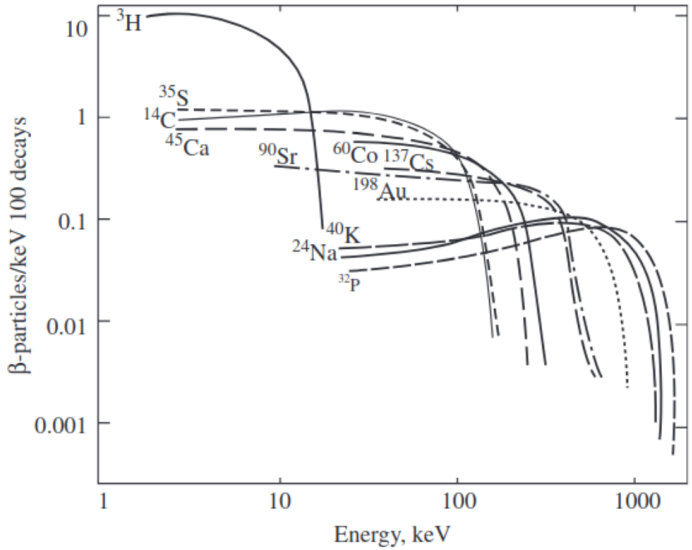
Overview of Beyond the Standard Model Reach in Beta-decay Experiments

Vedran Brdar

Fermilab

Northwestern University

Beta Decay



$$ {}^{A}_{Z}X_N \rightarrow {}^{A}_{Z\pm1}Y_{N\mp1} + e^{\mp} + \begin{pmatrix} \bar{\nu}_e \\ \nu_e \end{pmatrix} $$

Transition	Type	change	
		spin Δl	parity $\Delta\pi$
Allowed	Fermi	0	No
	Gamow-Teller	0, ± 1 (0 ↛ 0)	
1st Forbidden	non-unique 1st	0, ± 1	Yes
	unique 1st	±2	
2nd Forbidden	non-unique 2nd	± 2	No
	unique 2nd	± 3	

Hayen et al. arXiv:1709.07530

$$ N(W)dW = \frac{G_V^2 V_{ud}^2}{2\pi^3} F_0(Z,W)\, L_0(Z,W)\, U(Z,W)\, D_{\mathrm{FS}}(Z,W,\beta_2)\, R(W,W_0)\, R_N(W,W_0,M) \times Q(Z,W)\, S(Z,W)\, X(Z,W)\, r(Z,W)\, C(Z,W)\, D_C(Z,W,\beta_2)\, pW(W_0-W)^2\, dW $$

- an analytical description of the allowed β spectrum shape accurate to a few parts in 10^{-4}
- potential to test BSM

EFT Approach

Falkowski, et al. arXiv:2010.13797
Gonzalez-Alonso, et al. arXiv:1803.08732
Cirigliano, et al. arXiv:1907.02164

$$\mathcal{L} \supset -\frac{V_{ud}}{v^2}\Big[\ (1+\epsilon_L)\ \bar{e}\gamma_\mu\nu_L\cdot\bar{u}\gamma^\mu(1-\gamma_5)d\ +\ \tilde{\epsilon}_L\,\bar{e}\gamma_\mu\nu_R\cdot\bar{u}\gamma^\mu(1-\gamma_5)d$$
$$+\epsilon_R\,\bar{e}\gamma_\mu\nu_L\cdot\bar{u}\gamma^\mu(1+\gamma_5)d\ +\ \tilde{\epsilon}_R\,\bar{e}\gamma_\mu\nu_R\cdot\bar{u}\gamma^\mu(1+\gamma_5)d$$
$$+\frac{1}{4}\epsilon_T\ \bar{e}\sigma_{\mu\nu}\nu_L\cdot\bar{u}\sigma^{\mu\nu}(1-\gamma_5)d\ +\ \frac{1}{4}\tilde{\epsilon}_T\ \bar{e}\sigma_{\mu\nu}\nu_R\cdot\bar{u}\sigma^{\mu\nu}(1+\gamma_5)d$$
$$+\epsilon_S\,\bar{e}\nu_L\cdot\bar{u}d\ +\ \tilde{\epsilon}_S\,\bar{e}\nu_R\cdot\bar{u}d-\epsilon_P\,\bar{e}\nu_L\cdot\bar{u}\gamma_5 d\ -\ \tilde{\epsilon}_P\,\bar{e}\nu_R\cdot\bar{u}\gamma_5 d\Big]+\text{h.c.}$$

