Title: MeV Sterile Neutrinos in Light of the Cabibbo-Angle Anomaly

Speakers: Kohsaku Tobioka

Series: Particle Physics

Date: April 25, 2023 - 1:00 PM

URL: https://pirsa.org/23040070

Abstract: The mixing angles of the quark sectors are constrained by unitarity in the standard model. However, recent data indicates a about 3 sigma deviation from unitarity in the mixing angle between the 1st and 2nd generation down-type quarks, known as the Cabibbo angle anomaly. The observations include the charged-current weak decays of neutrons, nuclei, kaons, and the hadronic decay of tau leptons. Although the issue appears to lie in the quark sector, modifying the neutrino sector may offer a solution. In this talk, we discuss recent findings that suggest a sterile neutrino of MeV mass mixing with the electron-type neutrino can resolve the Cabibbo angle anomaly. We also examine the current bounds and future prospects of this scenario.

Zoom Link: https://pitp.zoom.us/j/98083942792?pwd=eHFRUmJUVGNJcVpTSHZXVXFKQm95QT09

MeV Sterile Neutrinos in Light of the Cabibbo-Angle Anomaly

Mar 25, 2023 [Perimeter Institute]

Kohsaku Tobioka

Florida State University, KEK Theory center

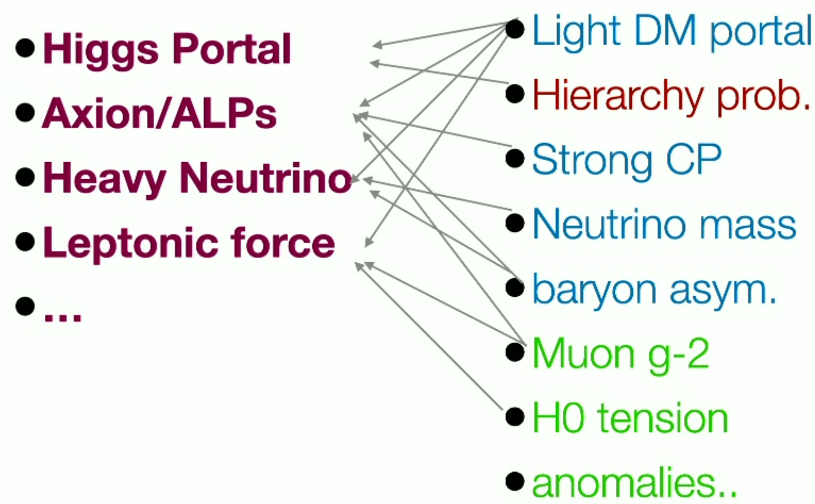
Unfinished work with Teppei Kitahara (Nagoya Univ., KEK)

Feebly Interacting Light Particles

Broad physics cases

- Possibility of feebly interacting light particles ∈ dark sectors, with various motivation
  Light DM, hierarchy problem, strong CP, ν mass, baryogenesis, (various anomalies…

Light Dark Sectors



Kohsaku Tobioka, Florida State University

Feebly Interacting Light Particles

Broad physics cases

- Possibility of feebly interacting light particles ∈ dark sectors, with various motivation
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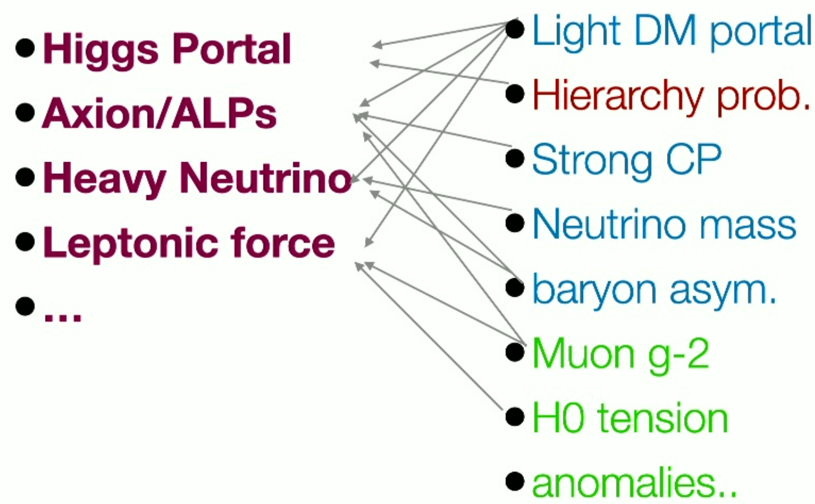
- Axion/ALP →the strong CP problem & DM.
- Muon g-2 →several light particles (heavy NP scenarios are compatible).
- ν mass→RH neutrinos, maybe heavy? But the light ones are viable, may resolve anomalies.

Light Dark Sectors



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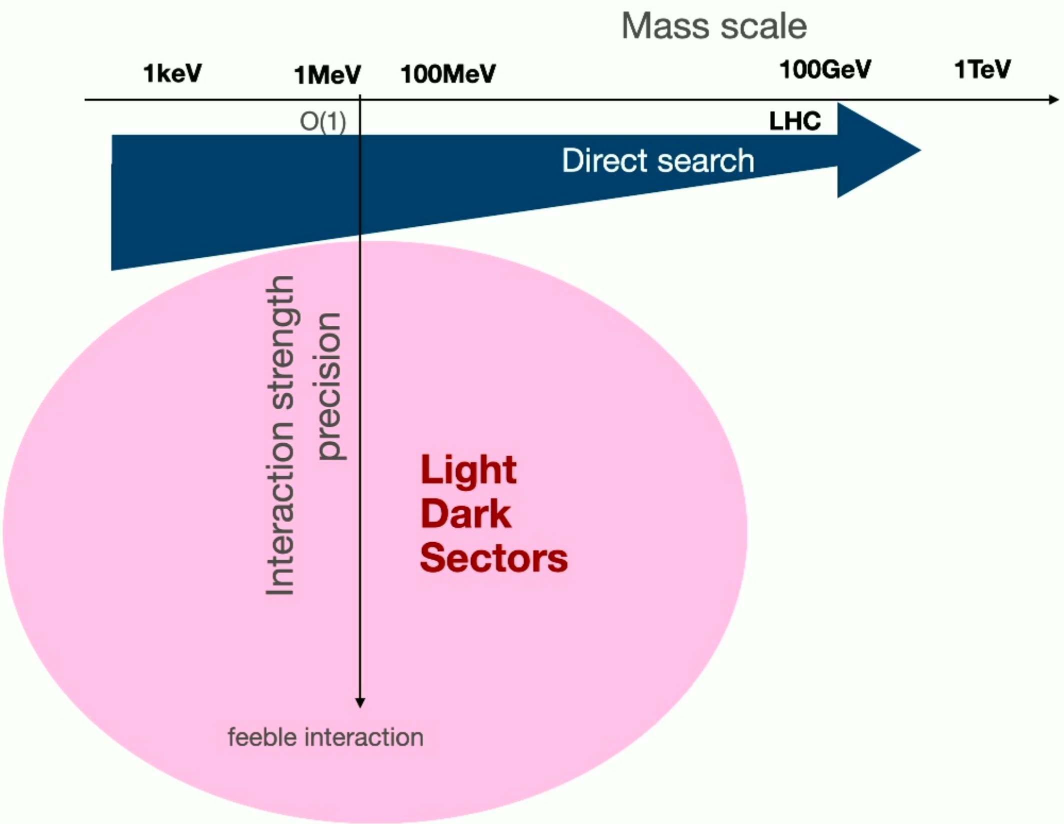
Difference between Heavy and Light NP

EFT vs model dependent approach.

- Heavy NP encoded in EFT. Use precision measurements
- Light X can be directly produced, but **EFT approach won't work**



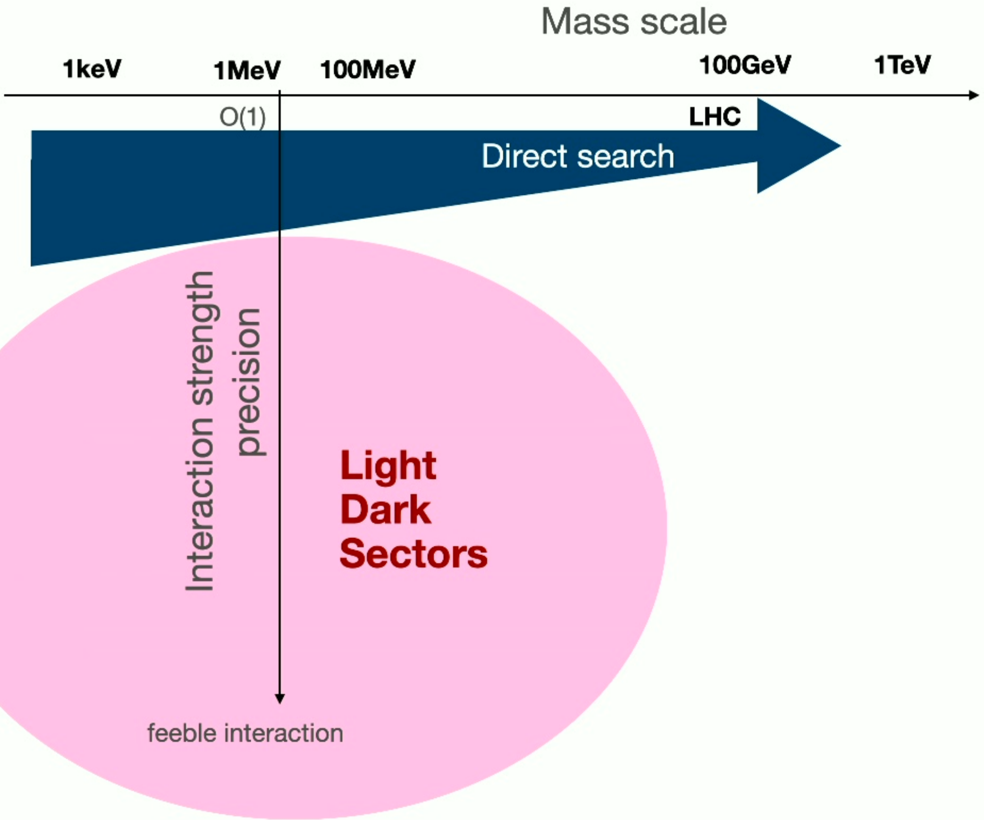
Kohsaku Tobioka, Florida State University

Difference between Heavy and Light NP

EFT vs model dependent approach.

