Sterile neutrinos from intersecting D-brane compactifications

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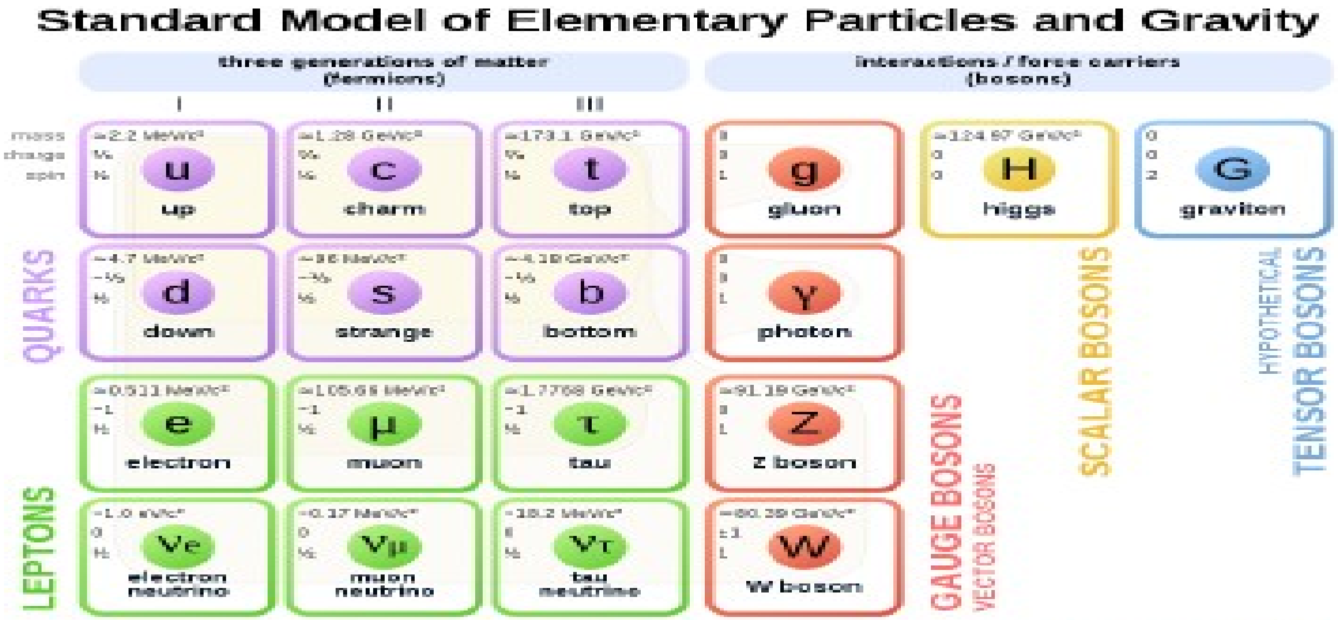
Outline

1. Standard Model Problems
2. Experimental Anomalies/1993-2026/
   Latest Results
3. String Theory models
4. String models from intersecting branes
5. Sterile interactions and constraints
6. Conclusions

STANDARD MODEL Neutrinos



- Accommodates 3 generations of neutrinos
- NO Mass term for neutrinos
- Baryon (B) & Lepton (L) number → classically conserved (global abelian symmetries)
- B & L broken non-perturbatively

  t'Hooft, Klinkhammer, & Manton
- B-L conserved

Standard Model "problems"

- **No mass term** for **neutrinos** in the SM
- **Only beyond the SM a mass term**