quark-level $\mathcal{L}$

nucleon-level $\mathcal{L}$

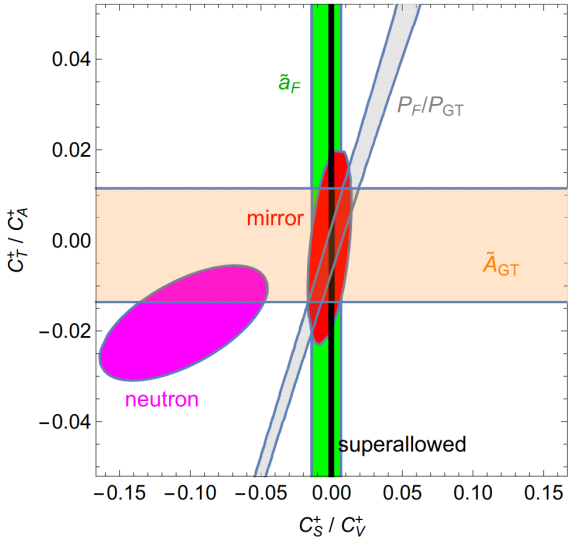
$$\mathcal{L}_{\text{Lee-Yang}} = -\bar{p}\gamma^\mu n\left(C_V^+\bar{e}\gamma_\mu\nu_L + C_V^-\bar{e}\gamma_\mu\nu_R\right) - \bar{p}\gamma^\mu\gamma_5 n\left(C_A^+\bar{e}\gamma_\mu\nu_L - C_A^-\bar{e}\gamma_\mu\nu_R\right)$$
$$-\ \bar{p}n\left(C_S^+\bar{e}\nu_L + C_S^-\bar{e}\nu_R\right) - \frac{1}{2}\bar{p}\sigma^{\mu\nu}n\left(C_T^+\bar{e}\sigma_{\mu\nu}\nu_L + C_T^-\bar{e}\sigma_{\mu\nu}\nu_R\right)$$
$$+\ \bar{p}\gamma_5 n\left(C_P^+\bar{e}\nu_L - C_P^-\bar{e}\nu_R\right) + \text{h.c.}$$

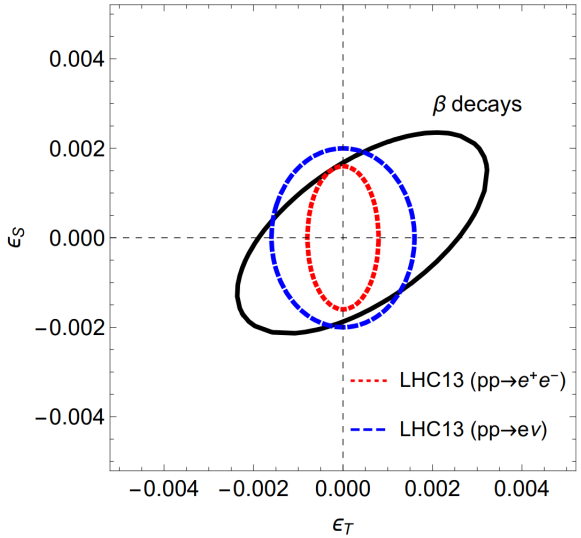
EFT Constraints

$$v^2 \begin{pmatrix} C_V^+ \\ C_A^+ \\ C_S^+ \\ C_T^+ \end{pmatrix} = \begin{pmatrix} 0.98571(41) \\ -1.25707(55) \\ 0.0001(10) \\ 0.0004(12) \end{pmatrix}$$

$$\begin{pmatrix} \hat{V}_{ud} \\ \epsilon_R \\ \epsilon_S \\ \epsilon_T \end{pmatrix} = \begin{pmatrix} 0.97377(41) \\ -0.010(13) \\ 0.0001(10) \\ 0.0005(13) \end{pmatrix}$$

Falkowski, et al. arXiv:2010.13797





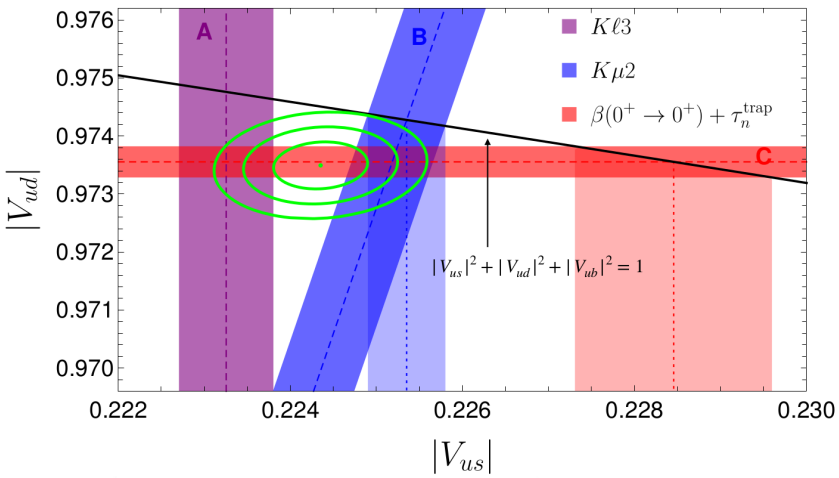
- precision measurements of beta decays probe similar scales as the LHC

The Cabibbo Angle Anomaly

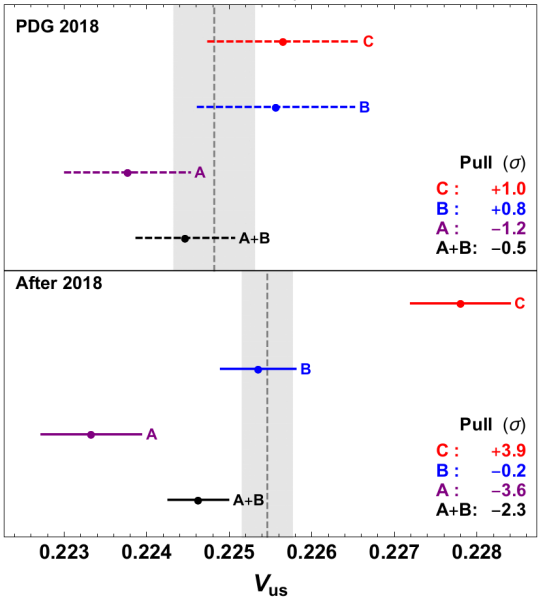
probing V_{ud} and V_{us}:

- $|V_{ud}|$ from superallowed $0^+ \to 0^+$ β decays $\Rightarrow |V_{ud}|^2 \approx \frac{0.971}{1+\Delta_R^V}$
- $|V_{us}|$ from $K \to \pi l \nu$
- $|V_{us}/V_{ud}|$ by comparing $K \to \mu\nu$ and $\pi \to \mu\nu$

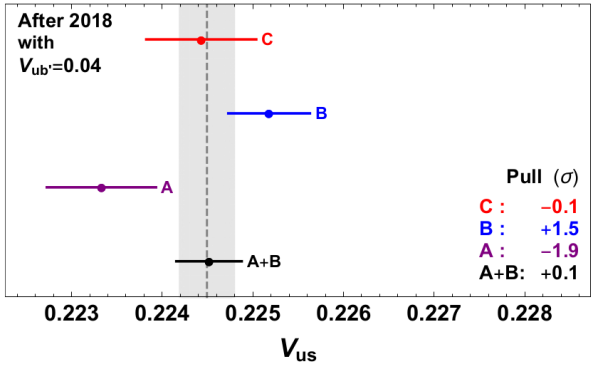
Manzari, SUSY 2021



Belfatto et al, 1906.02714



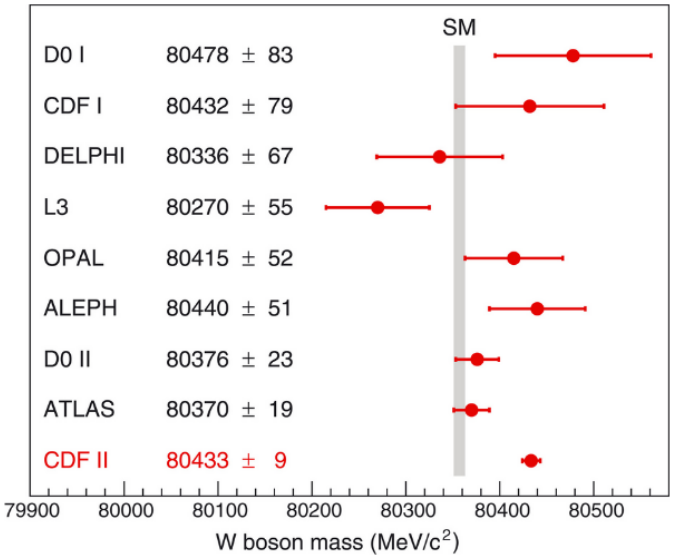
- possible solution is vector-like quark b'
- $h_i \Phi \overline{Q}_{Li} b'_R + M \bar{b}'_L b'_R +$ h.c.



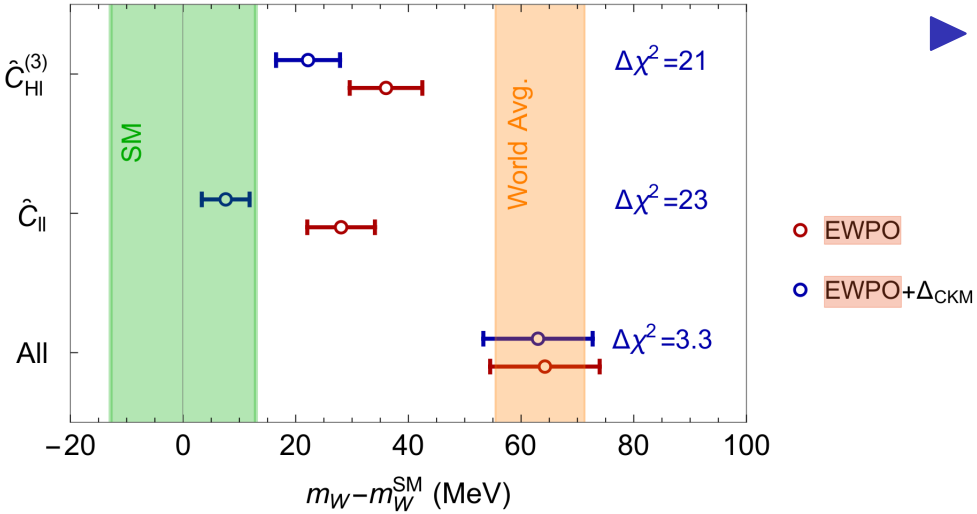
- there are more proposals such as vectorlike leptons, new gauge triplets...