- Heavy NP encoded in EFT. Use precision measurements
- Light X can be directly produced, but **EFT approach won't work**

- Strongly depends on nature of X: mass, production&decay patterns, lifetime. Model dependent signal/strategy.
- Data may tell the nature of X. X may be probed in other data. [falsifiable]



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Outline

- Sterile neutrino basic

- Cabibbo angle measurements (Vud, Vud), and **Cabibbo angle anomaly**

- Cabibbo angle anomaly implies MeV sterile neutrino

Right handed/sterile neutrinos

Compelling addition to the SM

- With SM singlet fermions =right-handed neutrinos N,
  SM can be extended in the renormalizable level [Majorana mass, neutrino Yukawa]

$$\mathscr{L}_{SM} + \lambda_\alpha \tilde{H}\bar{L}_\alpha N + \frac{1}{2} M_N N \bar{N}^c$$

- This extension is well motivated:
  1. SM neutrino mass by Seesaw mechanism [need 2+ RH neutrinos]
  2. Baryon asymmetry by Leptogenesis

- If the RH neutrino is NOT too heavy →sterile neutrinos (low energy d.o.f.)
  3. Several **anomalies** may be related to the sterile ν [reactor, short baseline]
  4. Or simply **portal to dark sector** containing dark matter.

Sterile neutrino basic

- RH extension $(\alpha = e, \mu, \tau)$ $$\lambda_\alpha \tilde{H}\bar{L}_\alpha N + \frac{1}{2}M_N N\bar{N}^c \to \lambda_\alpha v \bar{\nu}_\alpha N + \frac{1}{2}M_N N\bar{N}^c$$

- Diagonalize $$\begin{cases} N^c = \cos\theta_\alpha \nu_4 - \sin\theta_\alpha \nu'_\alpha \\ \nu_\alpha = \cos\theta_\alpha \nu'_\alpha + \sin\theta_\alpha \nu_4 \end{cases}$$

Mixing

$$\theta_\alpha \sim \frac{\lambda_\alpha v}{M_N},$$

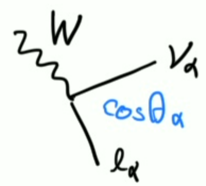
Mass [Seesaw mechanism]

$$m_{\nu'_\alpha} \sim \frac{(\lambda_\alpha v)^2}{M_N} \sim \theta_\alpha^2 M_N$$

$$M_{N'} \sim M_N$$

This relation is more complicated if two or more Ns exist

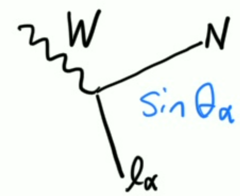
- SM weak interaction [charged current] $$gW^\mu \bar{L}_\alpha \gamma_\mu L_\alpha \to gW^\mu \bar{\ell}_\alpha \gamma_\mu \nu_\alpha$$



- New weak interaction [reduced coupling ν] $$gW^\mu \bar{\ell}_\alpha \gamma_\mu (\cos\theta_\alpha \nu'_\alpha + \sin\theta_\alpha \nu_4)$$

reduced coupling

Small coupling of sterile ν to SM



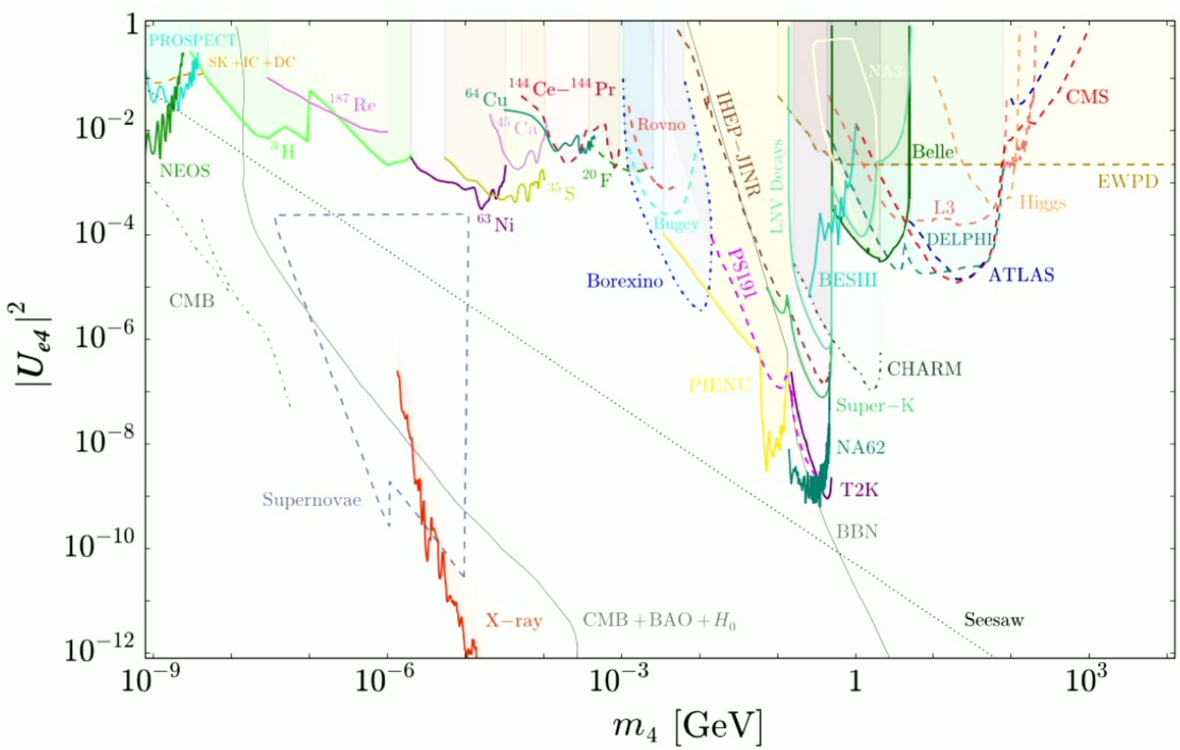
Just focus on mass prime(') for the rest of the talk.

Sterile neutrino basic

- For $M_N \ll 1$GeV → long-lived [stable particles in the lab]
- Widely studied. (cosmology, collider, reactor, rare meson decays, nuclear physics)
- New search ideas [e.g. ILC beam dump]

[arXiv:2206.13523] M. M. Nojiri, Y. Sakaki, KT, D. Ueda

Phys.Rept. **928** (2021) 1 B. Dasgupta, J. Kopp

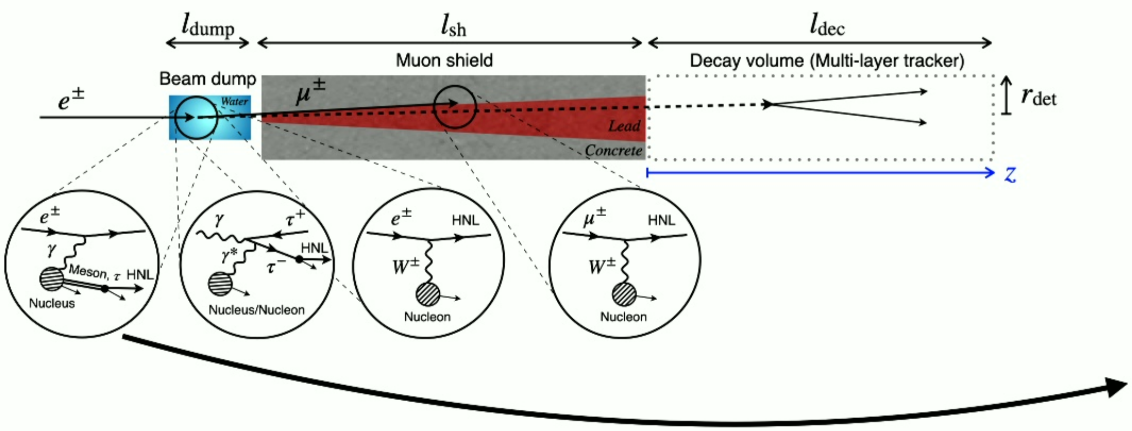


See also Phys.Rev.D **100** (2019) 073011 D. Bryman, R. Shrock

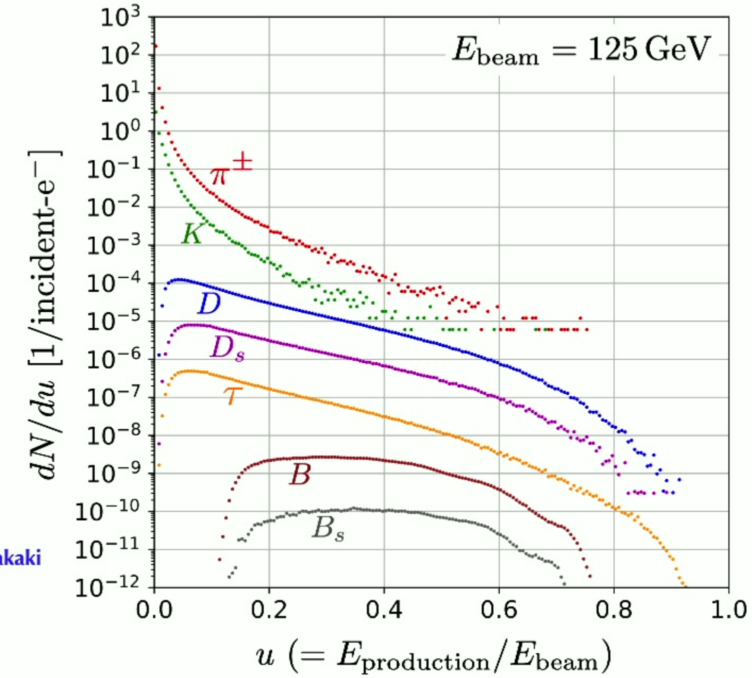
Sterile neutrino search at ILC beam dump

[arXiv:2206.13523] Accepted by JHEP. M. M. Nojiri, Y. Sakaki, KT, D. Ueda

- Linear collider has beam, so beam dump experiment is natural.
- ILC: very high energy [125GeV-500GeV] electron beam with high intensity [4E21 EoT/year]
- E_{cm}>10GeV produce **even heavy mesons and tau** which decay to sterile ν.



