H2020 MSCA COFUND
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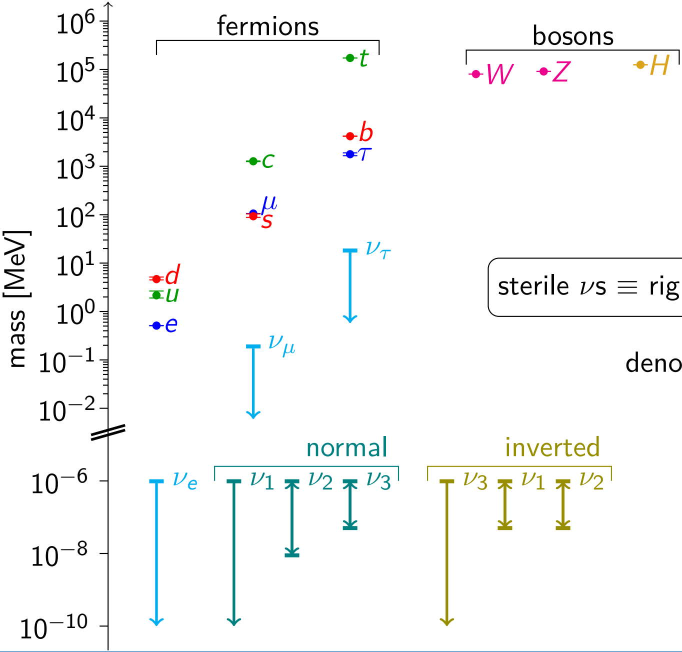
Sterile neutrinos with the PTOLEMY project

PTOLEMY general meeting, 06/10/2022

Masses in the Standard Model

[masses from PDG 2020]



sterile νs $\equiv$ right-handed fermions?

denote with N

Masses in the Standard Model

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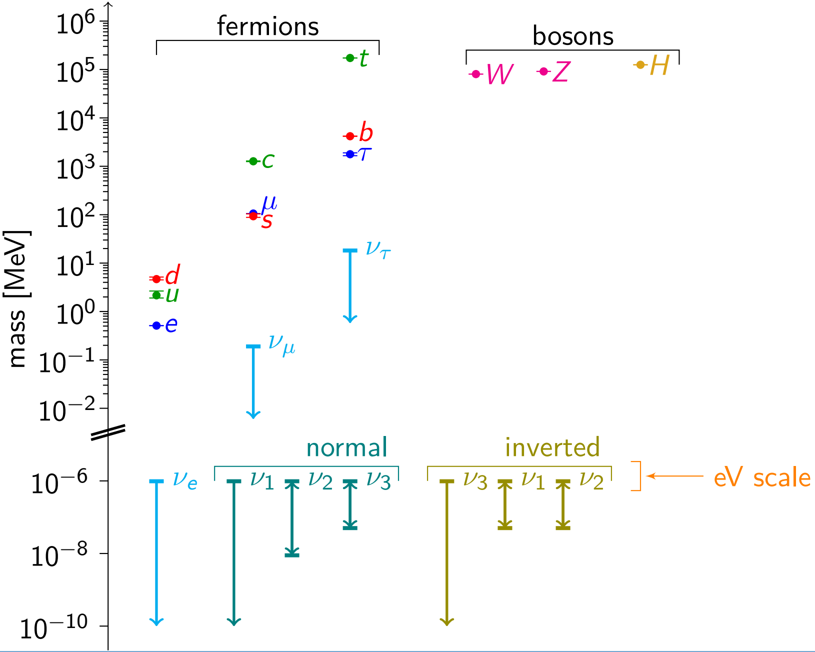

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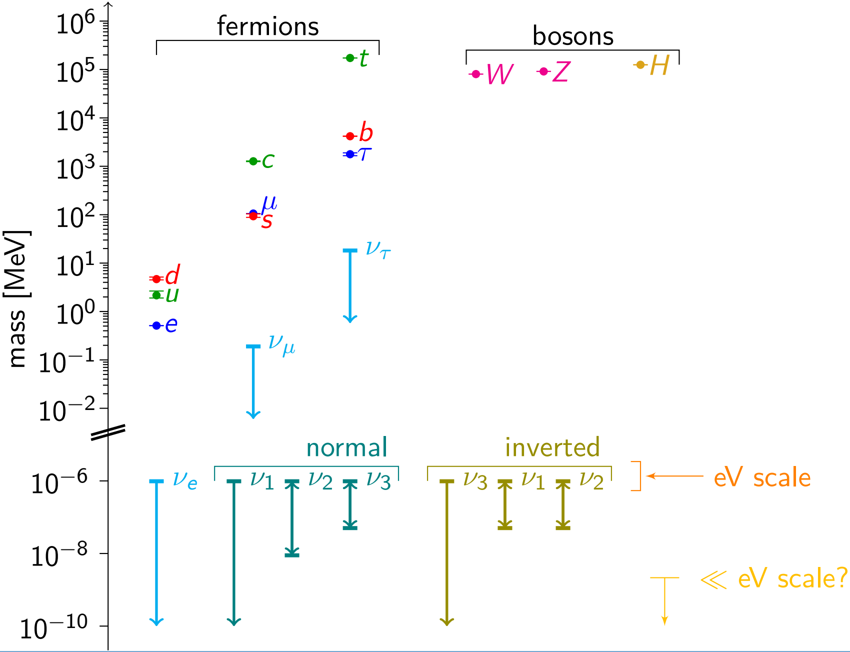