  (ν_R , etc.) $h_\nu \bar{L} \nu_R H$

- **No particles** that account **for** the

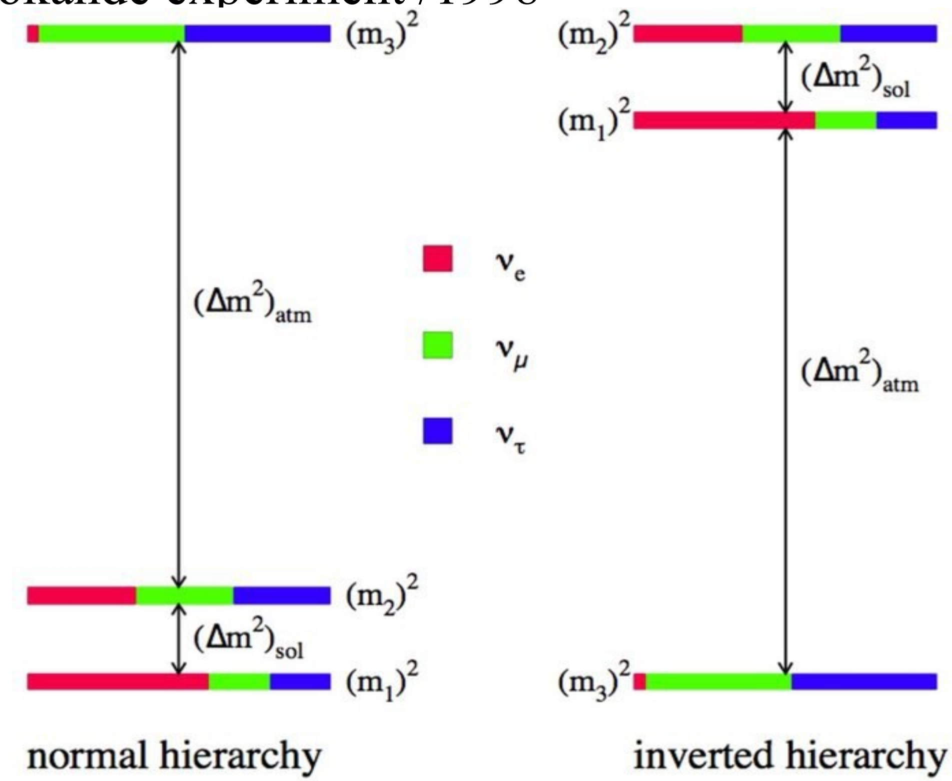
  observed Dark Matter (DM) abundance

Dark Matter (~26.8%) contributes 5x more to energy of the Universe than ordinary matter (~5%)

=> **SOMETHING ELSE is OUT THERE !!**

Πειραματικές παρατηρήσεις

- **Neutrino Oscillations / Neutrinos have a mass beyond the SM**
  - Super-Kamiokande experiment /1998
  - .



Fractional Flavour Content

● **Super-Kamiokande experiment** observed neutrino oscillations.

This proved that neutrinos change "flavors" (e.g., muon to tau) as they travel, which provided the first definitive experimental evidence that neutrinos possess a non-zero mass

Specifically, the decay chain of secondary particles—pions decaying into muons was observed, which subsequently decay into electrons and neutrinos:

$\pi+ \longrightarrow \mu+ + \nu_{\mu}$, $\mu+ \longrightarrow e+ + \nu_{e} + \tilde{\nu}_{\mu}$

The detector observed a deficit in the expected ratio of ν_{μ} to ν_{e},

revealing that the missing ν_{μ} had oscillated into ν_{τ}

Experiment anomalies (1993-2026)

Los Alamos National Laboratory

- **No 1 : LSND experiment anomaly (1993-1998)**
  - LSND observed neutrinos from stopped π+ beam, $\pi^+ \rightarrow \mu^+ + \nu_\mu$

Since the decay chain produces no $\tilde{\nu}_e$, none should be detected

via inverse beta decay($\mu^+ \rightarrow e^+ + \nu_e + \tilde{\nu}_\mu$)

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

  - However, **LSND observed a 3.8σ excess of $\tilde{\nu}_e$** *events, interpreted as evidence for short-baseline oscillations*

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

  - **: Due to a sterile neutrino with Δm^2 → 0.2–10 eV²/c⁴** range. The best-fit parameters were :

$$\sin^2 2\theta = 0.003, \Delta m^2 = 1.2\,\mathrm{eV^2/c^4}$$

Experiment anomalies (1993-2026)

Fermilab

- **No 2 : MiniBooNE anomaly (2002-2018)**

MiniBooNE operated at approximately 10 times the energy and baseline of LSND and observed an **unexpected surplus of electron neutrino and antineutrino events** in a muon-flavour neutrino beam. The combined significance of LSND and MiniBooNE reached around **6.1σ**.

The key point is that MiniBooNE was designed specifically to test LSND — and saw the same anomaly, dramatically increasing the statistical weight of the signal.