First evaluation



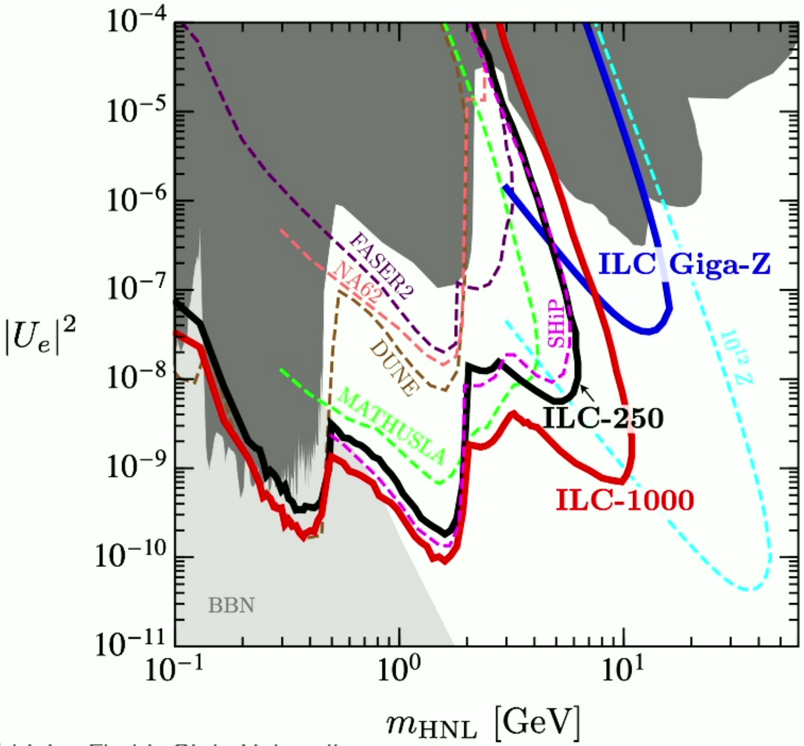
- SM spectrum including transport are calculated by PHITS Y. Sakaki
- One can use this information for **other long-lived particles**.

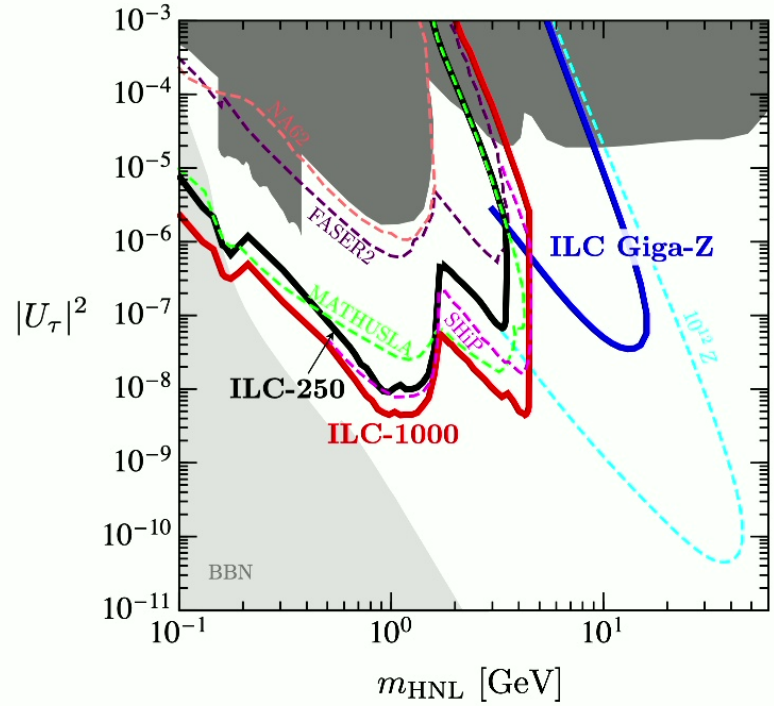
Sterile neutrino search at ILC beam dump

[arXiv:2206.13523] Accepted by JHEP. M. M. Nojiri, Y. Sakaki, KT, D. Ueda

- Just look for multi-track signal with simple detectors

- ILC-250(black) has a similar sensitivity to SHiP (proton beam)





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Quark mixing angles and unitarity

- In SM, the gauge and Yukawa couplings are NOT aligned.
  Still neutral current (Z,γ) and quark masses can diagonalize simultaneously.

Quark mixing angles and unitarity

- In SM, the gauge and Yukawa couplings are NOT aligned.
  Still neutral current (Z,γ) and quark masses can diagonalize simultaneously.

- Charged current is not diagonal.
  Cabibbo-Kobayashi-Maskawa (**CKM**) matrix **$V_{CKM}=V_{ij}$ (i=u,c,t; j=d,s,b)**.

$$g W^\mu \bar{u}_i V_{ij} \gamma_\mu P_L d_j$$

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- **V_{CKM}** is unitary.

$$VV^\dagger = 1 \xrightarrow{\text{examples}} (VV^\dagger)_{uu} = 1, \quad (VV^\dagger)_{uc} = 0$$

Kohsaku Tobioka, Florida State University

Cabibbo angle anomalies

- CKM unitarity: $(VV^{\dagger})_{uu} = 1$ $\quad V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1$

- At current precision, essentially it is Cabibbo angle.

$\delta V_{ud}^2, \delta V_{us}^2 \gg V_{ub}^2$ $\quad V_{ud}^2 + V_{us}^2 \simeq 1$ $\quad \cos\theta_c^2 + \sin\theta_c^2 = 1$

- Anomaly.

$$V_{ud,obs}^2 + V_{us,obs}^2 \equiv 1 + \Delta_{\text{CKM}} < 1$$

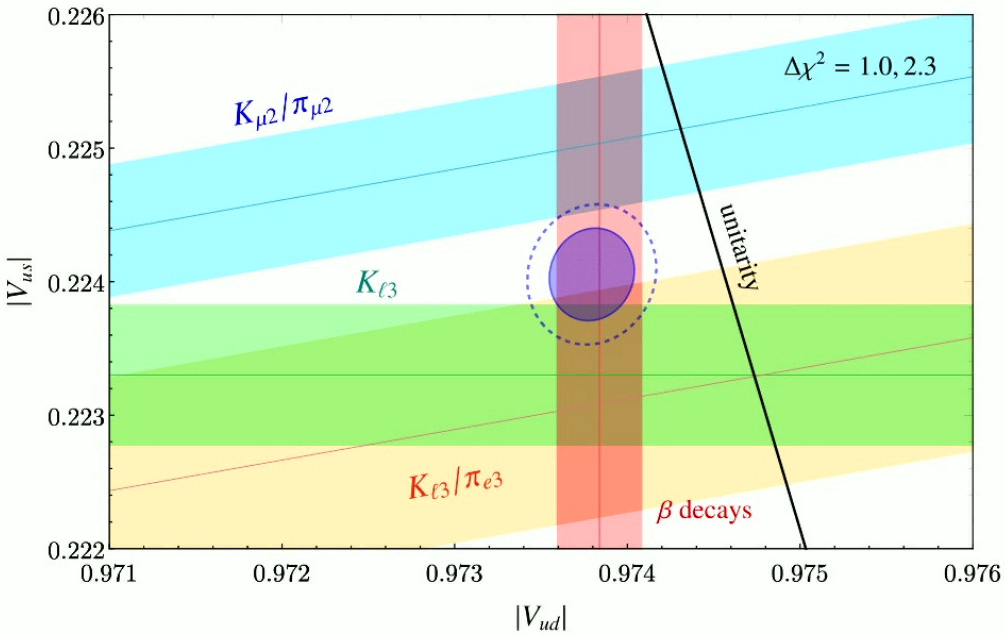
$$\Delta_{\text{CKM}} = -0.00151(53)$$

2.8-3.8σ

depends on neutron lifetime measurements

Originally ~4sigma, Belfatto, Beradze, Berezhiani, 1906.02714.
Recent status: Ciriglianoa et al. 2208.11707 [also 2212.06862]

Cabibbo angle anomalies



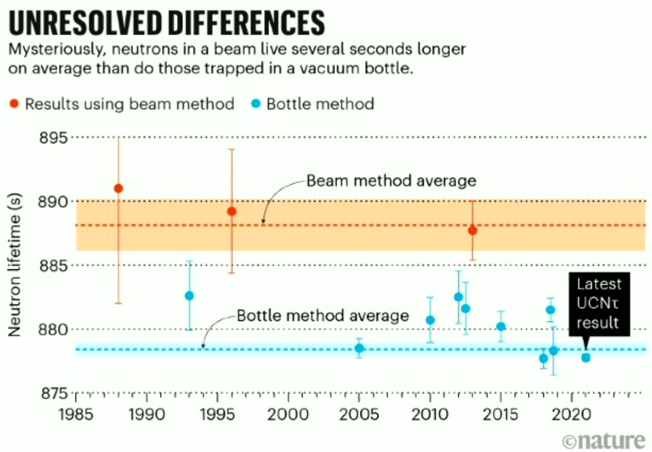
From 2212.06862

Bottle neutron τ: 2.8σ

$\Delta_{\text{CKM}} = -0.001\,51(53)$

Beam neutron τ: 3.8σ

$\Delta_{\text{CKM}} = -0.002\,34(62)$



Quark sector

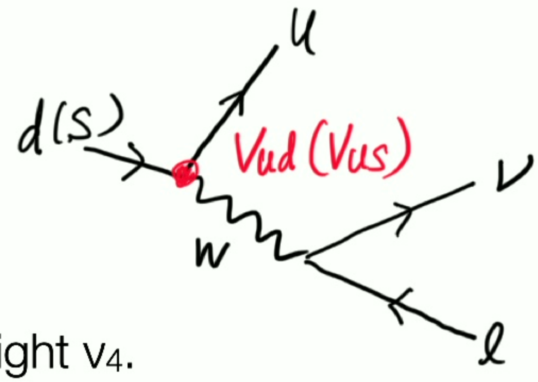
✦Cabibbo angle anomaly

?