Beta Decay and CDF Anomaly

Science 2022



Cirigliano et al., 2204.08440

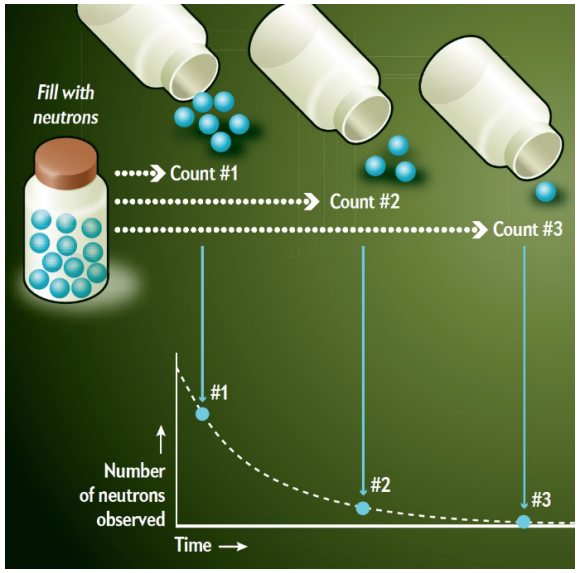


$\mathcal{O}_{HWB}$	$H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{HD}$	$\left\lvert H^\dagger D_\mu H \right\rvert^2$
$\mathcal{O}_{Hl}^{(3)}$	$\left(H^\dagger i \overleftrightarrow{D}^I_\mu H\right)\left(\bar{l}_p \tau^I \gamma^\mu l_r\right)$
$\mathcal{O}_{Hq}^{(3)}$	$\left(H^\dagger i \overleftrightarrow{D}^I_\mu H\right)\left(\bar{q}_p \tau^I \gamma^\mu q_r\right)$
$\mathcal{O}_{ll}$	$\left(\bar{l}_p \gamma_\mu l_r\right)\left(\bar{l}_s \gamma^\mu l_t\right)$

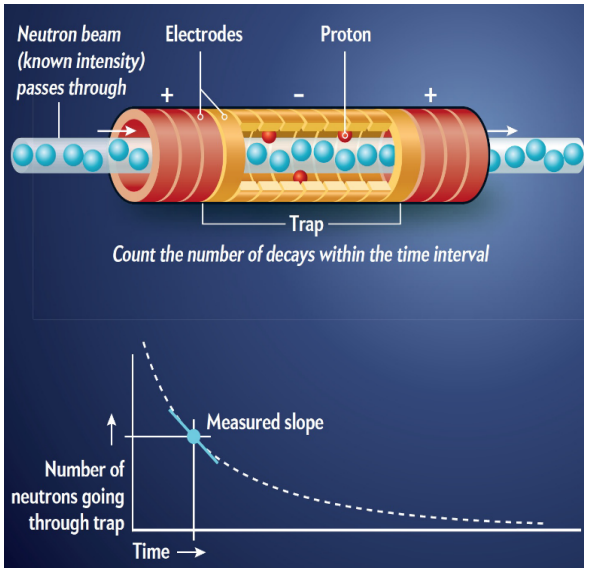
$$\frac{\delta m_W^2}{m_W^2} = v^2 \, \frac{s_w c_w}{s_w^2 - c_w^2} \left[2\, C_{HWB} + \frac{c_w}{2 s_w} C_{HD} + \frac{s_w}{c_w} \left(2\, C_{Hl}^{(3)} - C_{ll} \right) \right]$$

- global analyses of EW precision observables in SMEFT framework can explain W boson mass anomaly but it predicts % level violation of Cabibbo unitarity

Neutron Decay Anomaly

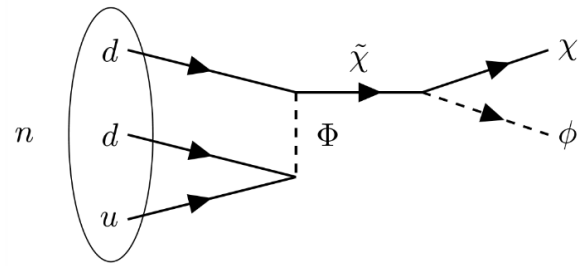


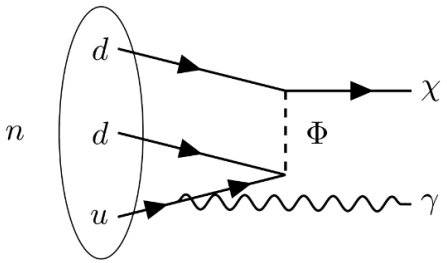
"Disappearance experiment"



"Appearance experiment"

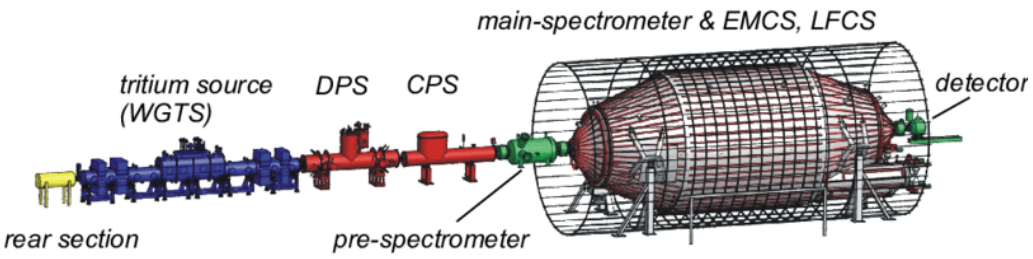
- Dark Matter interpretation? 1% Br into non-proton final state required
- $937.900\,\text{MeV} < m_{\text{DM}} < 938.783\,\text{MeV}$; constraints from neutron stars





