Light Bosons from Tritium Decay

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Motivations

The absence of New Physics signals at colliders suggest to look for it in less conventional directions.

One can consider that the New Physics is very light and coupled only with the EW sector.

Case of study: New Physics in experiments for neutrino mass determination.

Detection principle:

Study of the kinematics of the decay. In particular the endpoint energy.

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

Why tritium:

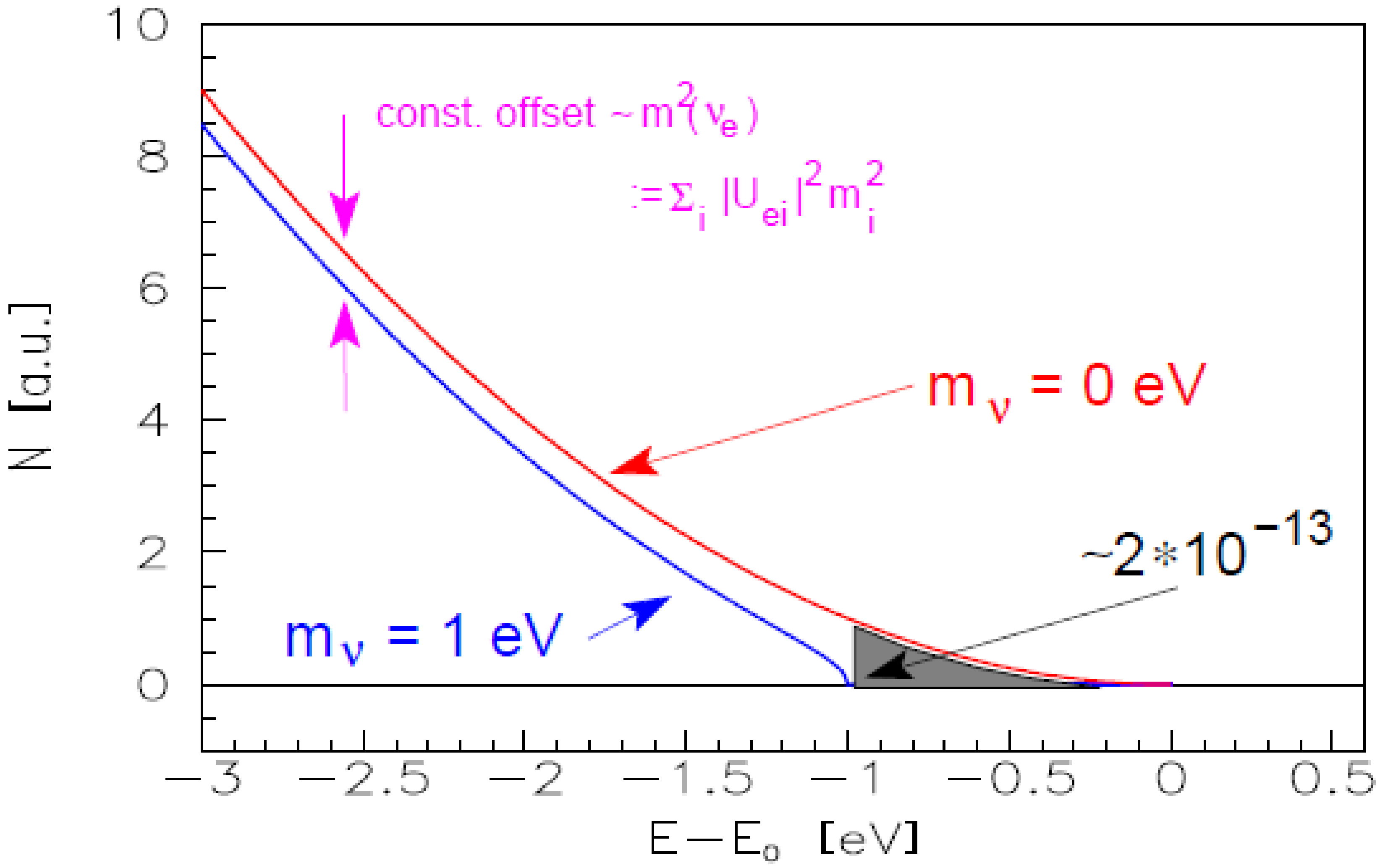
Low end point energy 18.6 KeV

Rather short half-life 12.3 y

Super-allowed shape of the spectrum

Simple electronic structure

} Low sistematics in the measurement of the β spectrum



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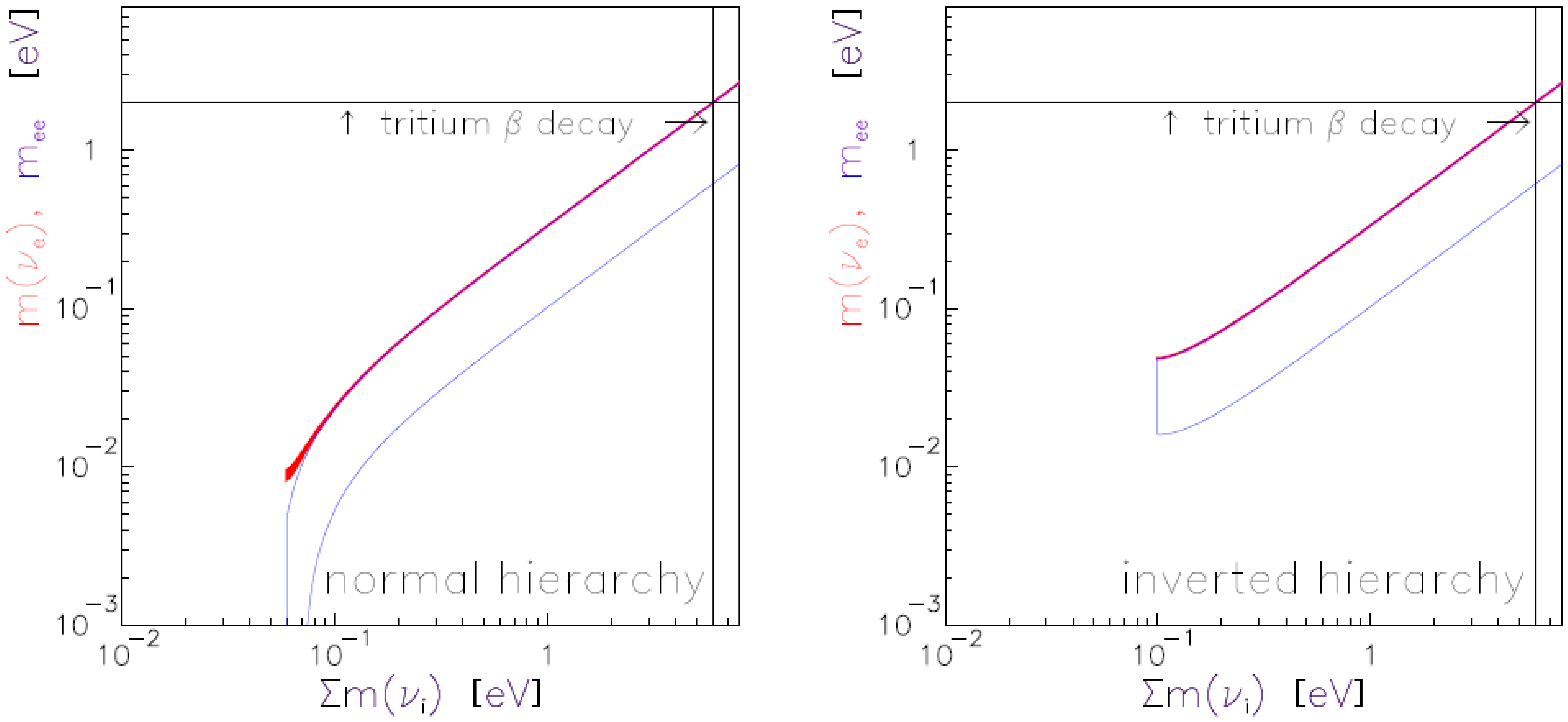

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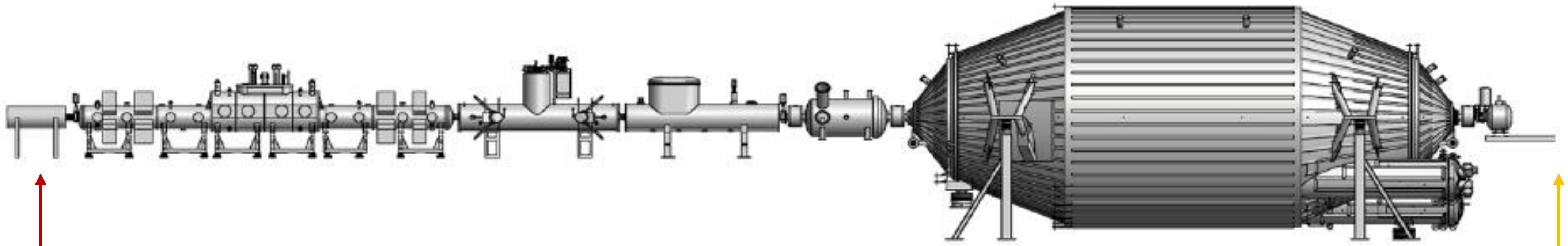