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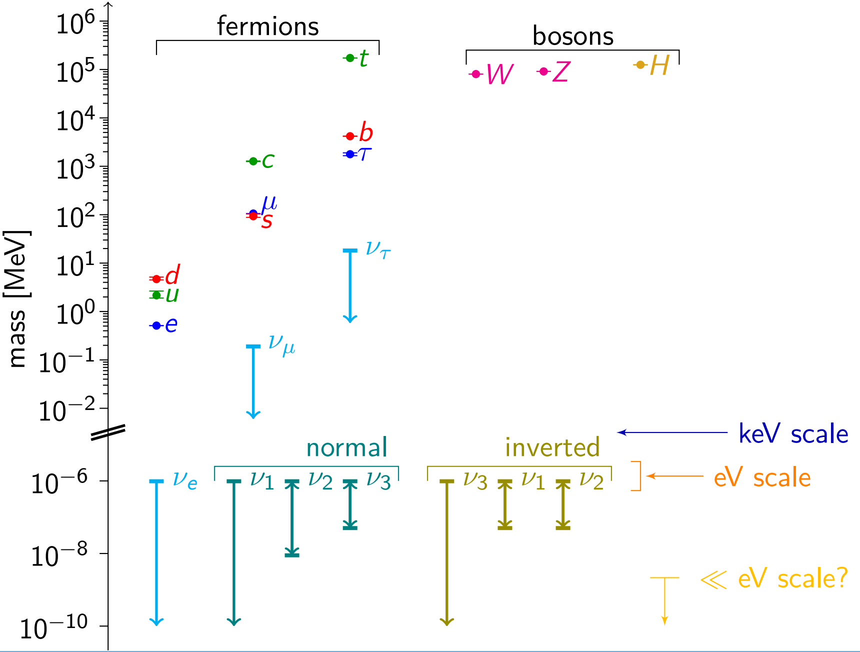

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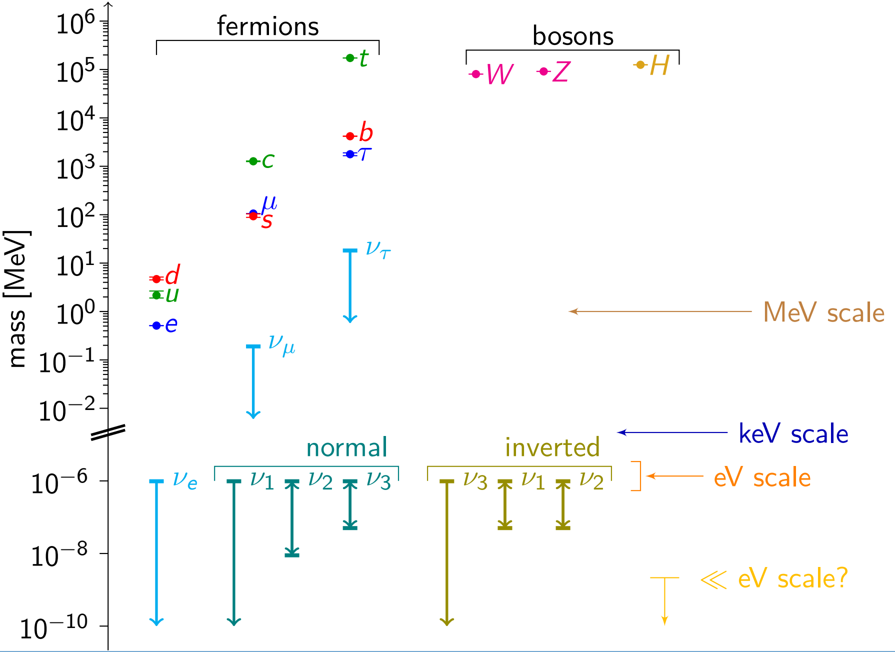

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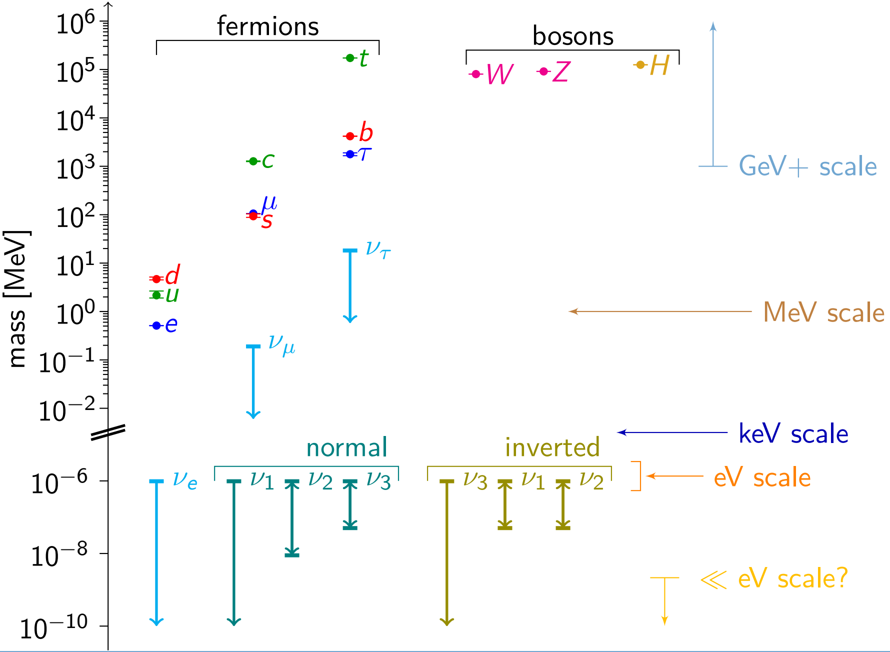

Short Baseline (SBL) anomalies

[SG+, JPG 43 (2016) 033001]

Do three-neutrino oscillations explain all experimental results?