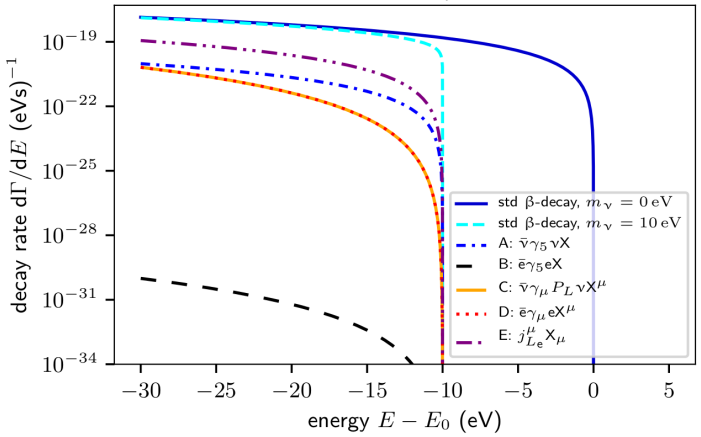
Fornal, Grinstein, 1801.01124
Rajendran, Ramani, 2008.06061
Tang et al., 1802.01595

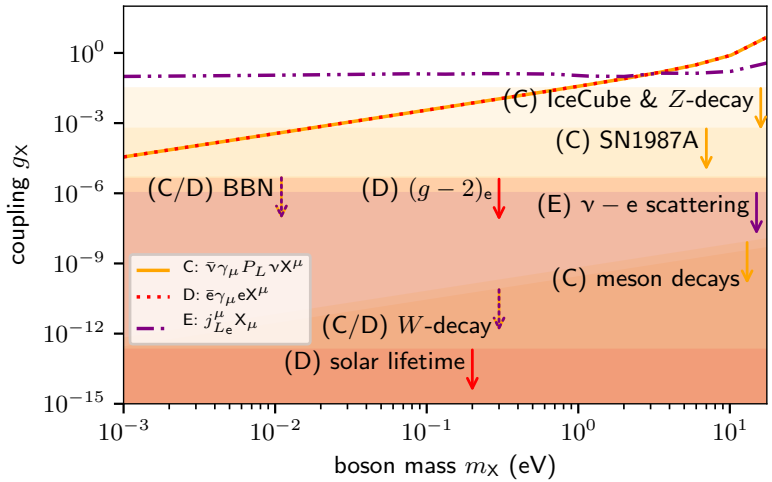
Emission of New Light Bosons at KATRIN

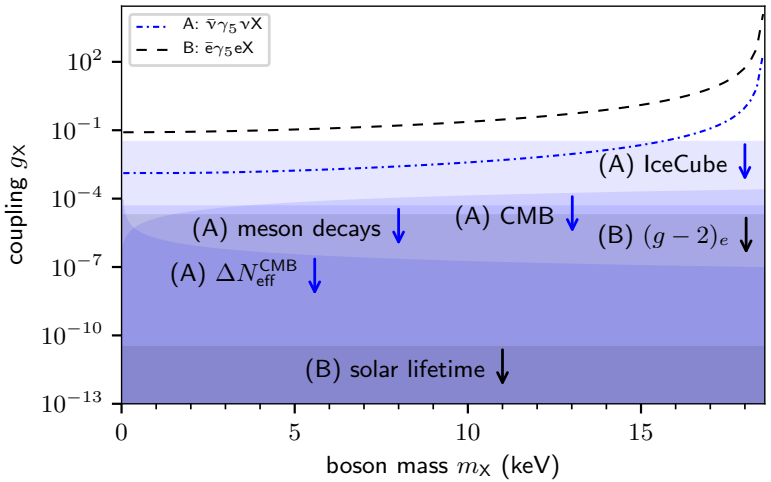


$$^3H \Longrightarrow {}^3He + e^- + \bar{\nu}_e + X$$

Arcadi et al., 1811.03530



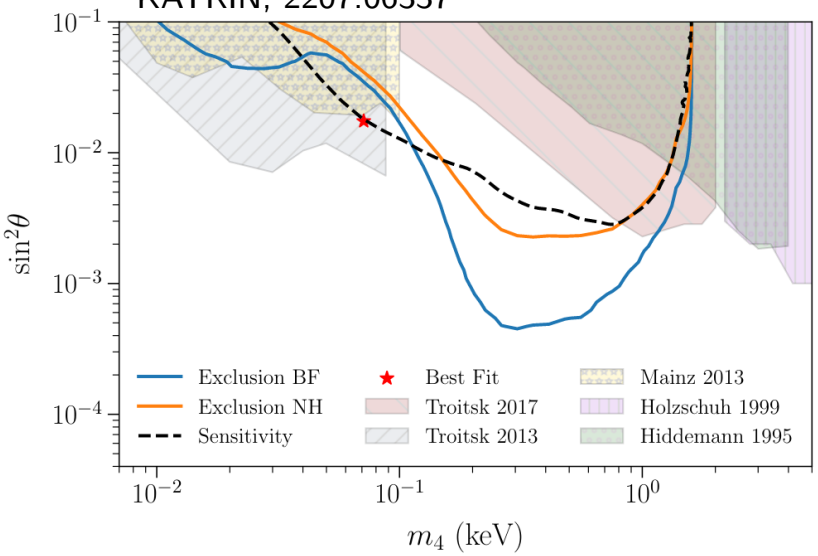




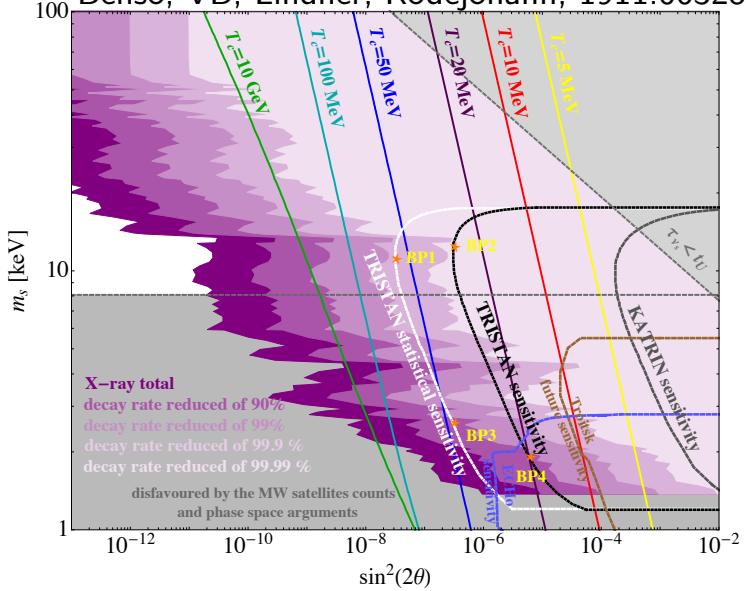
- complementary approach to accessing low energy new physics