Neutrino sector

✦sterile neutrino ν_4

Charged current measurements
involve charged leptons: semileptonic decay [th&ex clean]
→**neutrinos.** [Same situation for R_D]



Idea:

The true CKM is still unitarity, but $V_{ud(us),obs} \neq V_{ud(us)}$ by light ν_4.

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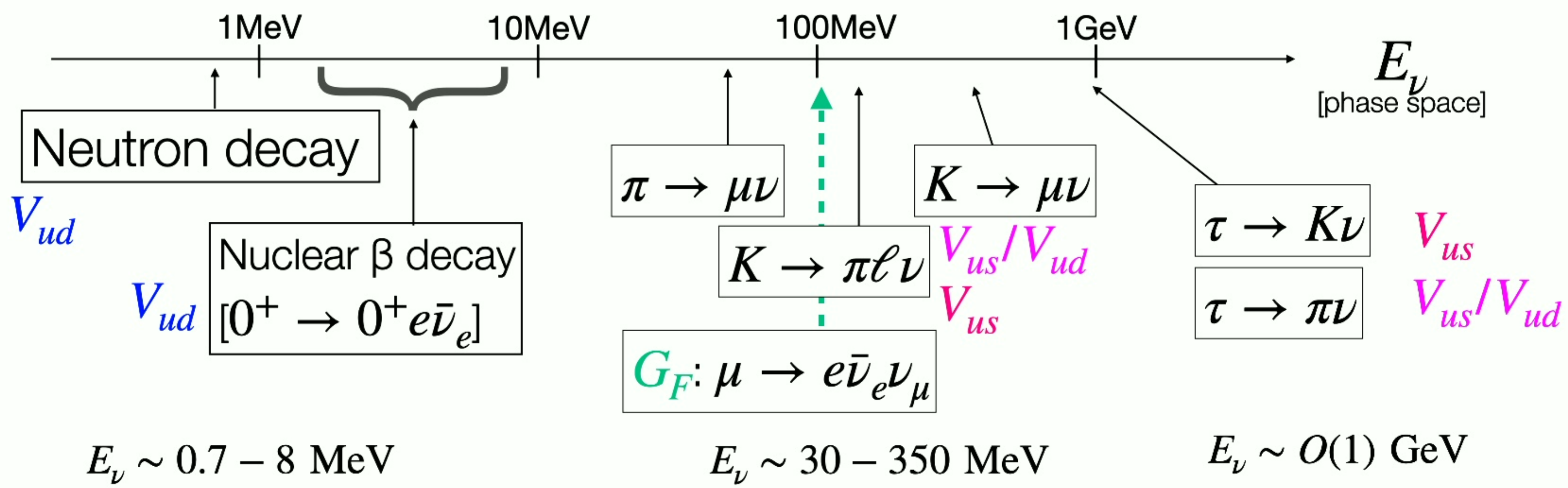
*All known scenarios for CAA are heavy new physics (TeV or more).

Cabibbo angle: how it is measured.

- Three combinations: V_{ud} , V_{us} , or V_{us}/V_{ud} .
- Categorize measurements by emitted neutrino energy E_ν

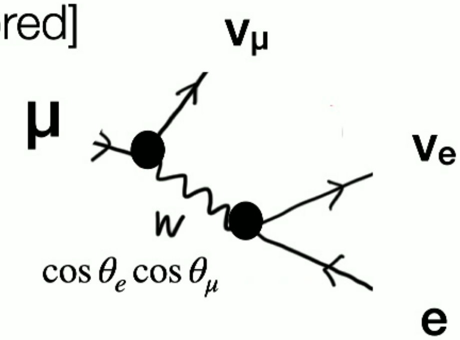


currently
2208.11707
$V_{ud} = 0.97384(26),\ V_{ud} = 0.22330(53),\ V_{us}/V_{ud} = 0.23108(51)$

Cabibbo angle anomaly and heavy/very light ν4

- Since $V^2_{ud,obs} + V^2_{us,obs} < 1$, we need $V_{ud,obs} < V_{ud}$ or $V_{us,obs} < V_{us}$.

1. Heavy ν4 (≫100MeV) does **NOT** work [unphysical $\theta^2_{\mu,e} < 0$ is favored]



*GF is modified.

$$G_{F,obs} \simeq G_F\left(1 - \frac{\theta_e^2}{2} - \frac{\theta_\mu^2}{2}\right)$$

We have to use observed GF to measure Vud,us

Neutron
Nuclear β decay

$$G_{F,obs}V_{ud,obs} \simeq G_F V_{ud}\left(1 - \frac{\theta_e^2}{2}\right) \qquad V_{ud,obs} \simeq V_{ud}\left(1 + \frac{\theta_\mu^2}{2}\right)$$

K->μν, πμν

$$G_{F,obs}V_{ud,obs} \simeq G_F V_{ud}\left(1 - \frac{\theta_\mu^2}{2}\right) \qquad V_{us,obs} \simeq V_{us}\left(1 + \frac{\theta_e^2}{2}\right)$$

Also

$$\left(\frac{V_{us}}{V_{ud}}\right)_{obs} \simeq \left(\frac{V_{us}}{V_{ud}}\right)$$

Cabibbo angle anomaly and heavy/very light ν$_4$

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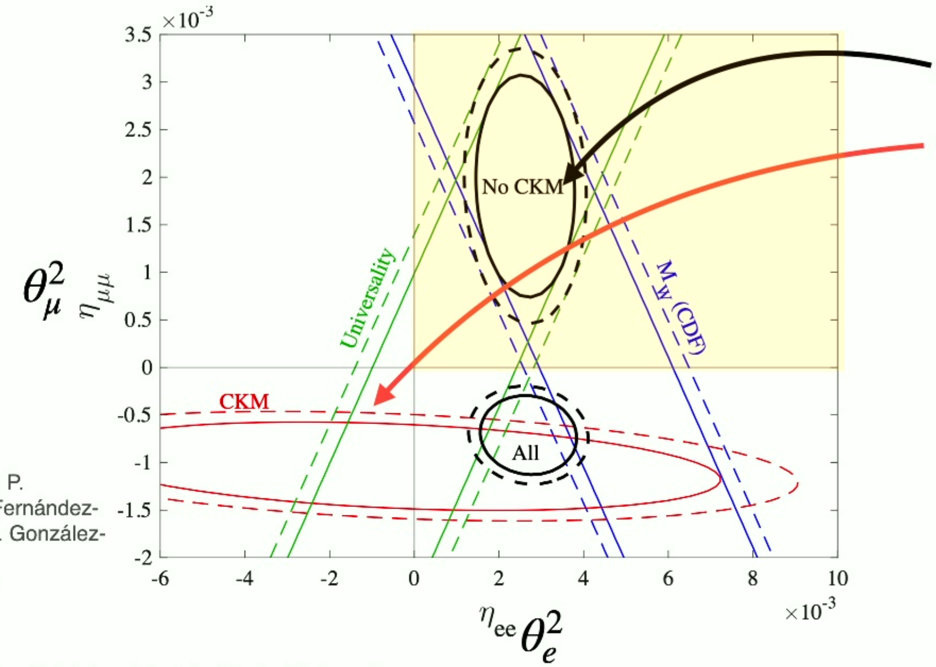


M. Blennow, P. Coloma, E.Fernández-Martínez, M. González-López 2204.04559

- The sign works for CDF mW anomaly
- Unphysical mixing angle is favored by Cabibbo angle

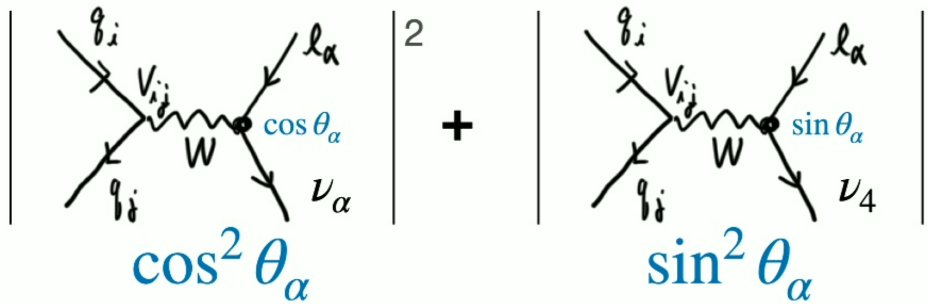
$$V_{ud,obs} \simeq V_{ud}\left(1 + \frac{\theta^2_\mu}{2}\right)$$

$$V_{us,obs} \simeq V_{us}\left(1 + \frac{\theta^2_e}{2}\right)$$

Cabibbo angle anomaly and heavy/very light ν₄

- Since $V_{ud,obs}^2 + V_{us,obs}^2 < 1$, we need $V_{ud,obs} < V_{ud}$ or $V_{us,obs} < V_{us}$.