New Physics in Tritium Decay

$$^3\mathrm{H} \to {}^3\mathrm{He}^+ + e^- + \bar{\nu}_e$$

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

$$E_e^{\max} = \frac{m_{^3\mathrm{H}}^2 - (m_{^3\mathrm{He}^+} + m_\nu + m_X)^2 + m_e^2}{2 m_{^3\mathrm{H}}}$$

Katrin Experiment



Source: 10^{11}electrons produced per second from β decay of high purity molecular tritium at 30 K

Spectrometer

Detector

Theoretical Model

$$\mathcal{L} = i g_{\nu J}\, \bar{\nu}\, \gamma_5\, \nu\, J$$

Model A

$$\mathcal{L} = i g_{eJ}\, \bar{e}\, \gamma_5\, e\, J$$

Model B

$$\mathcal{L} = g_{\nu L}\, \bar{\nu} \gamma^{\mu} P_L \nu Z'_{\mu}$$

Model C

$$\mathcal{L} = \bar{e} \gamma^{\mu} (g_{eL}\, P_L + g_{eR}\, P_R) e Z'_{\mu}$$

Model D

$$\mathcal{L} = g_{L_e}\, j^{\alpha}_{L_e} Z'_{\alpha} = g_{L_e} \left(\bar{\nu}_e \gamma^{\alpha} P_L \nu_e + \bar{e} \gamma^{\alpha} e \right) Z'_{\alpha}$$