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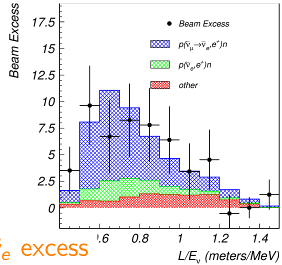
LSND



[Aguilar+, 2001]

3.8σ

$\bar{\nu}_\mu \to \bar{\nu}_e$ excess

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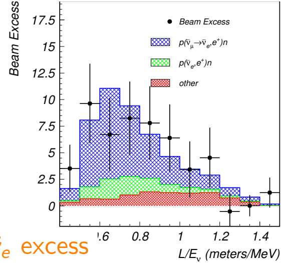

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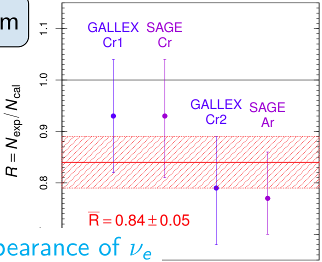
Gallium



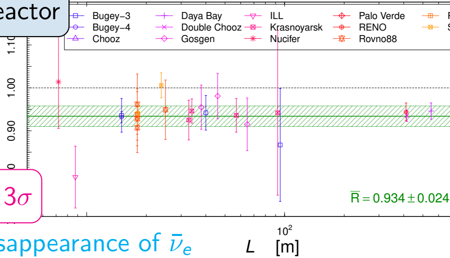
[Giunti, Laveder, 2011]

2.7σ

disappearance of ν_e

[Mention+, 2011] [Azabajian+, 2012]

Reactor



$\sim 3\sigma$

disappearance of $\bar{\nu}_e$

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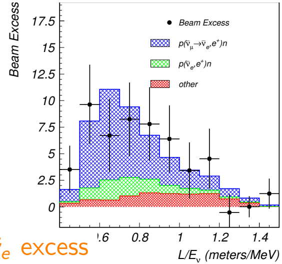

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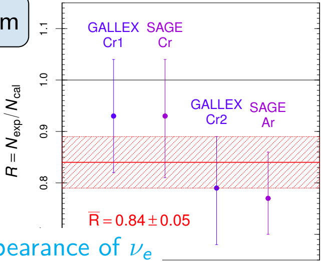

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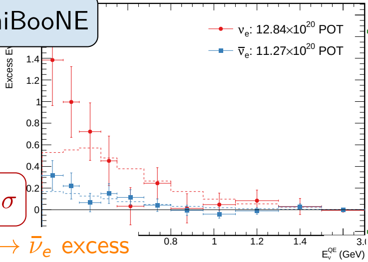
MiniBooNE



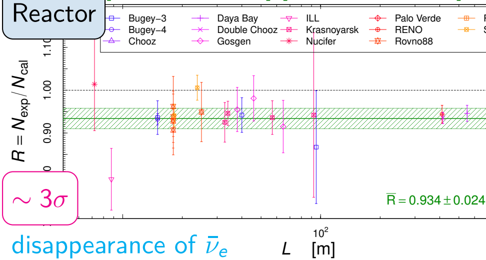
[Aguilar+, 2008-2018]

$\sim 5\sigma$

$\bar\nu_\mu \to \bar\nu_e$ excess

Reactor

[Mention+, 2011] [Azabajian+, 2012]



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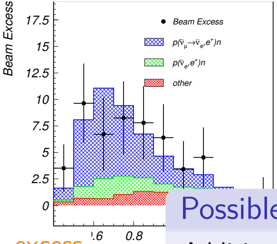

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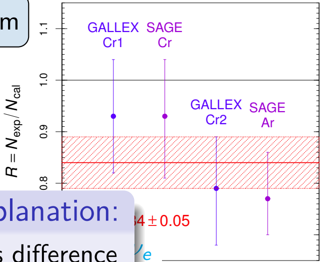

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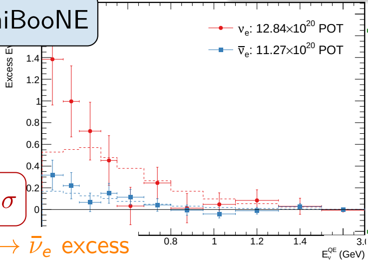

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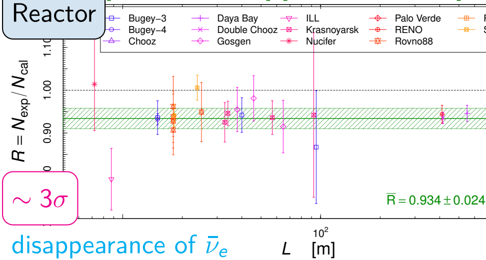