Experiment anomalies (1993-2026)

Multiple reactor experiments worldwide/

Daya Bay, DCHOOZ, RENO/distance~ 1 Km

- **No 3 : The Reactor Antineutrino Anomaly (RAA)**

When the expected flux of $\tilde{\nu}_e$ was recalculated from nuclear reactors (around 2011), they found that all short-baseline reactor experiments consistently detected ~3% fewer $\tilde{\nu}_e$ than predicted. This deficit, known as the Reactor Antineutrino Anomaly, is consistent with $\tilde{\nu}_e$ oscillating into a sterile state with $\Delta m^2 \sim 1\ eV^2$, over baselines of tens of meters before detectors could catch them.

Experiment anomalies (1993-2026)

GALLEX, SAGE, and BEST experiments

- **No 4 : The Gallium Anomaly**

The gallium anomaly describes the fact that GALLEX, SAGE, and most recently BEST observe lower rates of ν_e than expected from calibrated ^{51}Cr and ^{37}Ar radioactive electron capture decay sources. These experiments observe about 80% as many events as expected, an overall significance of about 4σ.

A more refined experiment found further evidence for the gallium anomaly in 2022 (the BEST experiment in Russia), strengthening the case.

Experiment anomalies (1993-2026)

Anomaly	Experiment(s)	Channel	Significance	Δm^2 hint
LSND	LSND (Los Alamos)	$\bar{\nu}_\mu \to \bar{\nu}_e$ appearance	3.8σ	0.2-10 eV^2
MiniBooNE	MiniBooNE (Fermilab)	$\nu_\mu \to \nu_e$ appearance	combined LSND /MiniBoone $\sim 6.1\sigma$	~0.5-1 eV^2
Reactor	Many reactor Experiments : **Daya Bay, DCHOOZ, RENO**	Disappearance $\tilde{\nu}_e$	$\sim 3\sigma$	~ 1 eV^2
Gallium	GALLEX, SAGE, BEST	Ve disappearance	$\sim 4\sigma$	~1 eV^2

RECENT RESULTS

Latest Results KATRIN/MicroBooNE

Summary Comparison

Metric / Feature	KATRIN Experiment	MicroBooNE Experiment
Primary Approach	Energy spectrum of tritium beta decay	Accelerator neutrino beam oscillations
Statistical Verdict	Excludes Gallium anomaly at **96.6% CL**	Excludes single sterile neutrino at **95% CL**
Historical Target	Gallium anomaly & Neutrino-4 claim	LSND and MiniBooNE anomalie
Main Takeaway	No "kinks" found in the decay spectrum	No excess or flavor-transition anomalies

$$|U_{e4}|^2 \sim \sin^2(\theta_{ee}) \sim 2 \times 10^{-2} \longrightarrow \text{KATRIN}$$