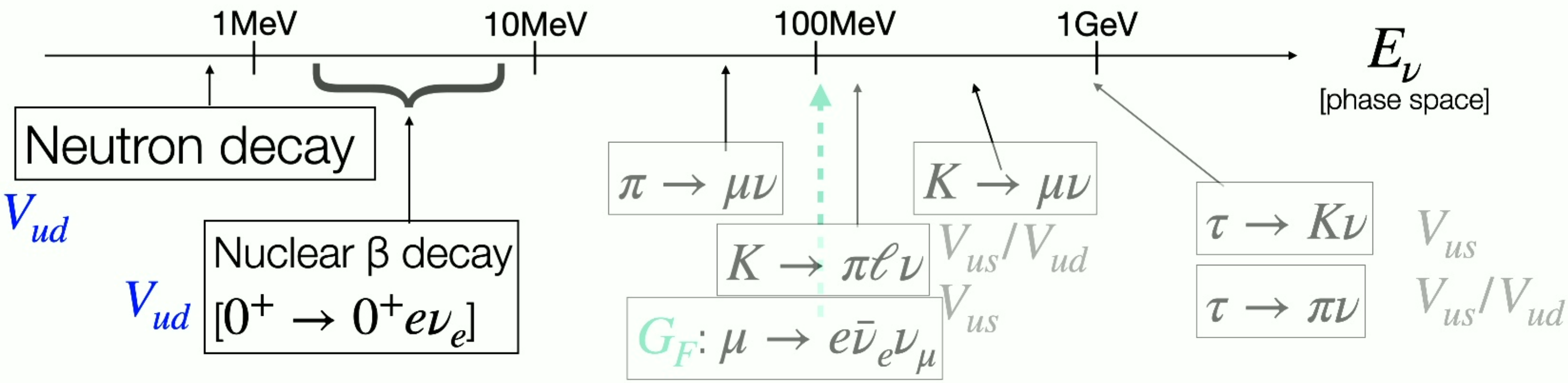
2. Too light ν_4 ($m_{\nu 4} \ll E_\nu$). Active and sterile neutrinos are indistinguishable.
   →Coupling reduction effect disappears =**SM-like**



= **SM** + correction $\mathcal{O}\left(\theta_\alpha^2 \frac{m_{\nu 4}^2}{E_\nu^2}\right)$

Cabibbo angle anomaly and O(MeV) ν_4

- Intermediate mass scale: $M_{\nu 4}$ ~O(1-10 MeV).
  Coupling reduction effect only appears in V_{ud} measurements.



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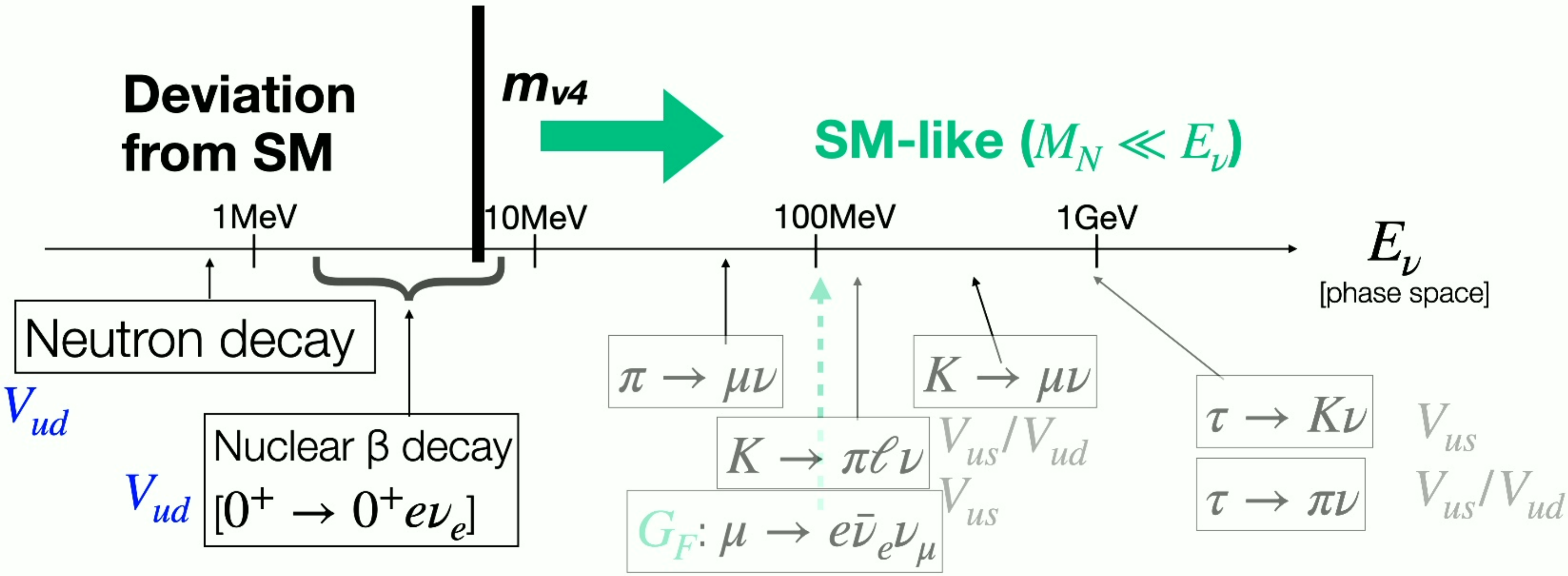
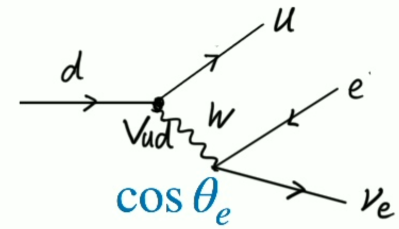


Neutron and Nuclear β decays



Neutron

- Approximately V-A.

* some uncertainty from the axial current.

- $E_\nu \sim 0.7$ MeV
- $\delta V_{ud}/V_{ud} \sim 4 - 9 \cdot 10^{-4}$

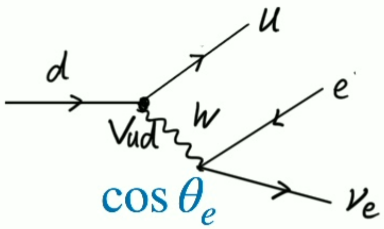
* Tension among lifetime measurements.

Nucleus

- Superallowed nuclear decay
  $J^P = 0^+ \to 0^+ + e\nu_e$
  =purely vecotr weak interaction: V_{ud}
- $E_\nu \sim 2 - 8$ MeV [3.2 MeV for **^{26}Al→^{26}Mg**]
- $\delta V_{ud}/V_{ud} \sim 3 \cdot 10^{-4}$

* Theory systematics increased over years.

Neutron and Nuclear β decays



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* Theory systematics increased over years.

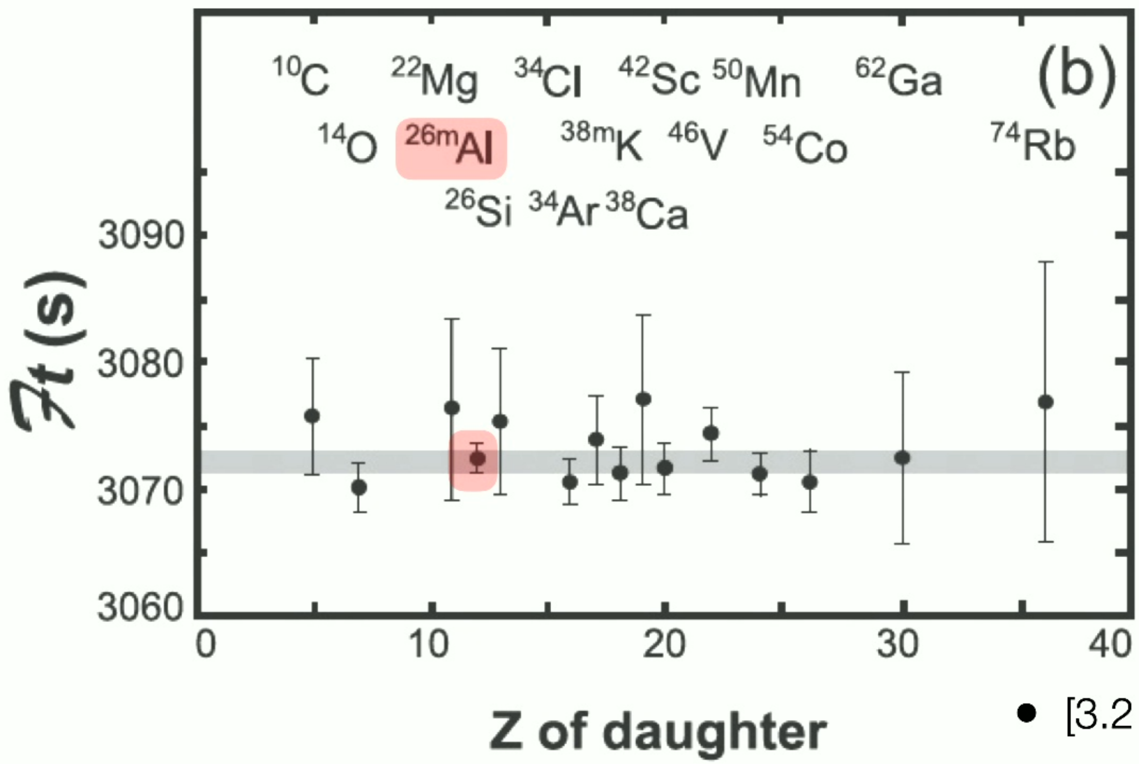
- If 10 MeV ν_4 mixes ν_e, β decays are modified: $V_{ud,obs} \simeq V_{ud}\left(1 - \frac{\theta_e^2}{2}\right)$ explains $V_{ud,obs}^2 + V_{us,obs}^2 < 1$