$\sim 3\sigma$

disappearance of $\bar{\nu}_e$

Possible common explanation:

Additional squared mass difference

$$\Delta m^2_{\text{SBL}} \simeq 1\ \text{eV}^2$$

Heavier neutrino states at oscillation/mass experiments

Oscillation probability:

$$P_{\nu_\alpha \to \nu_\beta}(L) = |\langle \nu_\alpha | \nu(L) \rangle|^2 = \sum_{k,j} U_{\beta k} U^*_{\alpha k} U^*_{\beta j} U_{\alpha j} \exp\left(-i \frac{\Delta m^2_{kj} L}{2E} \right)$$

oscillation length decreases with increasing Δm^2_{kj}!

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Concerning the mixing matrix (3+1 scenario):

$$U = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & c_{34} & s_{34} \\ 0 & 0 & -s_{34} & c_{34} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c_{24} & 0 & s_{24} \\ 0 & 0 & 1 & 0 \\ 0 & -s_{24} & 0 & c_{24} \end{pmatrix} \begin{pmatrix} c_{14} & 0 & 0 & s_{14} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -s_{14} & 0 & 0 & c_{14} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c_{23} & s_{23} & 0 \\ 0 & -s_{23} & c_{23} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} & 0 \\ 0 & 1 & 0 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 & 0 \\ -s_{12} & c_{12} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\Rightarrow |U|^2 = \begin{pmatrix} c^2_{14} c^2_{13} c^2_{12} & c^2_{14} c^2_{13} s^2_{12} & c^2_{14} s^2_{13} & s^2_{14} \\ \cdots & \cdots & \cdots & c^2_{14} s^2_{24} \\ \cdots & \cdots & \cdots & c^2_{14} c^2_{24} s^2_{34} \\ \cdots & \cdots & \cdots & c^2_{14} c^2_{24} c^2_{34} \end{pmatrix}, \; s_{i4} \simeq 0, \; c_{i4} \simeq 1$$

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Effect of neutrino masses in β and $0\nu\beta\beta$ decays:

$$K(T) = \left[(Q_\beta - T)\sum_{i=1}^{N_\nu} |U_{ei}|^2 \sqrt{(Q_\beta - T)^2 - m_i^2}\right]^{1/2} \quad \text{and} \quad m_{\beta\beta} = \left|\sum_k e^{i\alpha_k}\mu_k\right|, \text{ with } \mu_k \equiv {U_{ek}}^2 m_k$$

β decay

$$\beta \text{ decay: } \mathcal{N}(A, Z) \longrightarrow \mathcal{N}(A, Z+1) + e^- + \bar{\nu}_e$$

$$Q_\beta = M_i - M_f - m_e$$

total available energy

$$E_\nu = Q_\beta - T = Q_\beta - (E_e - m_e)$$

neutrino energy

notice that max electron energy is:

$$T_{\rm max} = Q_\beta - m_{\bar{\nu}_e}$$

Kurie function: (degenerate ν masses)

$$K(T) = \left[(Q_\beta - T)\sqrt{(Q_\beta - T)^2 - m^2_{\bar{\nu}_e}}\right]^{1/2}$$

Useful to describe the e^- spectrum near the endpoint

β decay

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$$m^2_{\bar{\nu}_e} = \sum |U_{ei}|^2 m_i^2$$

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Full expression:

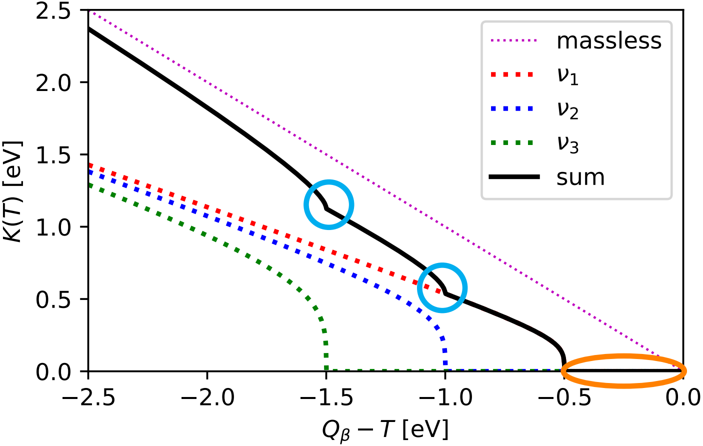
$$K(T) = \left[(Q_\beta - T)\sum_{i=1}^{N_\nu} |U_{ei}|^2 \sqrt{(Q_\beta - T)^2 - m_i^2}\right]^{1/2}$$

N_ν neutrinos with different masses m_i

mixing angles enter ($|U_{ei}|^2$)

β decay

$$K(T) = \left[(Q_\beta - T) \sum_{i=1}^{N_\nu} |U_{ei}|^2 \sqrt{(Q_\beta - T)^2 - m_i^2} \right]^{1/2}$$