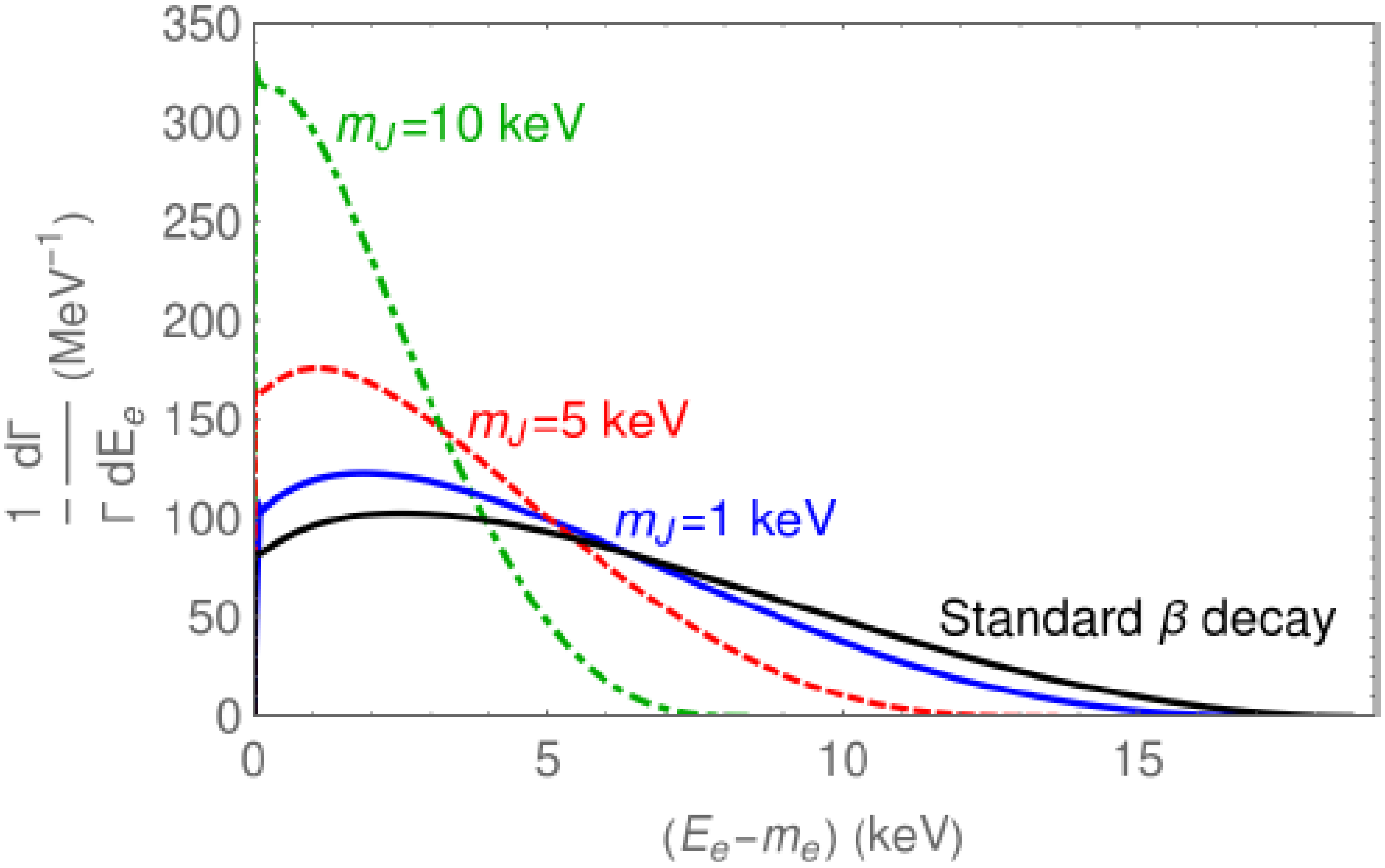
Model E

Theoretical Spectrum

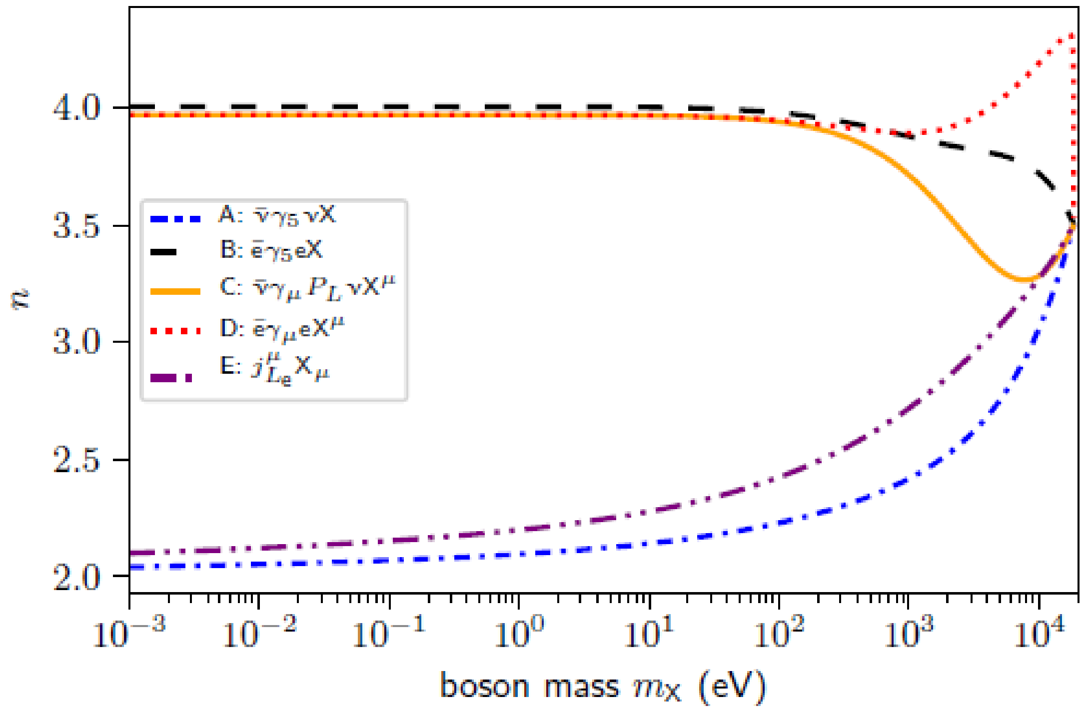
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = \left.\frac{\mathrm{d}\Gamma}{\mathrm{d}E}\right|_{\beta} + \left.\frac{\mathrm{d}\Gamma}{\mathrm{d}E}\right|_{X}$$