Superallowed 0+→0+ nuclear β decays

2020 J. Hardy, I. Towner

$$\mathcal{F}t \equiv ft(1+\delta_R')(1+\delta_{\rm NS}-\delta_C) = \frac{K}{2G_V^2\left(1+\Delta_R^V\right)}$$

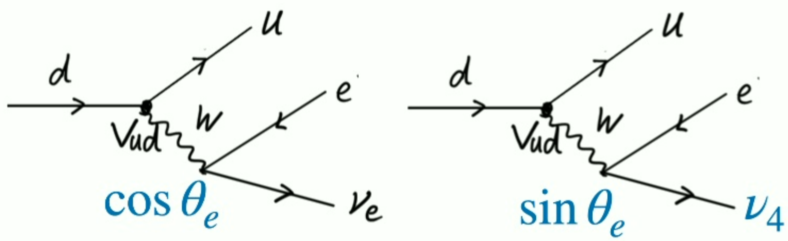
$$V_{ud} = G_V/G_F$$



- [3.2 MeV for **^{26}Al→^{26}Mg**]

Modification of β decays

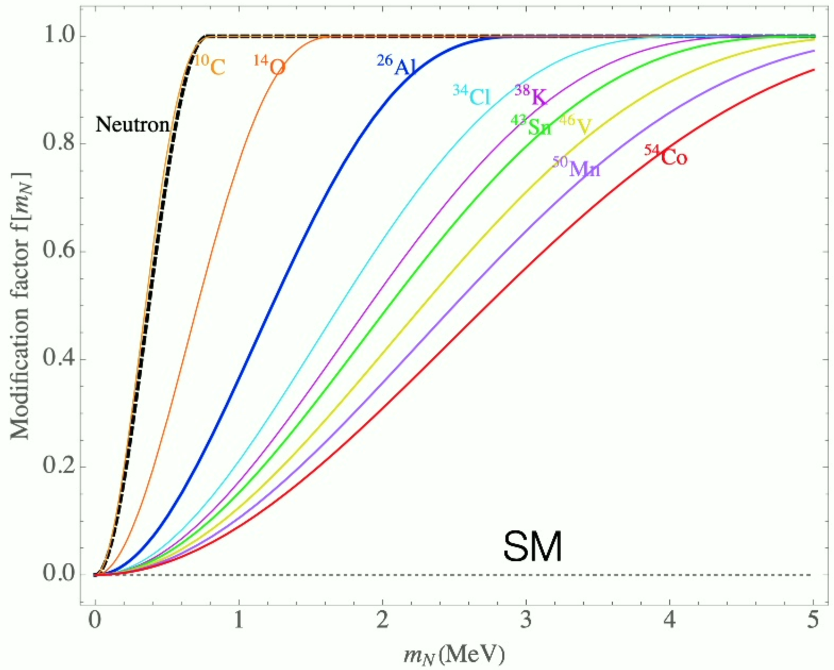
- More precisely depends on the $m_{\nu 4}$ and phase space of β decays [$V_{ud,obs} \simeq V_{ud,SM}$ if ν_4 is light <<E_ν]



some contribution from this diagram

$$V_{ud,obs} \simeq (1 - f(m_{\nu 4}, \delta M)\theta_e^2)V_{ud}$$

- Matrix element is not affected by $m_{\nu 4}$.
  Mainly phase space is modified.



Cabibbo angle anomaly and O(MeV) ν_4

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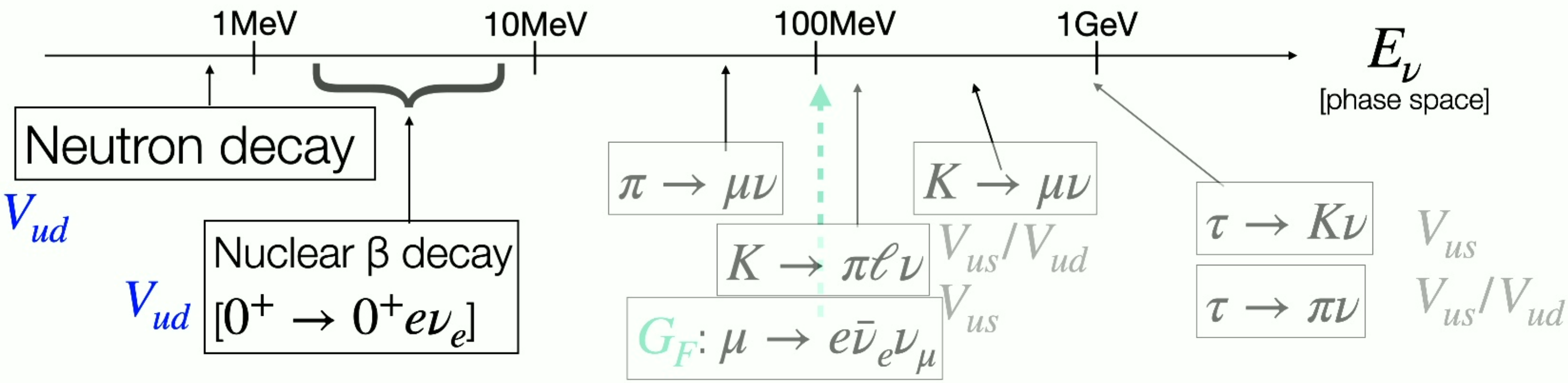
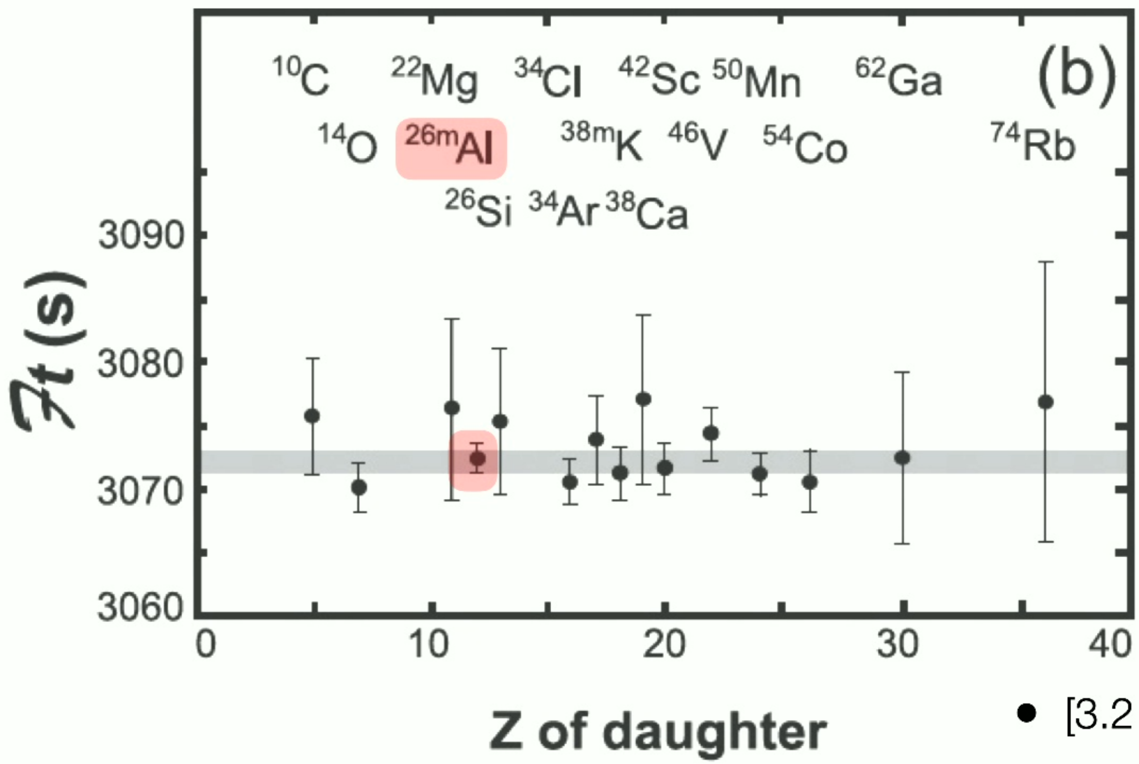