Fake case:
3 neutrinos

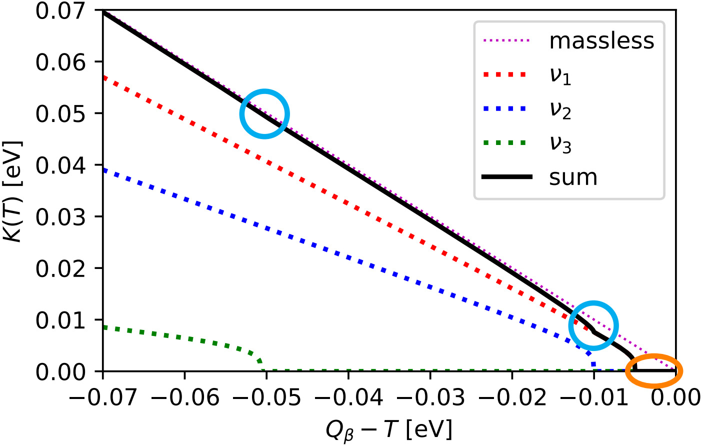
masses:
$m_i = i \cdot 0.5$ eV,

mixings:
$|U_{ei}|^2 = 1/3$

endpoint shifted + one kink for each mass eigenstate

β decay

$$K(T) = \left[(Q_\beta - T) \sum_{i=1}^{N_\nu} |U_{ei}|^2 \sqrt{(Q_\beta - T)^2 - m_i^2} \right]^{1/2}$$



Realistic case:
3 neutrinos,
normal
ordering

masses: $m_i =$
$[5, 10, 51]$ meV,

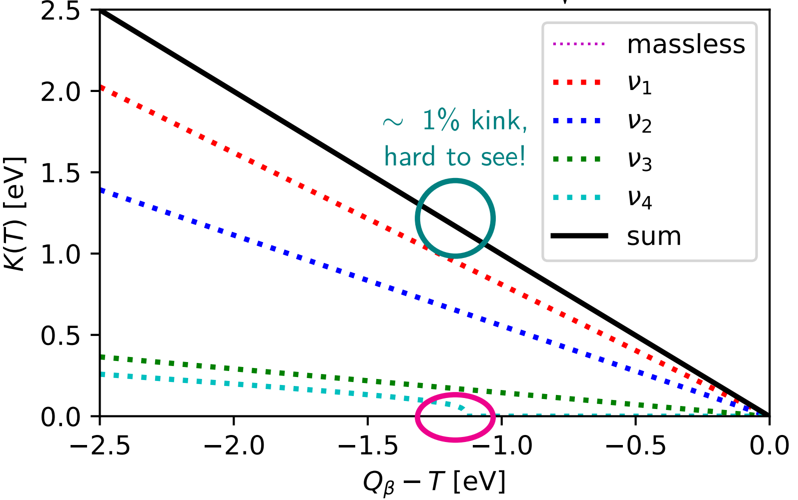
mixings:
$|U_{ei}|^2 =$
$[0.67, 0.31, 0.02]$

Much harder to see the endpoint shift and kinks!

Sterile neutrino in β decay

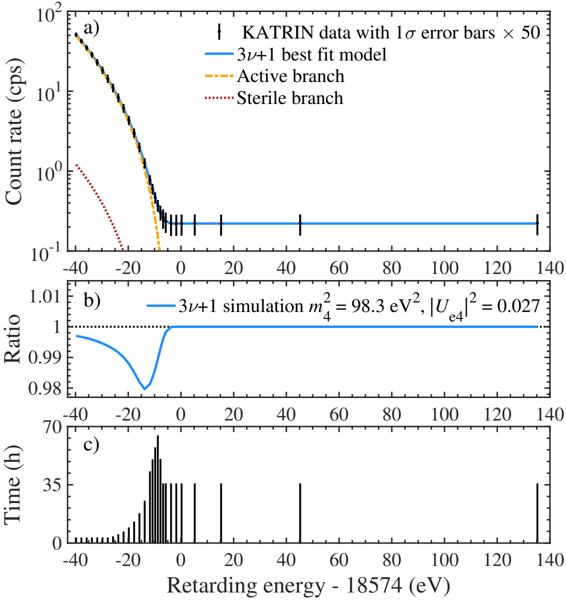
$$K(T) = \left[(Q_\beta - T) \sum_{i=1}^{N_\nu} |U_{ei}|^2 \sqrt{(Q_\beta - T)^2 - m_i^2} \right]^{1/2}$$

$|U_{e4}|^2 \sim 0.01$ $\qquad$ $m_4 \sim \sqrt{\Delta m^2_{41}} \simeq 1.15$ eV



Sterile neutrino in β decay

[KATRIN, PRD 105 (2022)]



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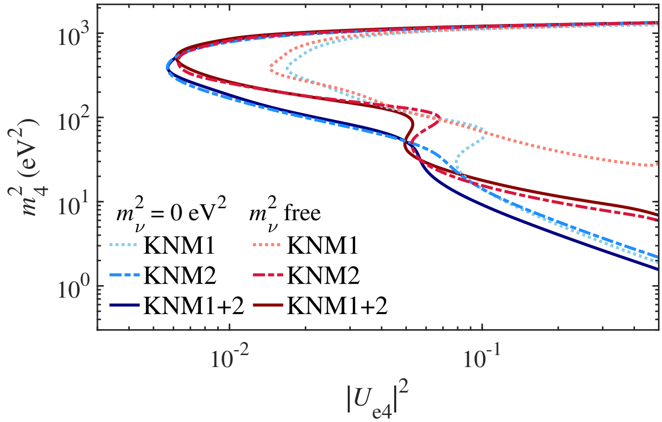