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E_e} = \frac{K}{\hbar}\sqrt{\frac{E_e}{m_e} - 1}\left(1 - \frac{E_e}{E_e^{\mathrm{max}}}\right)^n F(Z, E_e)$$

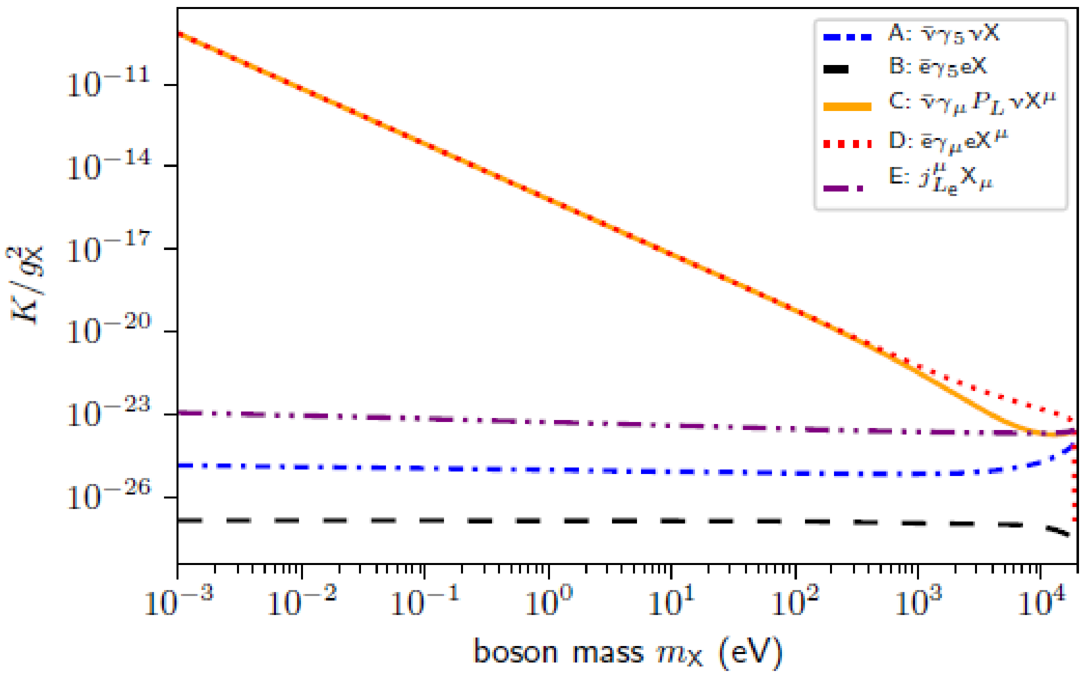
Mechanism	K/g_X^2	n
A: Pseudoscalars from neutrinos	10^{-25}	2
B: Pseudoscalars from electrons	10^{-27}	4
C: Vector bosons from neutrinos	$7 \cdot 10^{-16}(\mathrm{eV}/m_X)^2$	4
D: Vector bosons from electrons	$7 \cdot 10^{-16}(\mathrm{eV}/m_X)^2$	4
E: Vector bosons from both	$5 \cdot 10^{-24}$	2



350
300
250
200
150
100
50
0
0
5
10
15
$\frac{1}{\Gamma}\frac{d\Gamma}{dE_e}$ (MeV^{-1})
$(E_e - m_e)$ (keV)
m_J=10 keV
m_J=5 keV
m_J=1 keV
Standard β decay



4.0
3.5
3.0
2.5
2.0
n
A: $\bar{\nu}\gamma_5\nu X$
B: $\bar{e}\gamma_5 eX$
C: $\bar{\nu}\gamma_\mu P_L \nu X^\mu$
D: $\bar{e}\gamma_\mu eX^\mu$
E: $j^\mu_{L_e} X_\mu$
10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4}
boson mass m_X (eV)



10^{-11}
10^{-14}
10^{-17}
10^{-20}
10^{-23}
10^{-26}
K/g_X^2
A: $\bar{\nu}\gamma_5\nu X$
B: $\bar{e}\gamma_5 eX$
C: $\bar{\nu}\gamma_\mu P_L \nu X^\mu$
D: $\bar{e}\gamma_\mu eX^\mu$
E: $j^\mu_{L_e} X_\mu$
10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4}
boson mass m_X (eV)

Experimental signal

Radiative corrections: Energy loss of from electrons due to interactions with soft and virtual photons in the Coulomb field of the necleus.