- limits are not competitive with cosmology and high-energy lab searches

keV-scale Sterile Neutrino (DM) at KATRIN

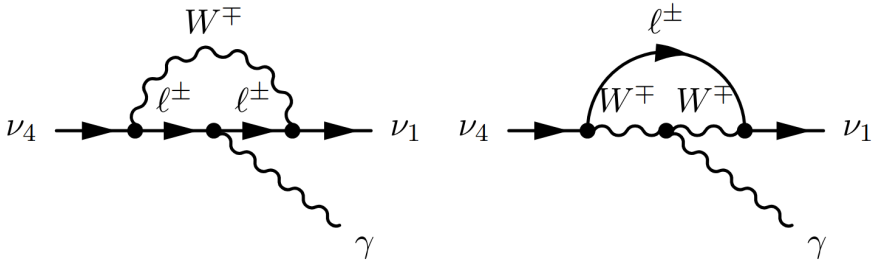
KATRIN, 2207.06337

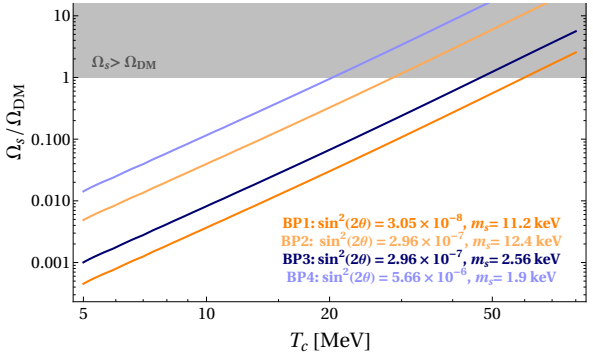


Benso, VB, Lindner, Rodejohann, 1911.00328



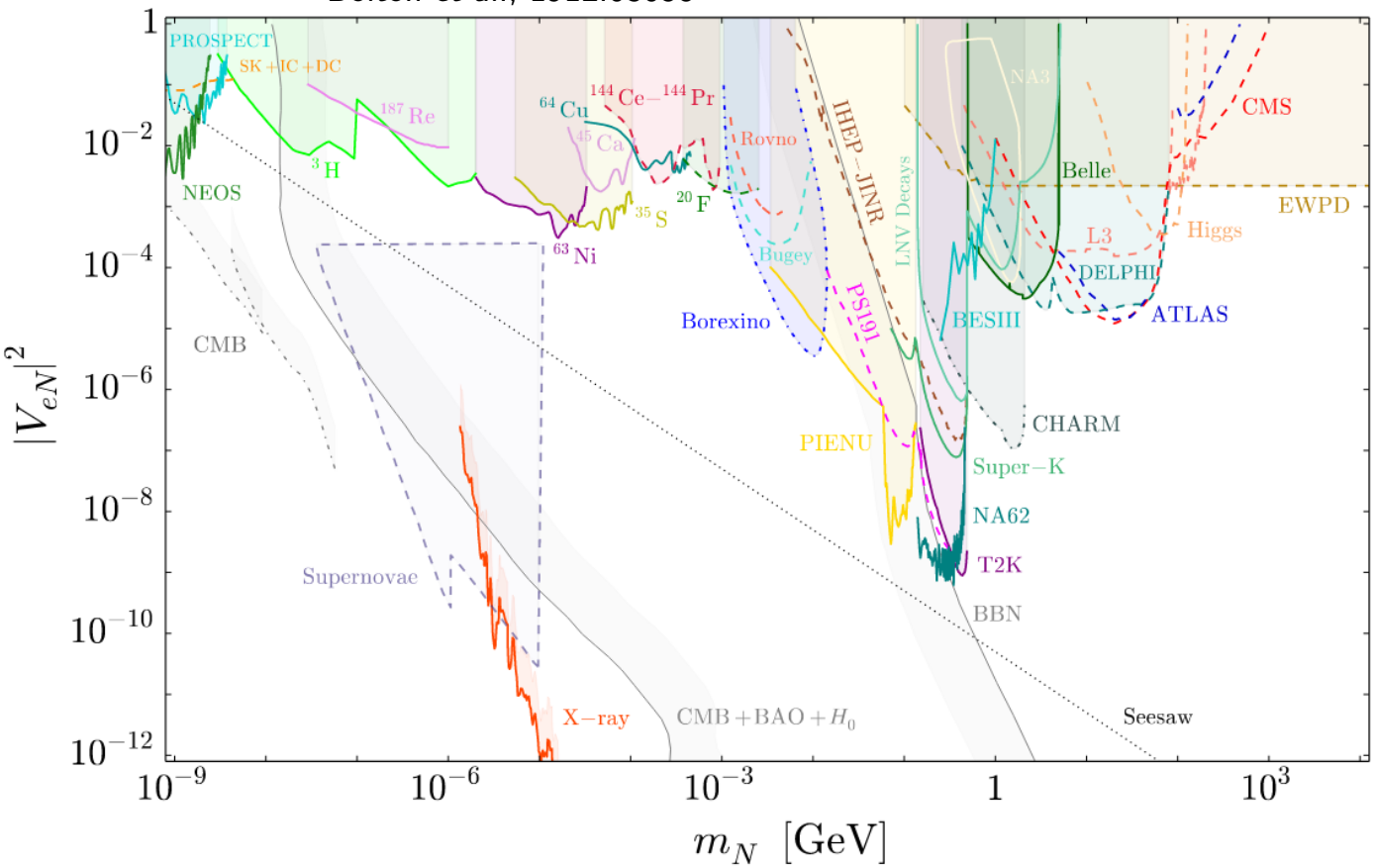
- KATRIN will reach $\sin^2 2\theta \sim 10^{-7}$
- DM in this region of parameter space?
- (i) Multicomponent DM or change ν_s decay rate
- (ii) lower $T_{\rm RH}$ to suppress production