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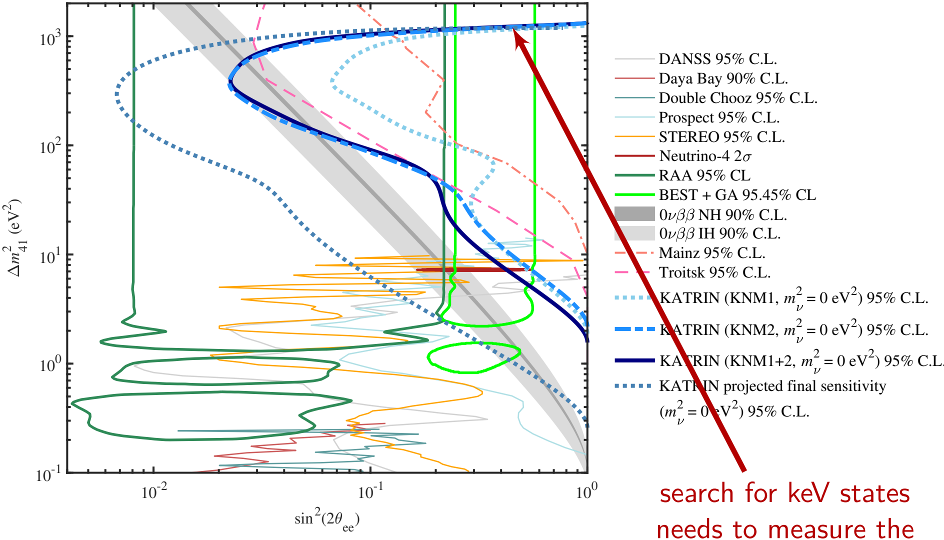


final sensitivity will test several oscillation results!

search for keV states needs to measure the spectrum much further from the endpoint...

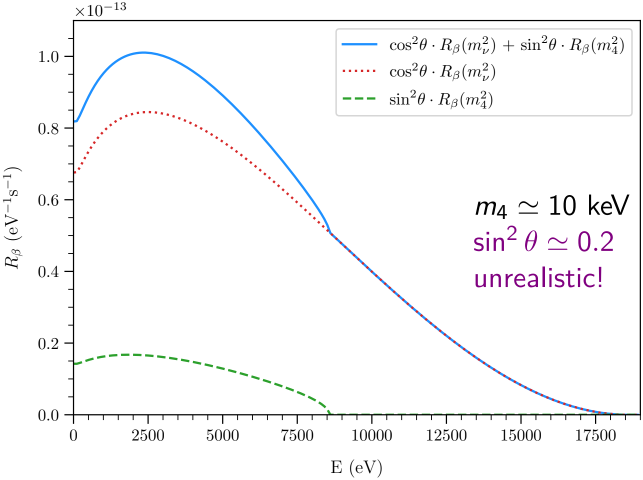
KATRIN at keV scale

[KATRIN, arxiv:2207.06337]

Observe β spectrum to detect heavier sterile neutrinos?

Consider a two neutrinos scenario, mixing $\theta \rightarrow 0$

Active: $\cos^2\theta$ Sterile: $\sin^2\theta$



$m_4 \simeq 10$ keV

$\sin^2\theta \simeq 0.2$

unrealistic!

KATRIN at keV scale

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Active: $\cos^2\theta$

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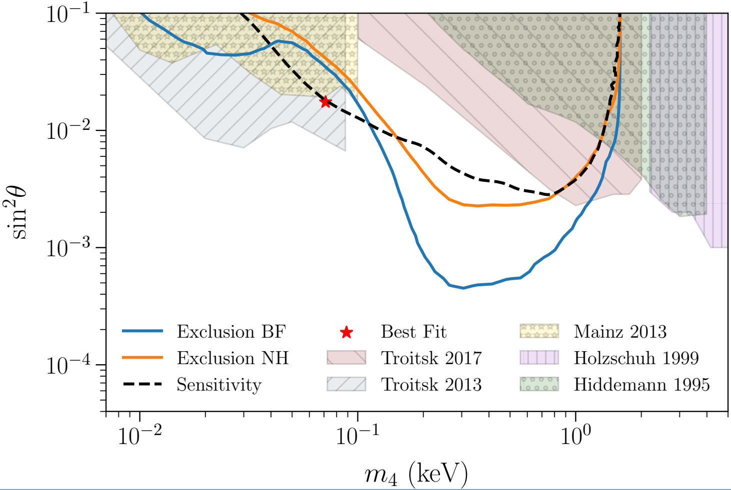