Molecular recoil: the recoil energy of the electron balances the one of the nucleus.

$$E_{\text{rec}} \approx E \cdot \frac{m_e}{m_{^3\text{HeT}^+}}$$

Final states: Decays of the molecular tritium can lead to molecules in excited states which reduce the maximal energy of the electron.

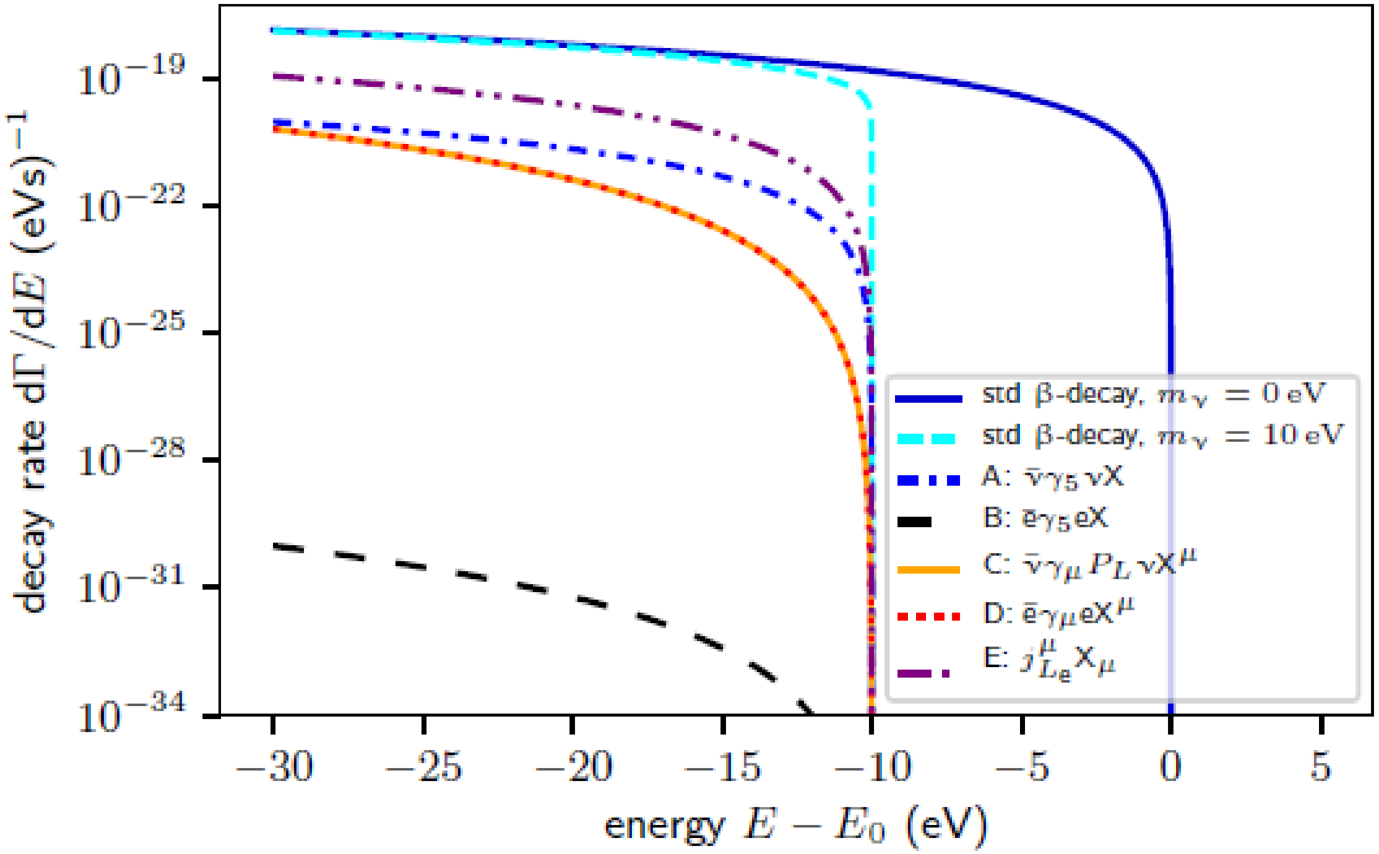
$$E_{\text{max},\,fs} = E_0 - E_{fs} - E_{\text{rec}} - (m_\nu + m_X)$$

