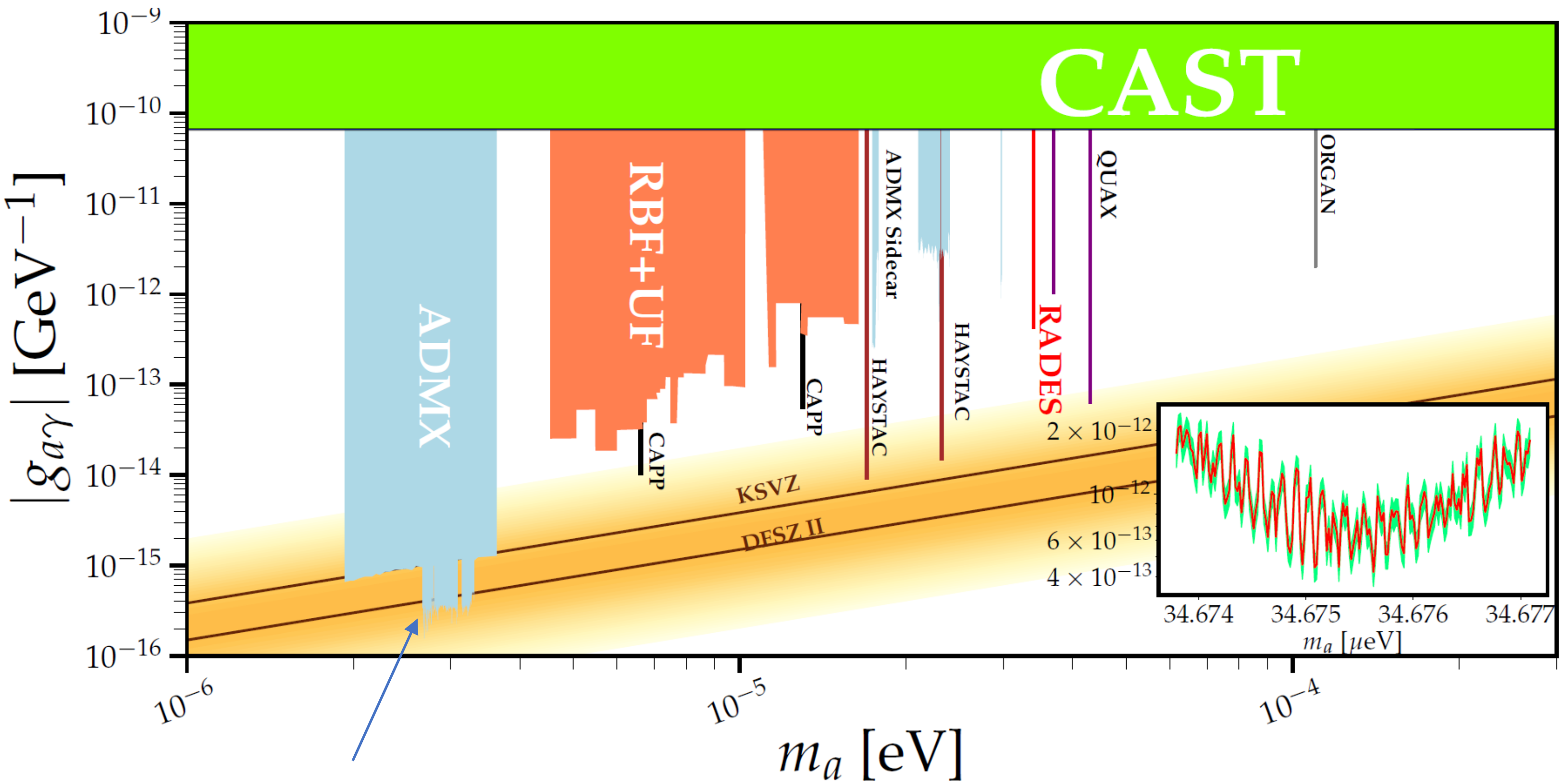
QCD axion DM: emergence of a microwave signal

$$P_{\text{axion}} = 2.2 \cdot 10^{-23}\ \text{W}\left(\frac{V}{136\ \text{L}}\right)\left(\frac{B}{7.6\ \text{T}}\right)^2\left(\frac{C}{0.4}\right) \cdot\left(\frac{g_\gamma}{0.36}\right)^2\left(\frac{\rho_a}{0.45\ \text{GeV cm}^{-3}}\right)\left(\frac{f}{740\ \text{MHz}}\right)\left(\frac{Q}{30000}\right)$$