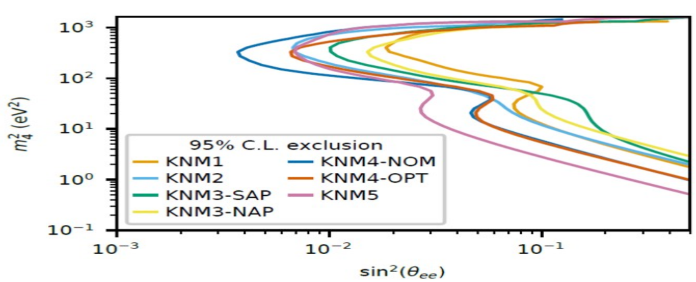
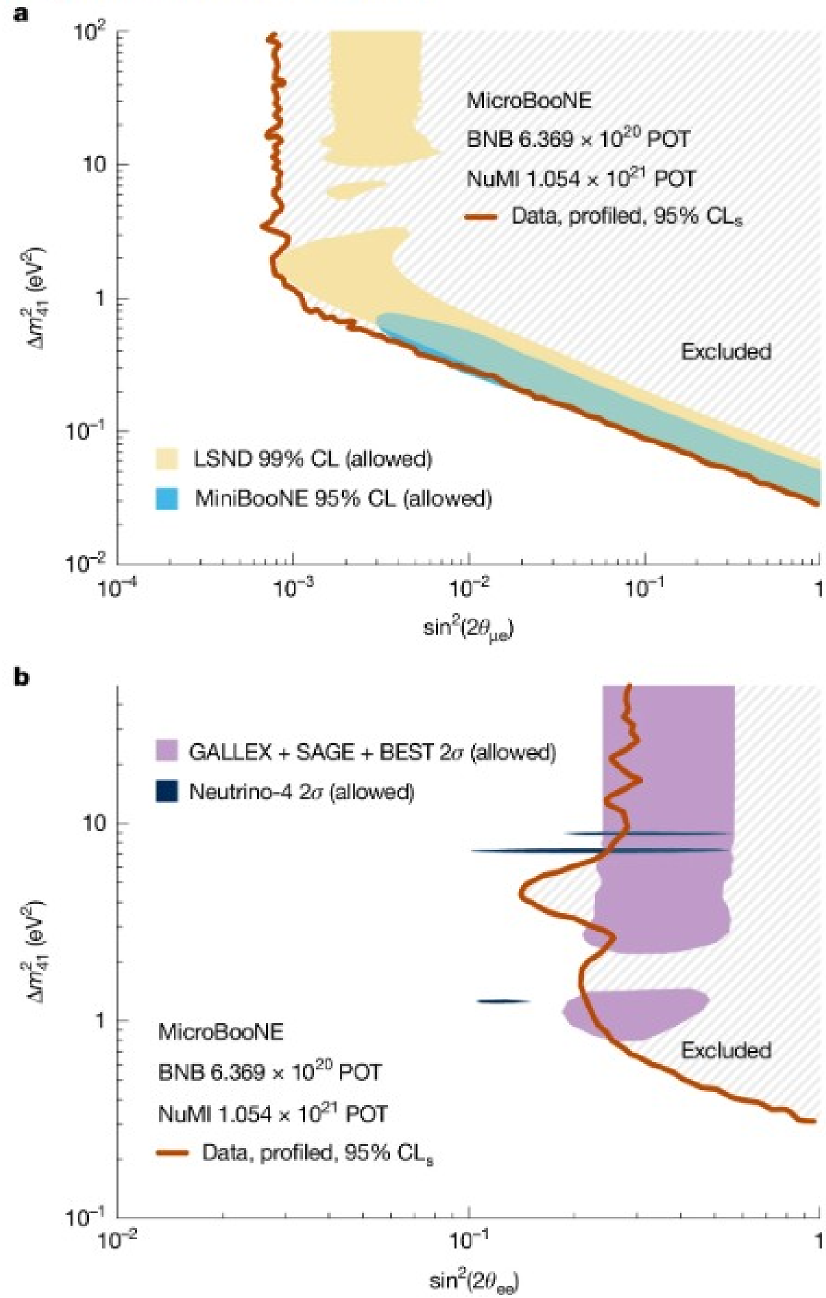


Fig. 7: Sterile neutrino exclusion contours for individual datasets from KATRIN measurement campaigns KNM1 to KNM5. The datasets include approximately 2.0 million electrons for KNM1, 4.3 million for KNM2, 2.5 million for KNM3, 10.2 million for KNM4, and 16.7 million for KNM5.