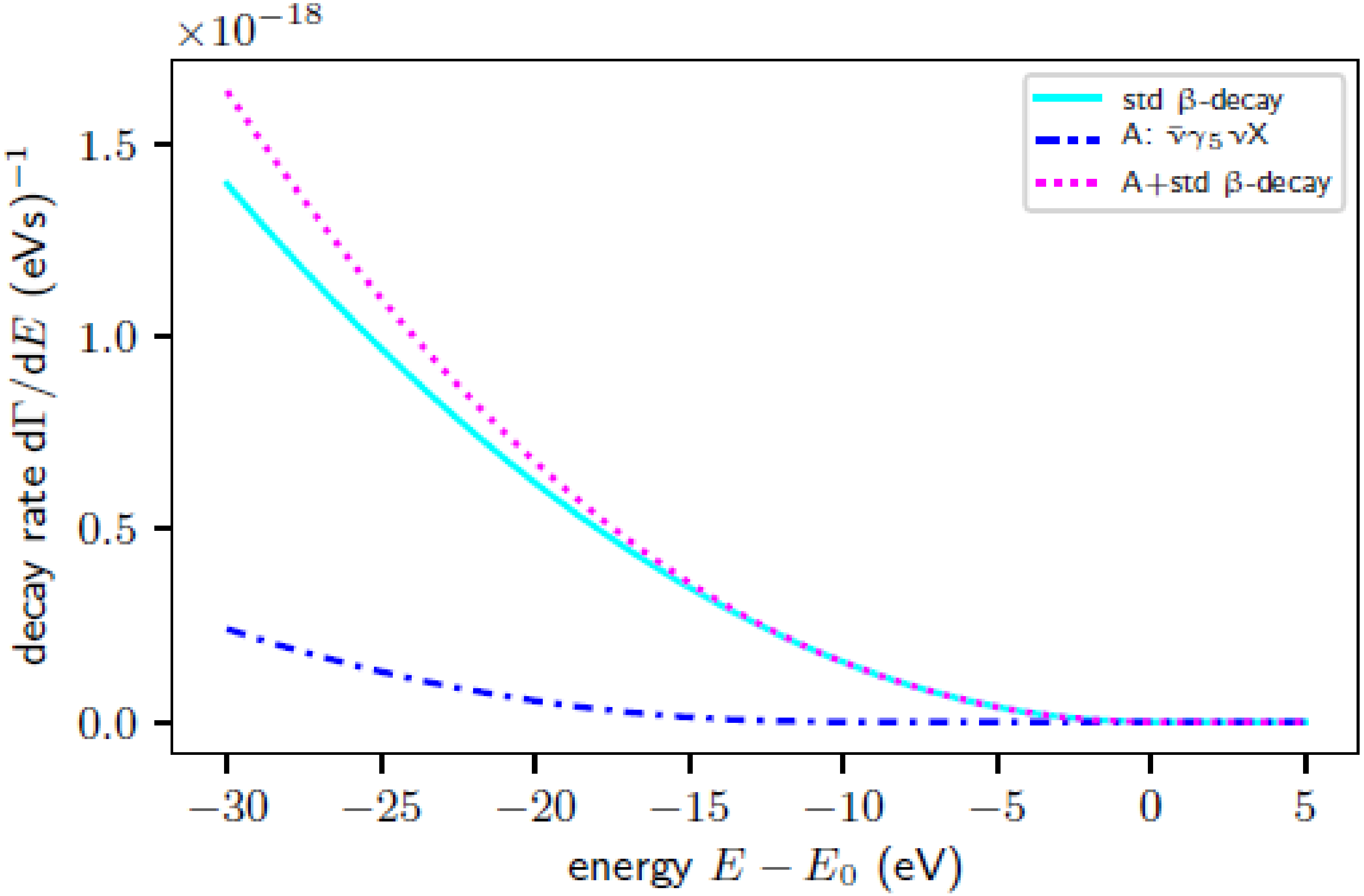
Doppler Effect: Source molecules are in thermal motion. Together with the bulk motion this causes a broadening of the electron spectrum of 100 meV.

$$\frac{d\Gamma}{dE} = \frac{K}{\hbar}\sqrt{\frac{E}{m_e}}F(Z,E) \times \sum_{fs} P_{fs} \cdot f_{\rm rad}(E - E_{fs}) \cdot \left(\frac{E_{\max,\, fs} - E}{E_{\max,\, fs} + m_e}\right)^n$$