β and Neutrino Capture spectra

[PTOLEMY, JCAP 07 (2019) 047]

$$\frac{d\widetilde{\Gamma}_{\rm CNB}}{dE_e}(E_e) = \frac{1}{\sqrt{2\pi}\sigma}\sum_{i=1}^{N_\nu}\bar{\sigma}\, N_T\,|U_{ei}|^2\, n_0\, f_c(m_i)\ \times\, e^{-\frac{[E_e-(E_{\rm end}+m_i+m_{\rm lightest})]^2}{2\sigma^2}}$$

$$\frac{d\Gamma_\beta}{dE_e} = \frac{\bar{\sigma}}{\pi^2}N_T\sum_{i=1}^{N_\nu}|U_{ei}|^2 H(E_e, m_i)$$

$$\frac{d\widetilde{\Gamma}_\beta}{dE_e}(E_e) = \frac{1}{\sqrt{2\pi}\sigma}\int_{-\infty}^{+\infty} dx\, \frac{d\Gamma_\beta}{dE_e}(x)\, \exp\left[-\frac{(E_e-x)^2}{2\sigma^2}\right]$$

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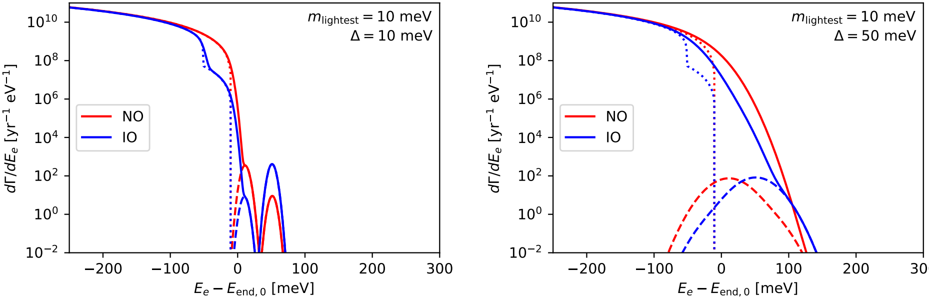

PTOLEMY and the ν_4

[PTOLEMY, JCAP 07 (2019) 047]

$\Gamma_{\mathrm{C}\nu\mathrm{B}} = \mathcal{O}(10)/\mathrm{yr}$

$$\boxed{\Gamma_4 \simeq \Delta N_{\rm eff}\, |U_{e4}|^2\, f_c(m_4)\, \Gamma_{\rm CNB}}$$

[SG+, PLB 2018]

$m_4 \simeq 1.15$ eV

$|U_{e4}|^2 \simeq 0.01$

$\Delta N_{\rm eff} =$??

[de Salas+, 2017]

$f_c(m_4) = \mathcal{O}(10^2)$

Γ_4 depends probably on new physics!

PTOLEMY and the ν_4

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[SG+, PLB 2018]

$m_4 \simeq 1.15$ eV

$|U_{e4}|^2 \simeq 0.01$

$\Delta N_{\text{eff}} =$ **??**

[de Salas+, 2017]

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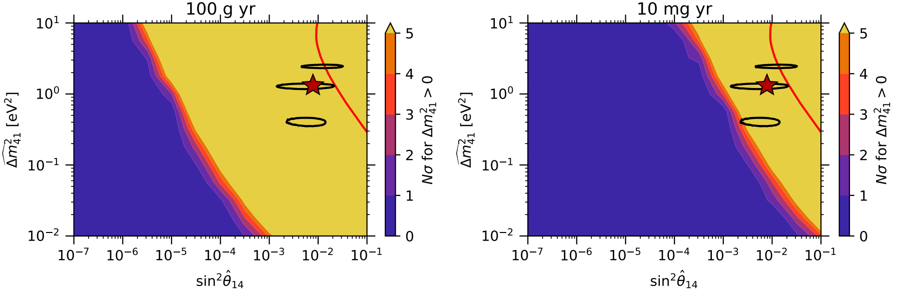
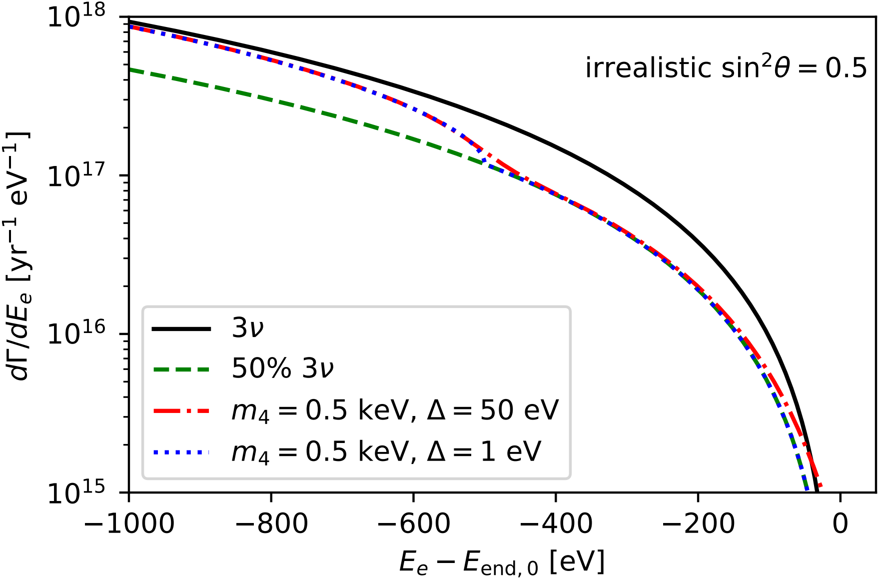
Γ_4 depends probably on new physics!