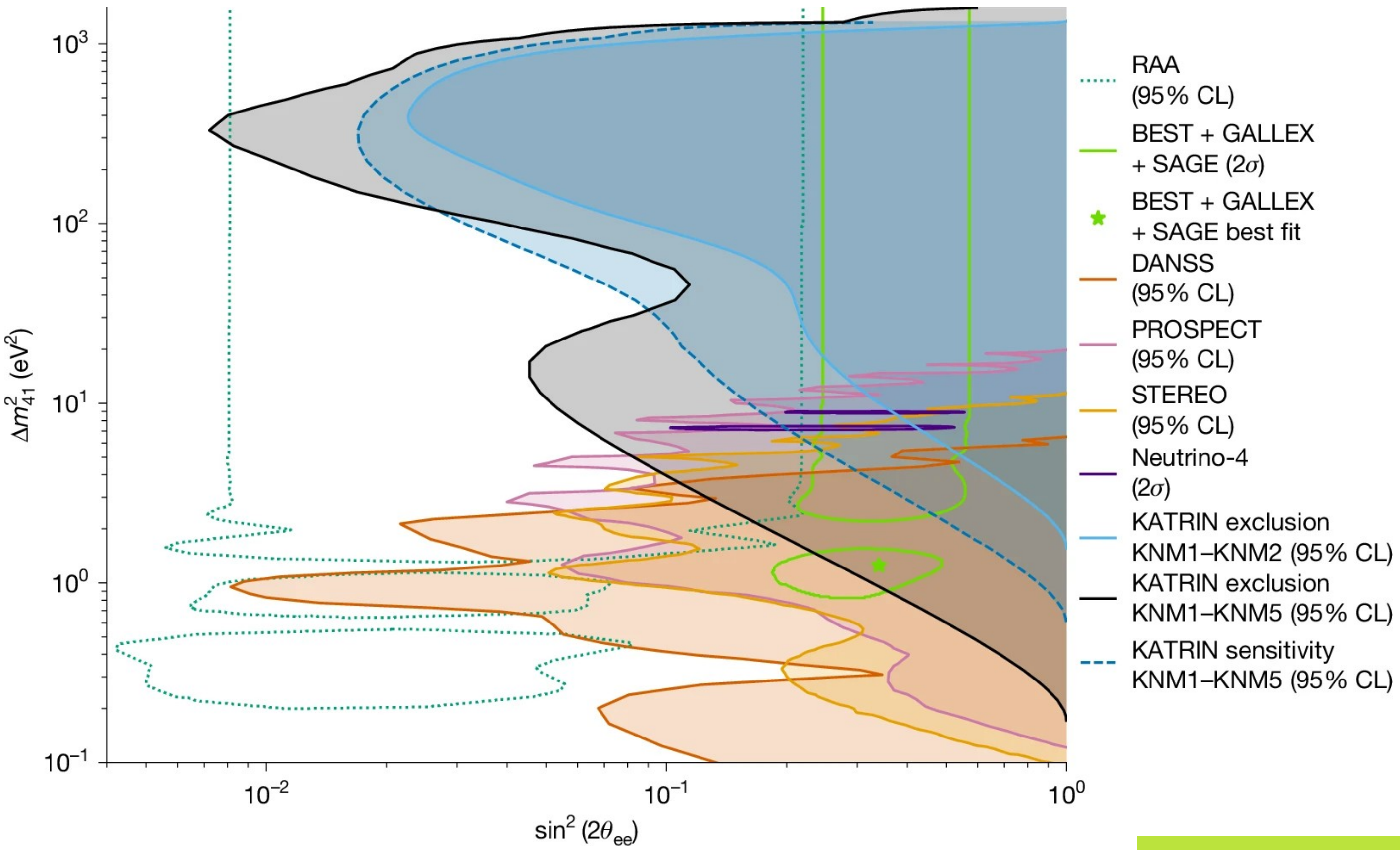
Fig. 3: Constraints on parameters of the 4ν oscillation model.

From: Search for light sterile neutrinos with two neutrino beams at MicroBooNE



The 95% CL exclusion curves plane obtained from the analysis of the first five KATRIN campaigns with a fixed mν = 0 eV (black)

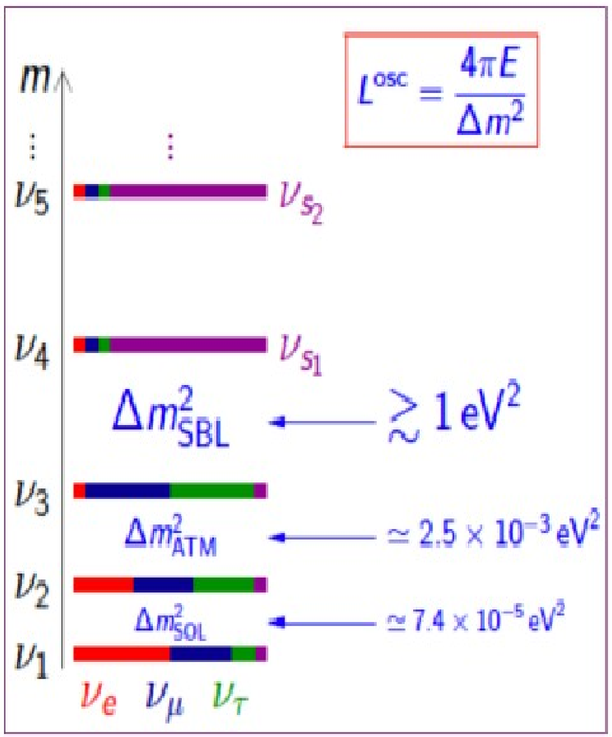
→ most of RAA, GA parameter space excluded