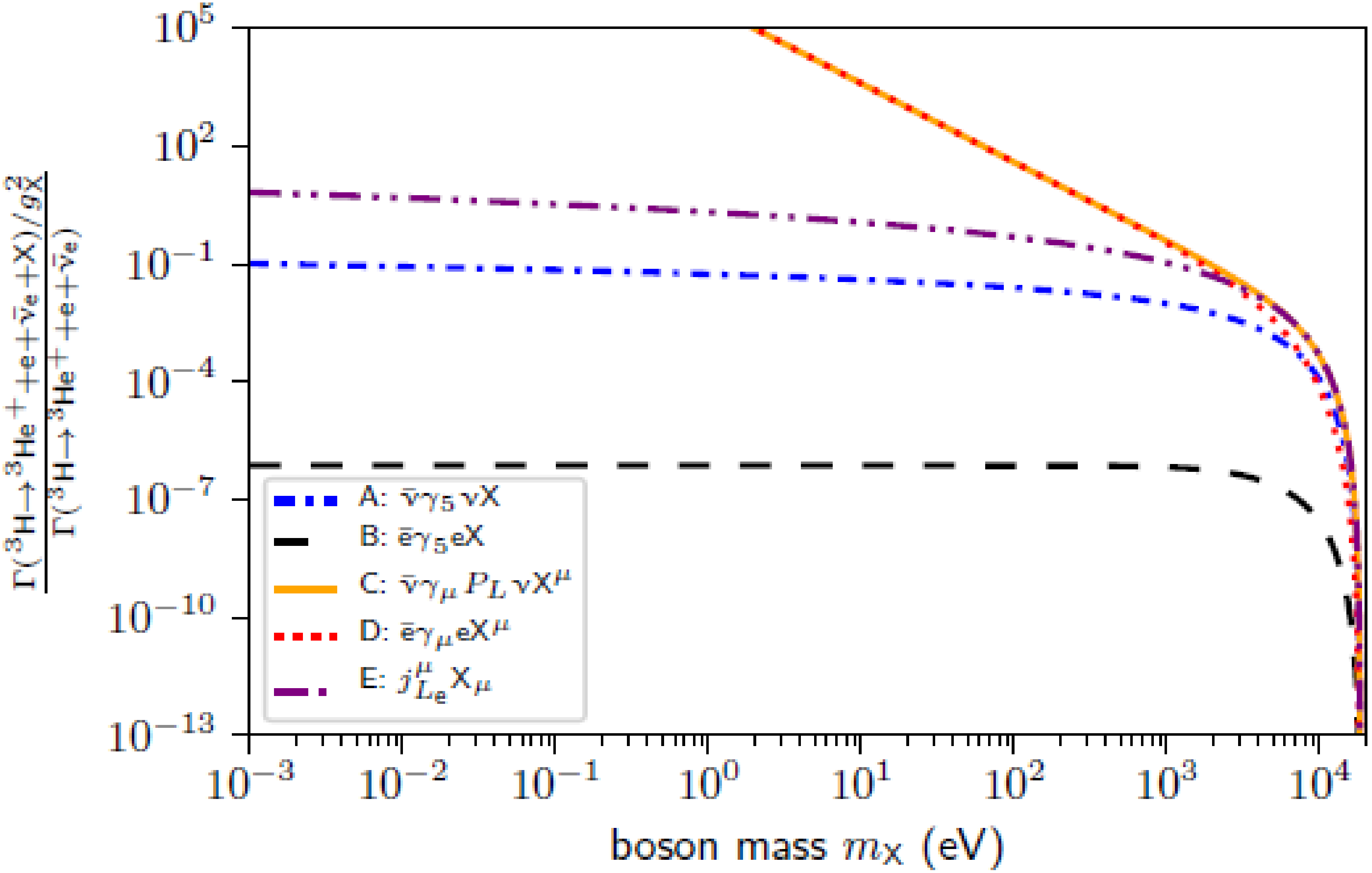
Radiative corrections

Final states effect





$\times 10^{-18}$
decay rate $d\Gamma/dE$ (eVs)$^{-1}$
1.5
1.0
0.5
0.0
std β-decay
A: $\bar{\nu}\gamma_5\nu X$
A+std β-decay
−30
−25
−20
−15
−10
−5
0
5
energy $E - E_0$ (eV)



10^5
10^2
10^{-1}
10^{-4}
10^{-7}
10^{-10}
10^{-13}
$\frac{\Gamma(^3H \to ^3He^+ + e + \bar{\nu}_e + X)/g_X^2}{\Gamma(^3H \to ^3He^+ + e + \bar{\nu}_e)}$
A: $\bar{\nu}\gamma_5\nu X$
B: $\bar{e}\gamma_5 e X$
C: $\bar{\nu}\gamma_\mu P_L \nu X^\mu$
D: $\bar{e}\gamma_\mu e X^\mu$
E: $j^\mu_{L_e} X_\mu$
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
10^4
boson mass m_X (eV)

Determining the reach of KATRIN

Sensitivity in the mass and coupling of the new boson determined through profile likelihood method.

Scenario I: Current setup. Only the spectrum close to the endpoint is studied. Sensitivity to masses of the order of few (tens) of eV

Scenario II: Future KATRIN setup. The full β spectrum is considered. Sensitivity to masses up to the KeV.

Complementary constraints

Laboratory constraints

Three-body decays

$$Z \to \nu\nu X$$

$$W \to e\nu X$$

$$P \to e\nu X$$

Anomalous magnetic moment of the electron.

Neutrino-electron scattering

Neutrinoless double-β decay (only for majoron-like models)

Astrophysics constraints:

Modification of high energy neutrinos path (modified scattering rate between high energy neutrinos and Cosmic Neutrino Background)

Energy loss in stars. (e.g. $e + Ze \to e + Ze + X, \gamma + e \to e + X$)

Cosmological constraints:

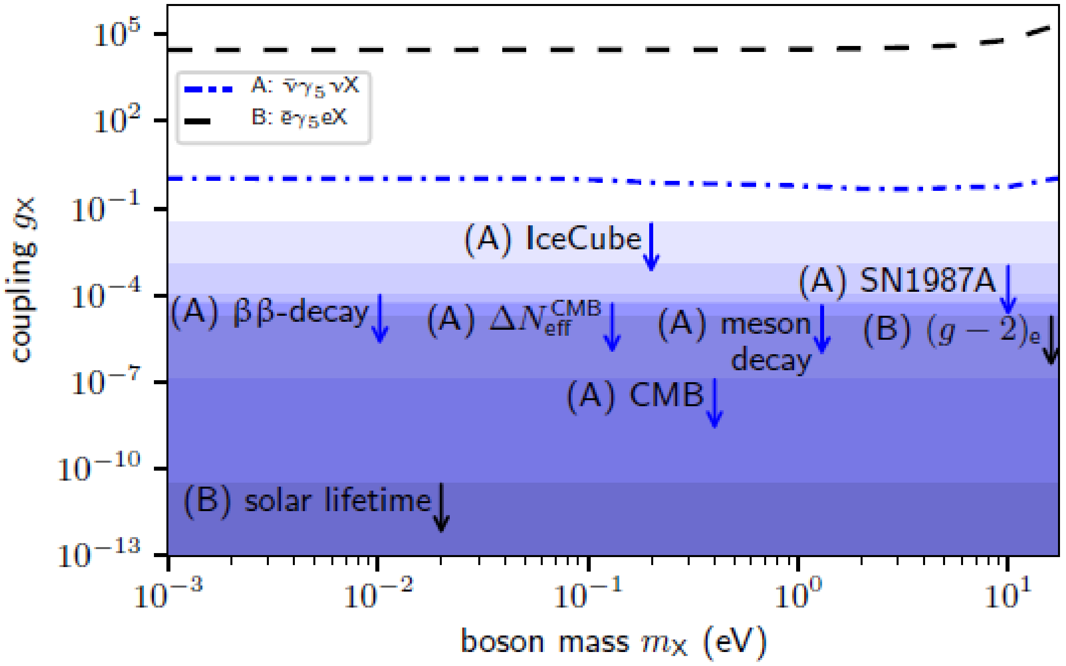
BBN (N_{eff})