Still possible to measure mass/mixing through β spectrum



black: DANSS+NEOS 3σ (2018) red: KATRIN 90% forecast $\Delta = 0.1$eV, $E - E_0 \in [-5, 10]$eV

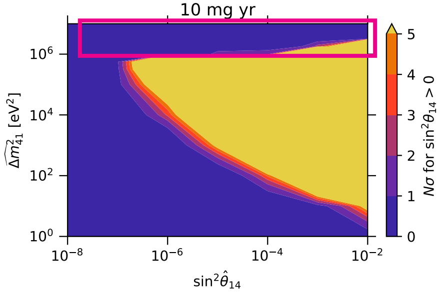
PTOLEMY and the keV sterile neutrino



PTOLEMY and the keV sterile neutrino

PTOLEMY can observe keV sterile even with RF

$\Delta = 10$ eV, $E - E_0 \in [-1000, 100]$ eV

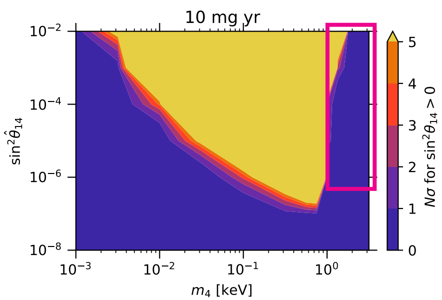


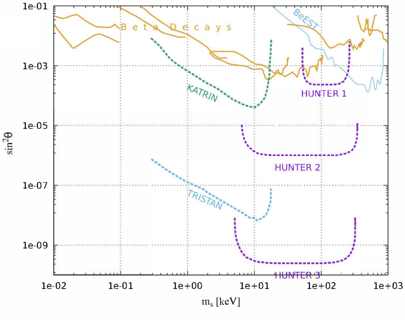
$\Delta m^2_{41} > 1$ keV^2 should not be detectable:
kink outside observed energy window,
effect of $|U_{14}|^2$ degenerate with A_β

PTOLEMY and the keV sterile neutrino

PTOLEMY can observe keV sterile even with RF

$\Delta = 10$ eV, $E - E_0 \in [-1000, 100]$ eV





[arxiv:2203.07323]

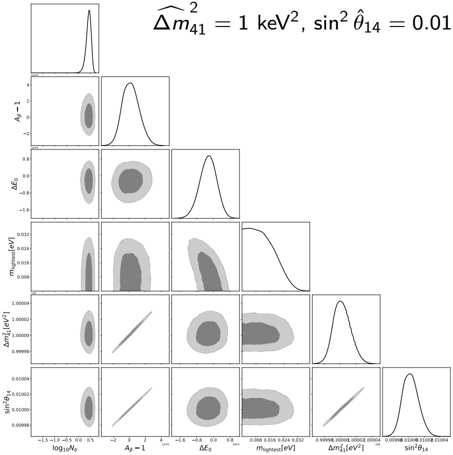
$m_4 > 1$ keV^2 should not be detectable:
kink outside observed energy window,
effect of $|U_{14}|^2$ degenerate with A_β

PTOLEMY and the keV sterile neutrino

PTOLEMY can observe keV sterile even with RF

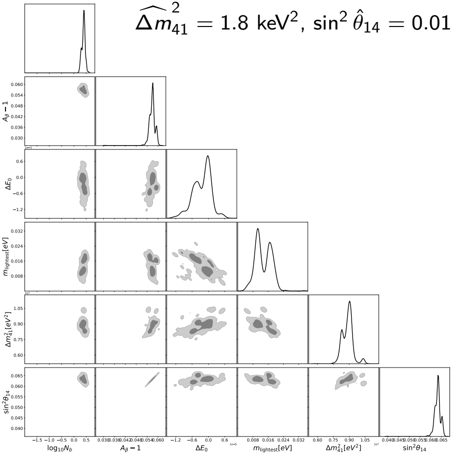
$\Delta = 10$ eV, $E - E_0 \in [-1000, 100]$ eV

$\widehat{\Delta m}^2_{41} = 1$ keV^2, $\sin^2\hat{\theta}_{14} = 0.01$



fully converged

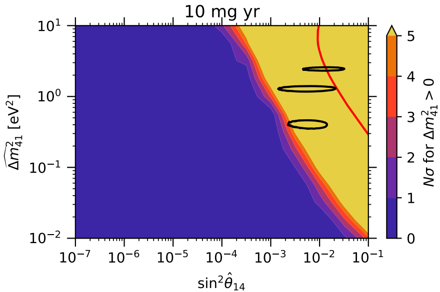
$\widehat{\Delta m}^2_{41} = 1.8$ keV^2, $\sin^2\hat{\theta}_{14} = 0.01$



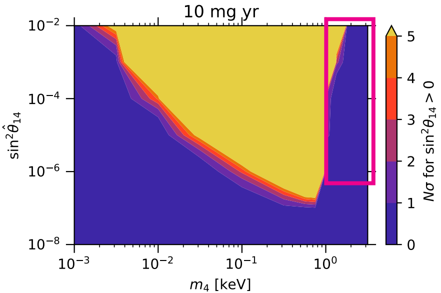
"converged" to wrong values

Conclusions - sterile neutrinos at PTOLEMY

eV scale



keV scale



What is left to do?

understand analysis problems when $m_4 \gtrsim |E - E_0|$

study more configurations (Δ, $E - E_0$ range of observation, target mass)

Thank you for the attention!