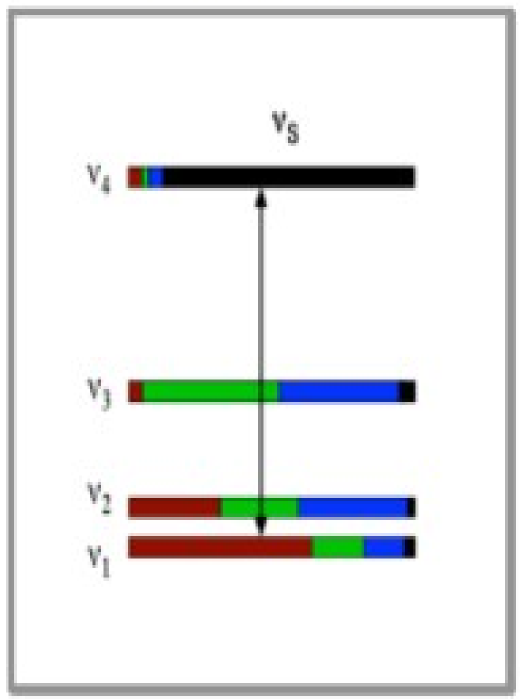
RECENT RESULTS

→ a region with small mixing angles remains viable

Anomalies solution : Sterile-Active neutrino oscillations



3+1 scheme



$$\Delta m^2_{41} \sim 1\ eV^2$$

Sterile Neutrinos N in Gauge Theories

mass terms

$$m_D \nu^c \nu + m_N \nu^c N + \mu N N$$

$$m_D = \lambda_1 \langle h \rangle, \; m_N = \lambda_2 \langle H \rangle, \; \mu = \frac{\lambda_3}{M_{GUT}} \langle \tilde{\bar{N}} \rangle^2$$

an effective mass matrix is created

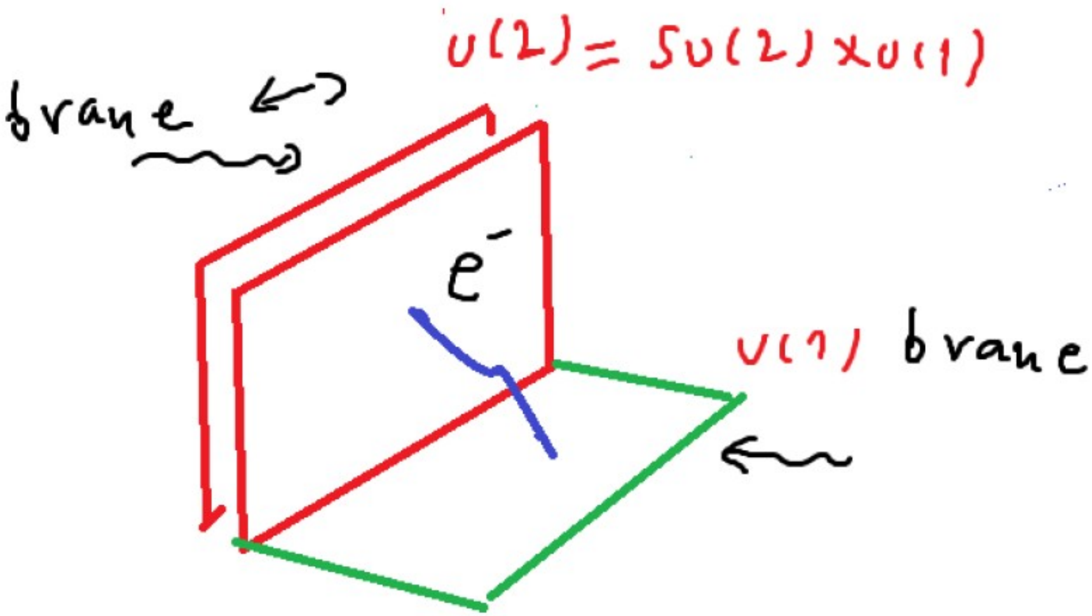
$$m_\nu^{eff} = \begin{pmatrix} 0 & m_D & 0 \\ m_D & 0 & m_N \\ 0 & m_N & \mu \end{pmatrix}$$