Cavity experiment sites (blue)
Non-cavity axion DM experiments (red)

status of haloscopes

2104.13798



ADMX 2020

Axion DM – EM effects

- axion-modified Maxwell equations:

$$\vec{\nabla} \cdot \vec{E} = \rho_e + \underline{g\vec{B} \cdot \nabla a}$$

$$\vec{\nabla} \times \vec{B} - \frac{\partial \vec{E}}{\partial t} = g\underline{\vec{E} \times \vec{\nabla} a} - \underline{g\vec{B}\frac{\partial a}{\partial t}} + \vec{j}_e$$

$$\vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \; ,$$

Effective charge: (how to search?)

Axio-magnetic current:
Abracadabra (MIT)
1905.06882

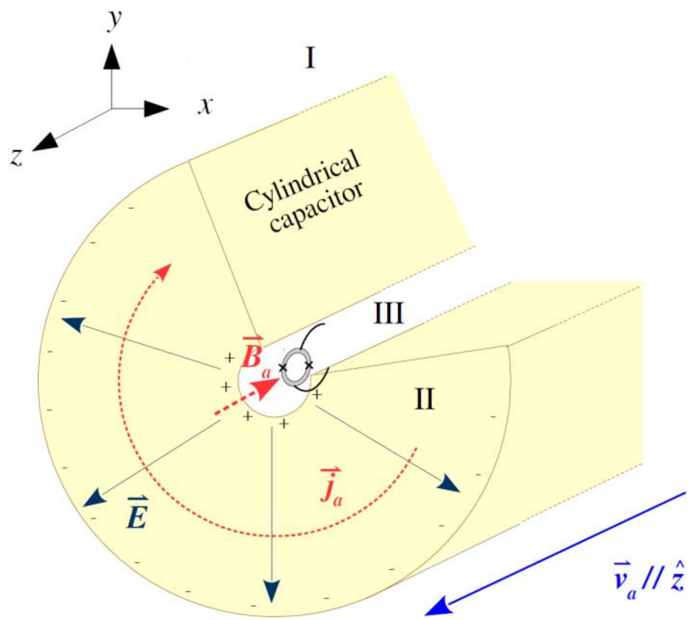
Axio-electric current $\vec{j}_a = g\vec{E} \times \vec{\nabla} a$

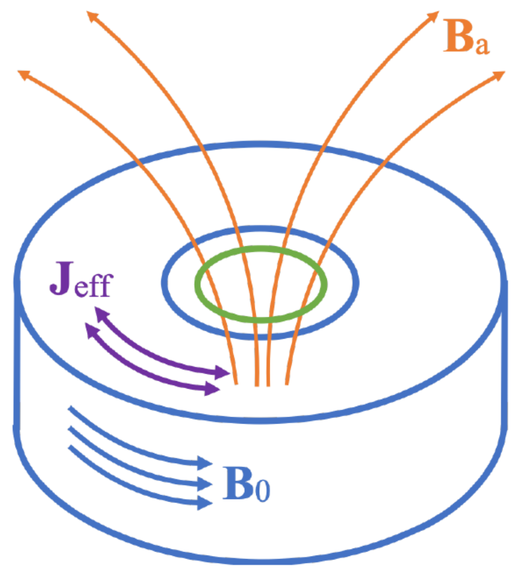
DM axion flow Induces a magnetic signal
inside E field: see 2012.13946

$$\vec{\nabla} \times \vec{B} = g_{a\gamma}(\vec{E}_0 \times \vec{v})\sqrt{2\rho_{\mathrm{DM}}}\cos[m_a(1+\frac{1}{2}v^2)t] \equiv \vec{j}_a$$