Superallowed 0+→0+ nuclear β decays

2020 J. Hardy, I. Towner

$$\mathcal{F}t \equiv ft(1+\delta_R')(1+\delta_{\rm NS}-\delta_C) = \frac{K}{2G_V^2\left(1+\Delta_R^V\right)}$$

$$V_{ud} = G_V/G_F$$



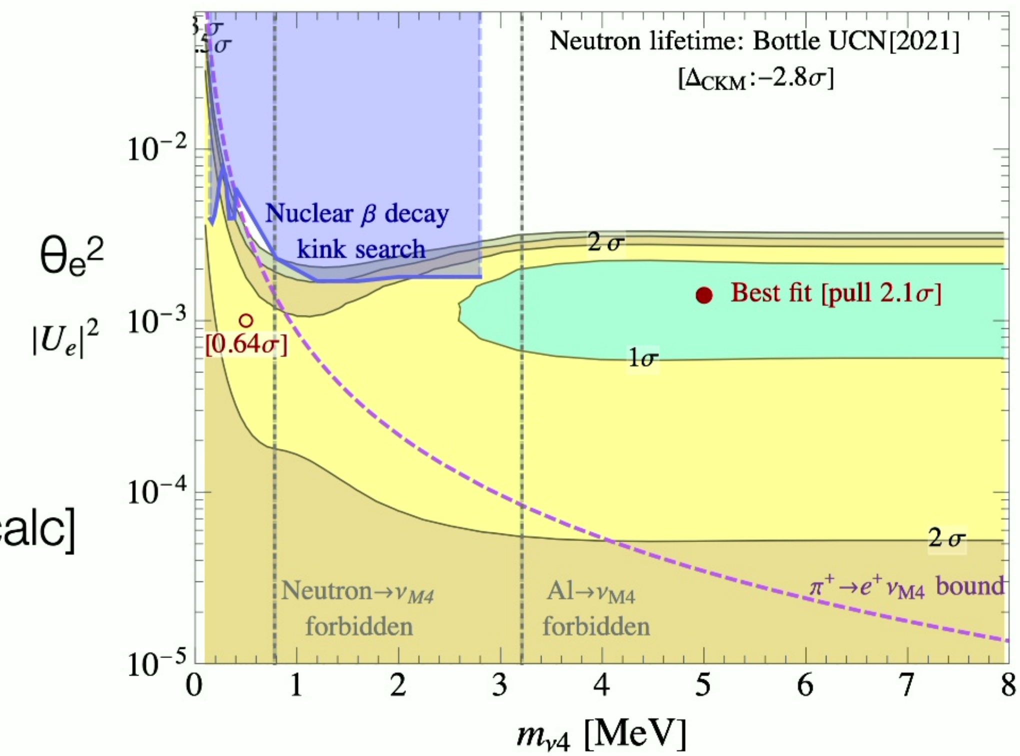
- [3.2 MeV for **^{26}Al→^{26}Mg**]

Fit results

- Sterile ν_4 mixing with electron ν
- Anomaly is explained by $\theta^2 \sim 10^{-3}$
- Currently the fit is driven by nuclear beta decays
- Choice of dataset [neutron, theory calc] modifies the result

Bottle neutron

$|V_{ud}|_{n(\text{UCN best})} = 0.97413(43)[\tau_n = 877.75(36), \text{sec}]$



Fit results

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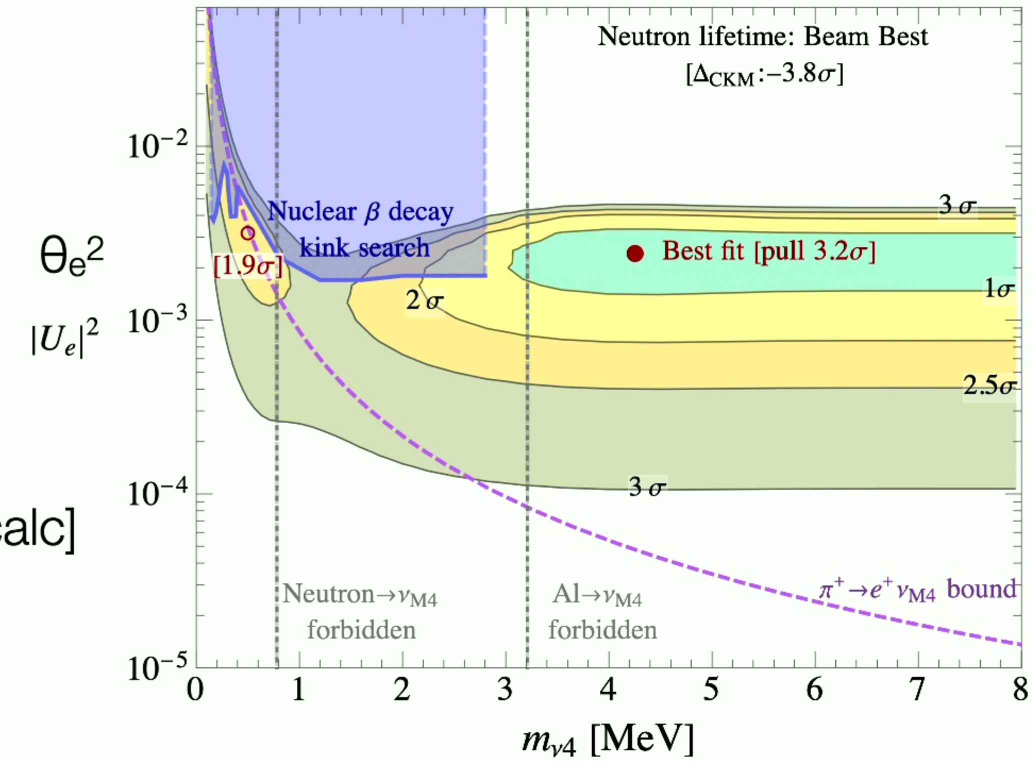
- Anomaly is explained by $\theta^2 \sim 10^{-3}$
- Currently the fit is driven by nuclear beta decays
- Choice of dataset [neutron, theory calc] modifies the result

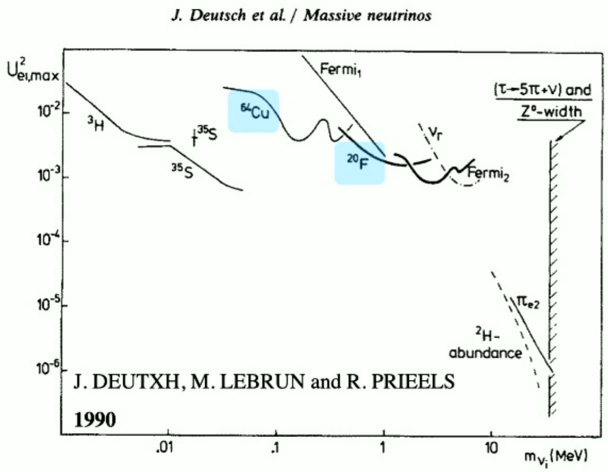
Beam neutron

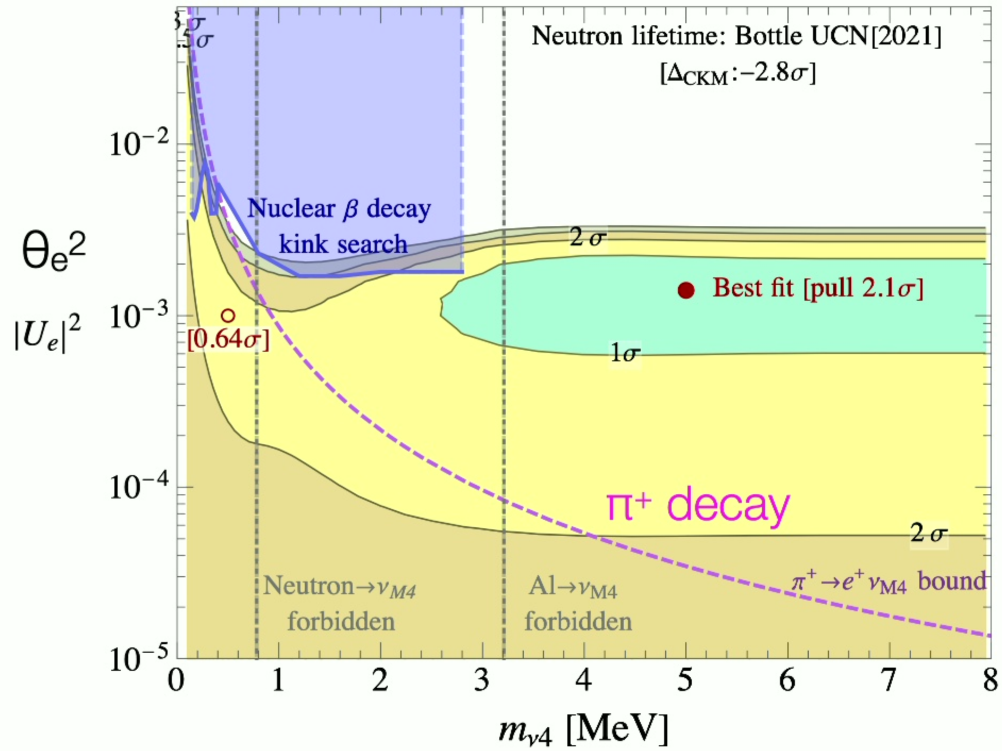
$|V_{ud}|_{n(\text{beam best})} = 0.96866(131)[\tau_n = 887.7(2.2), \text{sec}]$



Bounds from direct search

- Bump hunt in nuclear decay [blue]





- $\pi^+ \to e N$ bound [magenta, dotted]. mass enhancement $m_{\nu 4}^2/m_e^2$.