Leontaris, Shafi

String Theory Models

- **Particles stretch between intersecting D6 branes at angles**

Bachas, Berkooz, Douglas, Leigh; Blumenhagen, Goerlish, Kors, Lust; Angelantonj, Bianchi, Pradisi, Sagnotti



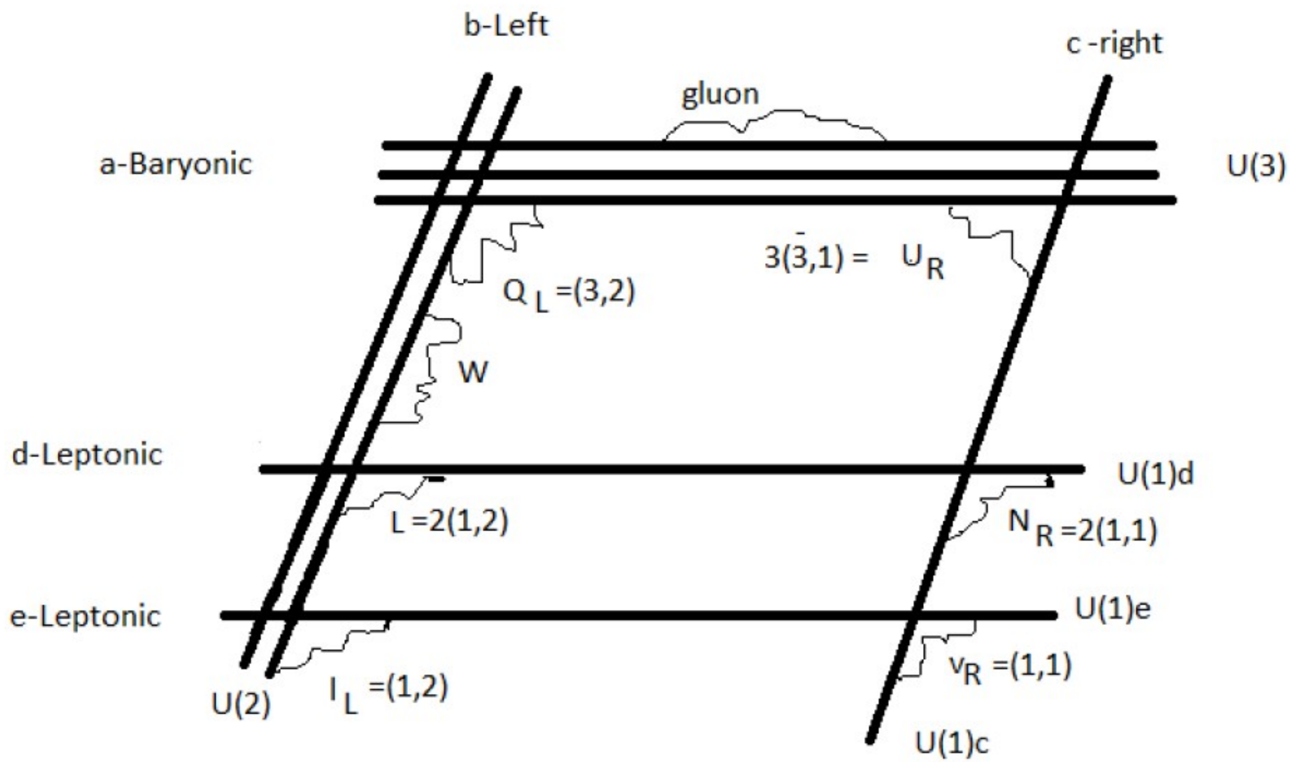
- **offer candidate particles with non-SUSY models with gauged B & L**

Ibanez, Marchesano and Rabadan, C. K.