One effective charge
Two effective displacement currents

Sketch of axio-electric and axio-magnetic effective currents





$$\vec{E} \times \vec{k}_a$$

Depend on both E field
and axion flux directions

$$\vec{B} \cdot \partial_t a$$

(anti)parallel with
B field direction

Birefringence (axion as medium)

Axion field is a parity-violating medium.
It rotates the linear polarization of light.

$$\Delta\theta = \frac{1}{2} g_{a\gamma} \Delta a$$

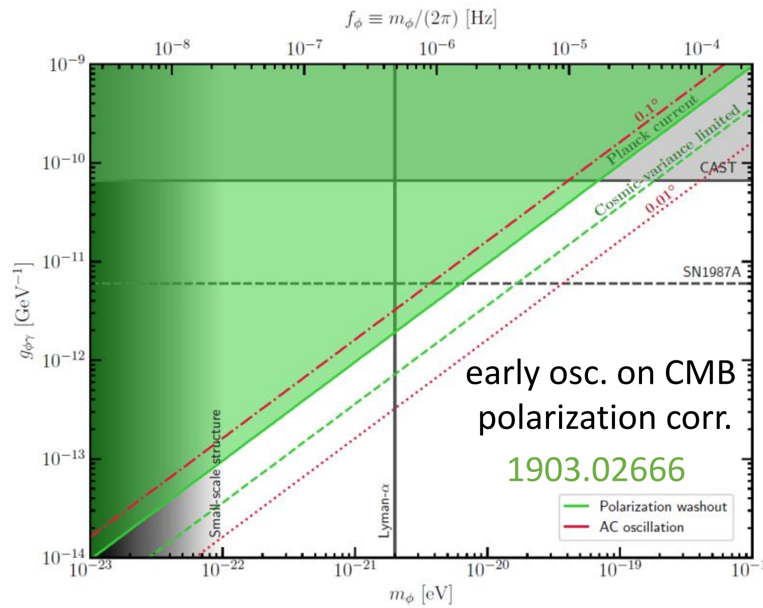
only determined by a field difference between initial & final positions (for freq. $\omega >> m_a$)

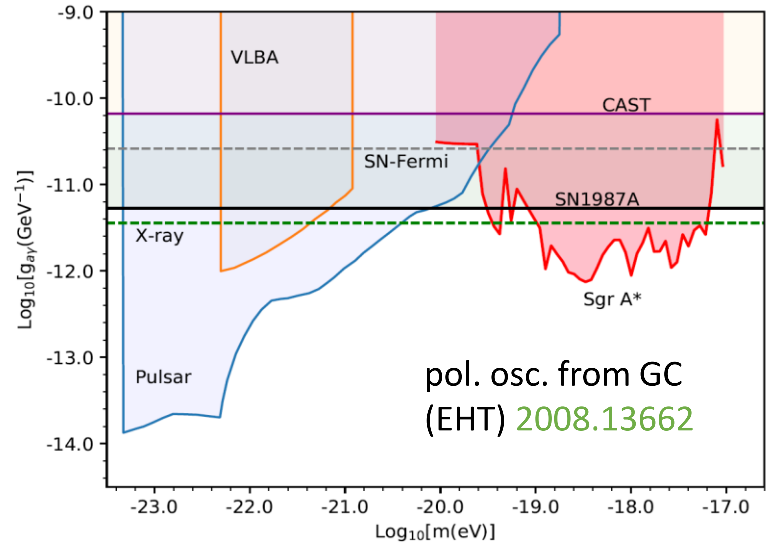
Harari, Sikivie, 92'

Comparison: Faraday effect

$$\theta_{\rm Faraday} = \frac{2\pi e^3}{m_e^2 k^2} \int \mathrm{d}\boldsymbol{x} \cdot \boldsymbol{B}(x)\, n_e(x)$$

lab birefringence & dichroism under B-field, see





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