Phys.Rev.D **100** (2019) 073011 D. Bryman, R. Shrock

However, this can be relaxed by

$$\frac{x_q^{*ij} x_l^{\ell I}}{m_\phi^2}(\overline{u}_{R,j} Q_i)(\overline{L}_\ell N_I)$$

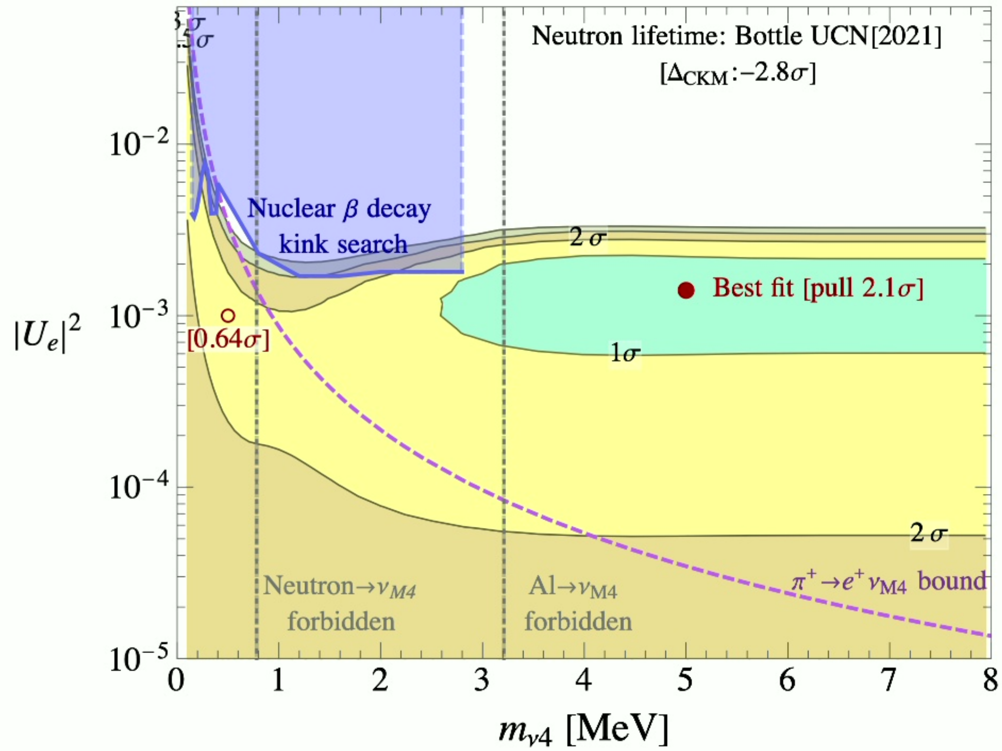
Other potential bounds

✳ Cosmology bound[not shown]
Long-lived sterile affect ΛCDM
Late-time decay. BBN

✳ Borexino N→e+e-ν_e
[not shown, 1311.5347].

🡇

- N decays to SM neutrinos quickly



Sterile neutrino cosmology

- ν_4 coupled to SM bath, decouples similar to standard neutrinos

$$T_{N,dec} \sim T_{\nu,dec}\theta^{-2/3} \sim 20\text{MeV}$$

- Vanilla scenario: ν_4 decay (neutrinos or eev if $m_{\nu 4} > 2m_e$) happens late. Lifetime ~10^7sec.
  Constrained as non-standard cosmology.

- If there is a mediator ϕ, like neutrino force of ~100MeV, sterile ν_4 can decay faster to SM neutrinos before neutrino decoupling.
  e.g. $\nu_4 \to \nu + \phi^* \to 3\nu$

- ν decoupling, BBN and after would be the standard one.

ν_4 decouples from SM bath

$T_{N,dec} \sim 20\text{MeV}$

ν_4 back to SM

$N \to \nu + \phi^* \to 3\nu$

Active neutrinos decouple

$T_{\nu,dec} \sim 2\text{MeV}$

BBN 0.1MeV

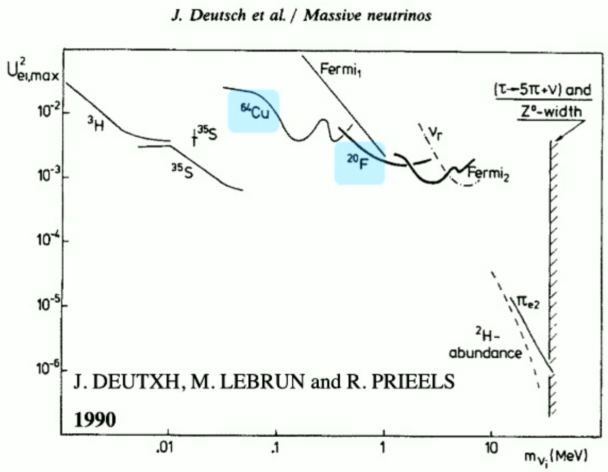
0.01MeV

Prospects of this scenario

- The favored sterile neutrino mass $m_{\nu 4}$ is **0.3-10MeV**.
The most interesting situation: the anomaly remains only in neutron decay data.
- No anomaly is expected from tau/kaon decays because $M_N \ll E_\nu$.
- Further tests:
Shape analysis (bump hunt) in nuclear beta decay.
- Neutrinoless double beta decay can be also relevant.

Bounds from direct search

- Bump hunt in nuclear decay [blue]

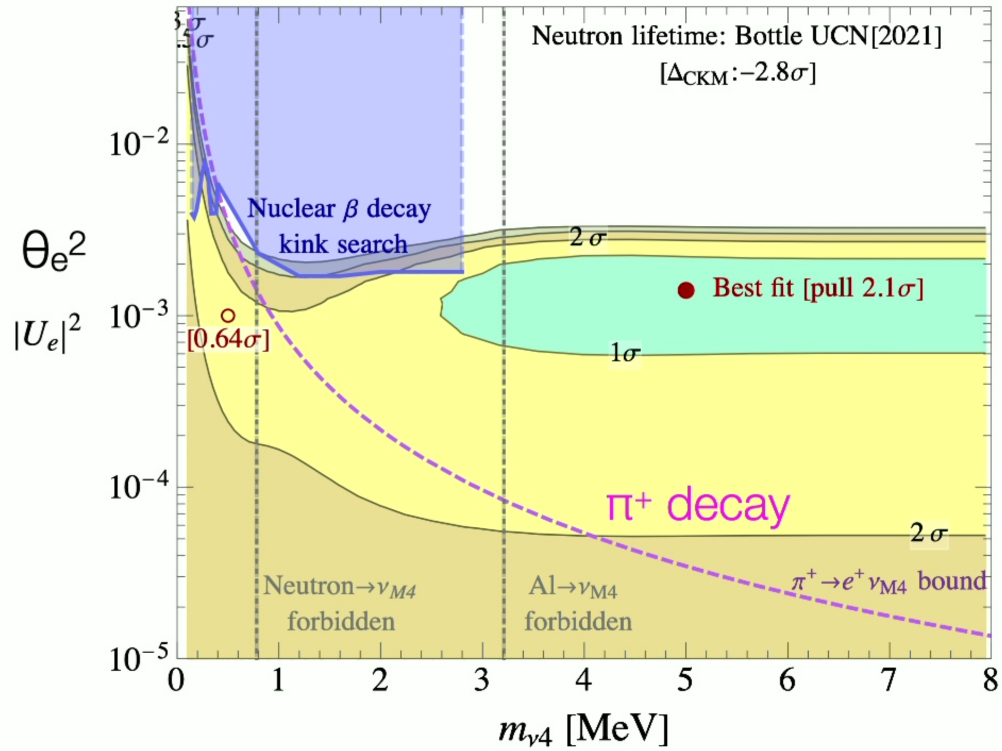


- π^+ ->e N bound [magenta, dotted]. mass enhancement $m_{\nu 4}^2/m_e^2$.

Phys.Rev.D **100** (2019) 073011 D. Bryman, R. Shrock

However, this can be relaxed by

$$\frac{x_q^{*ij} x_l^{\ell I}}{m_\phi^2}(\overline{u}_{R,j} Q_i)(\overline{L}_\ell N_I)$$

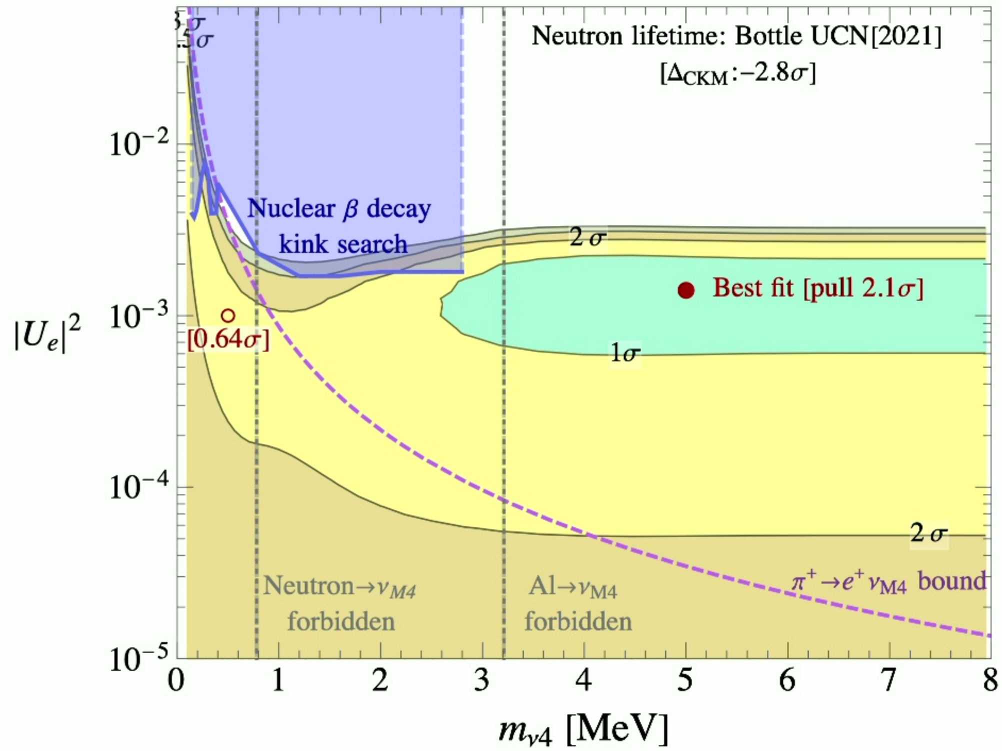


Other potential bounds

- ✳ Cosmology bound[not shown]
  Long-lived sterile affect ΛCDM
  Late-time decay. BBN

- ✳ Borexino N→e+e-ν_e
  [not shown, 1311.5347].

- N decays to SM neutrinos quickly



Sterile neutrino cosmology

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