Constraints on Sterile Neutrino Across the Scales

Bolton et al., 1912.03058

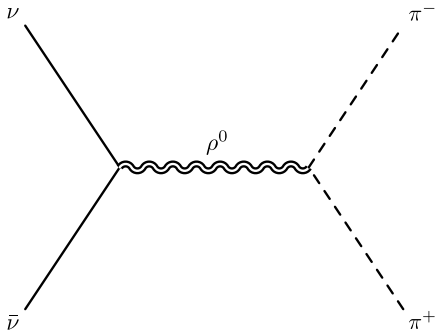


- complementary constraints from beta decays of ^{20}F, ^{35}S, ^{45}Ca...
- KATRIN/TRISTAN and Project 8 will improve these limits

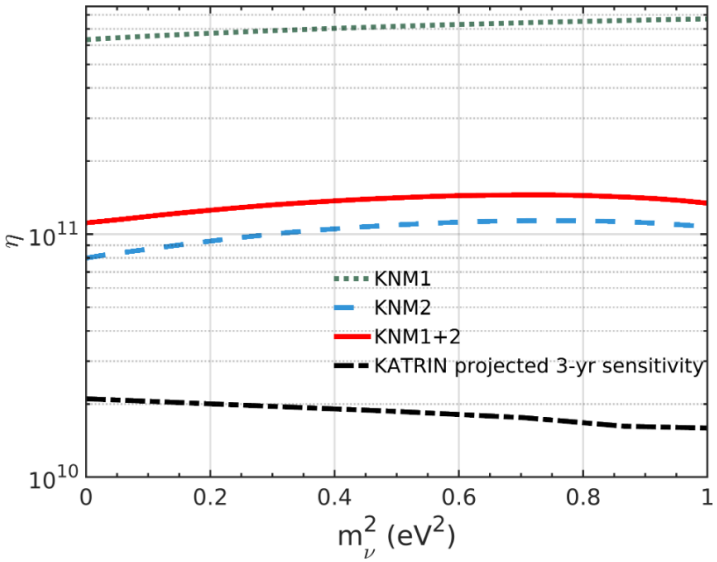
Constraints on CνB Overdensity

- $\nu_e + N_Z^A \Longrightarrow N_{Z+1}^A + e^-$
- standard $C\nu$B density $n_0 = 56\,\mathrm{cm}^{-3}$
- KATRIN constraints $10^{11} n_0$
- improvements are expected in future form PTOLEMY collaboration

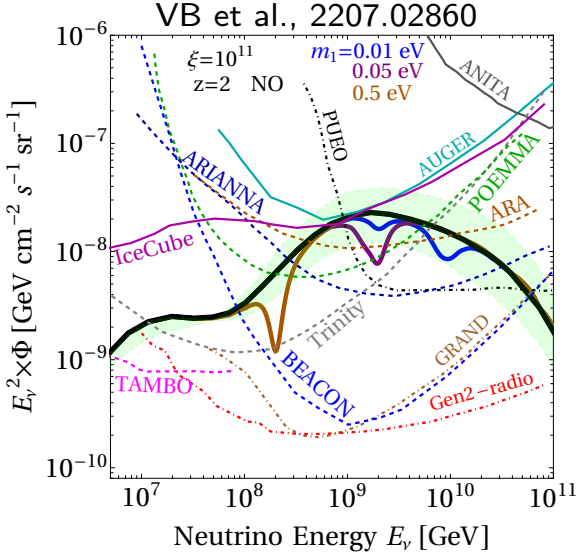
- new probe of relic neutrino clustering using cosmogenic neutrinos
- new physics in the form of neutrino self-interactions required (2201.00939)