5-Stack 3 generation Standard Model with no extra fermions at low energies + V_R + no proton decay

C.K

$$SU(3) \times SU(2) \times U(1)_a \times U(1)_b \times U(1)_c \times U(1)_d \times U(1)_e$$



IIA compactifications on toroidal orientifolds with intersecting D6-branes in 4D

Blumenhagen, Kors, Lust

Standard Model + ν_R

GAUGE GROUP

- SU(3)a x SU(2)b x U(1)a x U(1) b x U(1)c x U(1) d x U(1)e

Matter Fields		Intersection	Q_a	Q_b	Q_c	Q_d	Q_e	Y
Q_L	$(3,2)$	$I_{ab}=1$	1	-1	0	0	0	1/6
q_L	$2(3,2)$	$I_{ab^*}=2$	1	1	0	0	0	1/6
U_R	$3(\bar{3},1)$	$I_{ac}=-3$	-1	0	1	0	0	$-2/3$
D_R	$3(\bar{3},1)$	$I_{ac^*}=-3$	-1	0	-1	0	0	1/3
L	$2(1,2)$	$I_{bd}=-2$	0	-1	0	1	0	$-1/2$
l_L	$(1,2)$	$I_{be}=-1$	0	-1	0	0	1	$-1/2$
N_R	$2(1,1)$	$I_{cd}=2$	0	0	1	-1	0	0
E_R	$2(1,1)$	$I_{cd^*}=-2$	0	0	-1	-1	0	1
ν_R	$(1,1)$	$I_{ce}=1$	0	0	1	0	-1	0
e_R	$(1,1)$	$I_{ce^*}=-1$	0	0	-1	0	-1	1

Fermionic spectrum SM + ν_R's + sterile (s) → At low energy only the SM gauge group survives :

[PROTON IS STABLE - No fine tuning] C.K, hep-th/0205147

NEUTRINO MASSES

$$Y_j^U Q_L U_R^j h_1 + Y_j^D Q_L D_R^j H_2 \quad +$$
$$Y_{ij}^u q_L^i U_R^j H_1 + Y_{ij}^d q_L^i D_R^j h_2 +$$
$$Y_h^l \; l_L^h \; \nu_R^h \; h_1 + \; Y_h^e l_L^h e_R^h H_2 \quad +$$
$$Y_{ij}^N L^i N_R^j h_1 + Y_{ij}^E L_i E_R^j H_2 + \; h.c$$

$$i = 1, 2, \; j = 1, 2, 3,$$

can also produced via chiral symmetry breaking

$$\alpha'(LN_R)\;(Q_L U_R)^\star, \;\; \alpha'(l\nu_R)(q_L U_R)$$

Ibanez, Marchesano and Rabadan, C. K.

via the u-quark chiral condensate

$$\frac{< u_R u_L >}{M_s^2} = \frac{(240MeV)^3}{M_s^2}$$

Neutrino masses ~ (0.1-10) GeV if Ms → (1-10) TeV

consistent with ↔

atmospheric ν-data

Sterile Neutrinos from Intersecting Branes

Eigenstate basis (ν_L, ν_R, N1)

$$M_\nu = \begin{pmatrix} 0 & m_D & m_\Sigma \\ m_D & 0 & m_N \\ m_\Sigma & m_N & 0 \end{pmatrix}$$

I. Antoniadis, C.K

RESULTS

Under the $D/N << 1 \rightarrow$ light order $0 < N << D \leq 0.0805$

$\rightarrow$ heavy order $0 < N << 0.9195 \leq D$

$$M\nu L = mD - (mN\, m\Sigma)/MD - (mD^2)/(2mN)$$

$m_{sterile} \geq 0$

Light order : **$m_{sterile} \geq 0$, $M\nu R \leq 0.161$ eV, $M\nu L \leq 0.037$ eV**

- Data from dark Energy Spectroscopic Instrument(DESI), the

Cosmic Microwave Backgroundand terrestrial experiments at 95% conf.

Level $\rightarrow$ lightest $M\nu < 0.037$ eV

- ΛCDM cosmological + DESI galaxy surveys $\Sigma m\nu < 0.064$ eV

Conclusions

- KATRIN has not ‘killed’ the sterile neutrino; it has made its ‘living space’ much smaller
- Sterile neutrinos are naturally appearing in string D6-brane models
- Constraints on the mass of sterile neutrino are found