2202.04587

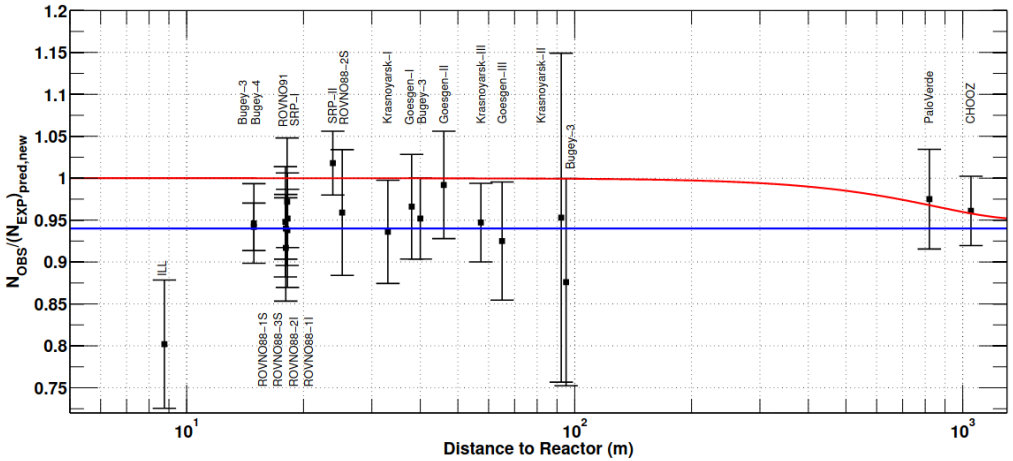


VB et al., 2207.02860

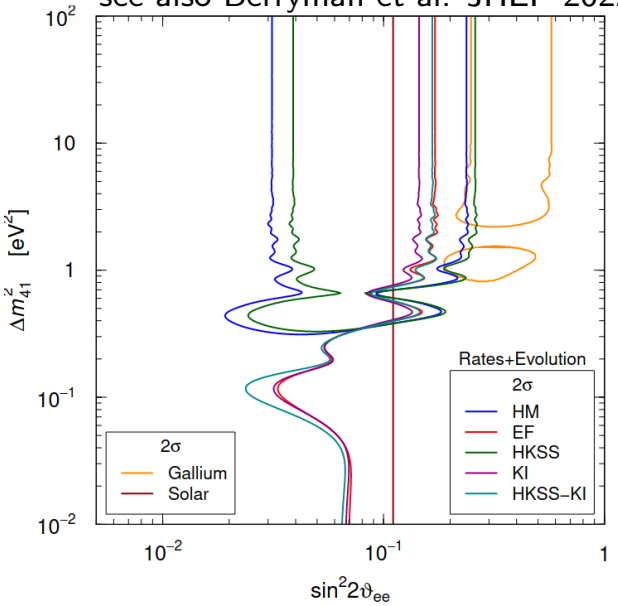


eV-scale Sterile Neutrino

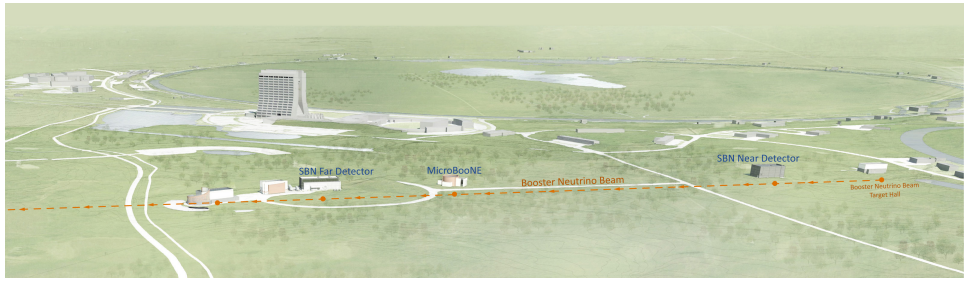
Huber PRC 2011, Mention et al., PRD 2011



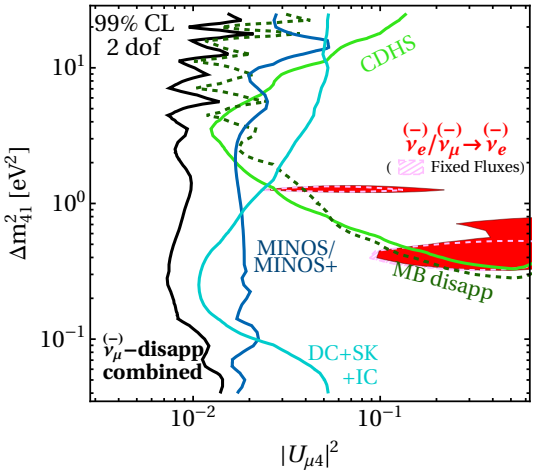
Giunti et al. PLB 2022
see also Berryman et al. JHEP 2022



- reactor anomaly is fading away
- constraint on $|U_{e4}|$ is important for LSND and MiniBooNE where $\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$ is probed



Kopp et al., arXiv:1803.10661



Summary

- measurements and theoretical calculations of beta decay spectra for a number of radionuclides have reached precision that makes this process a powerful probe of new physics
- scenarios that can be tested include heavy new physics via EFTs, dark matter and sterile neutrinos
- upcoming measurements from KATRIN and Project 8 will further improve the existing constraints
- reactor anomaly is disappearing; further efforts in flux calculation and data collection are important for short baseline program at Fermilab