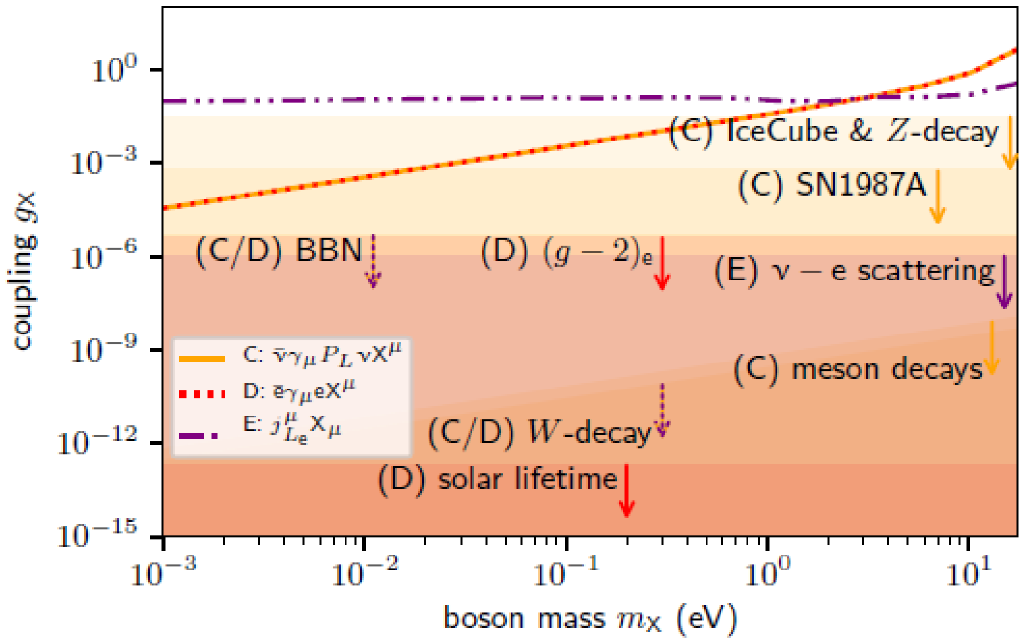
CMB (N_{eff} and modification of the CMB power spectrum (modified self interaction rate alters the free-streaming lenght of the neutrinos)

Model C: $g_{\nu L}\, \bar\nu\gamma^\mu P_L \nu Z'_\mu$	
Z decay	$g_{\nu L} \lesssim 3\times 10^{-2}$ [43]
W decays	$g_{\nu L} \lesssim 2.5\times 10^{-7}\left(\frac{m_{Z'}}{1\,\text{keV}}\right)$ [43]
Meson decays	$g_{\nu L} \lesssim 6\times 10^{-7}\left(\frac{m_{Z'}}{1\,\text{keV}}\right)$ [33, 44]
$\Delta N_{\text{eff}}^{\text{BBN}}$	$g_{\nu L} \lesssim 2.2\times 10^{-7}\left(\frac{1\,\text{keV}}{m_{Z'}}\right)$ $(m_{Z'}\simeq \mathcal{O}(\text{keV}))$ $g_{\nu L} \lesssim 4.6\times 10^{-6}$ $(m_{Z'}\simeq \mathcal{O}(\text{eV}))$ [79]
CMB	$g_{\nu L} \lesssim 1.2\times 10^{-2}\left(\frac{m_{Z'}}{1\,\text{MeV}}\right)$ $(m_{Z'}\gg 1\,\text{eV})$ [85]
Supernova 1987A	$g_{\nu L} \lesssim 12\left(\frac{m_{Z'}}{1\,\text{MeV}}\right)$ $(m_{Z'}\geq 60\,\text{eV})$ $g_{\nu L} \lesssim 5.6\times 10^{-4}$ $(m_{Z'}< 60\,\text{eV})$ [58]
IceCube	$g_{\nu L} \lesssim 0.03$ [60]
Model D: $g_{eV}\, \bar e\gamma^\mu e Z'_\mu$	
W decays	$g_{eV} \lesssim 2.5\times 10^{-7}\left(\frac{m_{Z'}}{1\,\text{keV}}\right)$ [43]
Solar lifetime	$g_{eV} \lesssim 2\times 10^{-13}$ [55]
$\Delta N_{\text{eff}}^{\text{BBN}}$	$g_{eV} \lesssim 4.6\times 10^{-6}$ [79]
$(g-2)_e$	$g_{eV} \lesssim 4.0\times 10^{-6}$ [49, 51]
Model E: $g_{L_e}\, (\bar\nu_e\gamma^\mu P_L \nu_e + \bar e\gamma^\mu e)\, Z'_\mu$	
Z decay	$g_{L_e} \lesssim 3\times 10^{-2}$ [43]
$\Delta N_{\text{eff}}^{\text{BBN, CMB}}$	as models C and D
ν–e scattering	$g_{L_e} \lesssim 10^{-6}$ [43, 52]

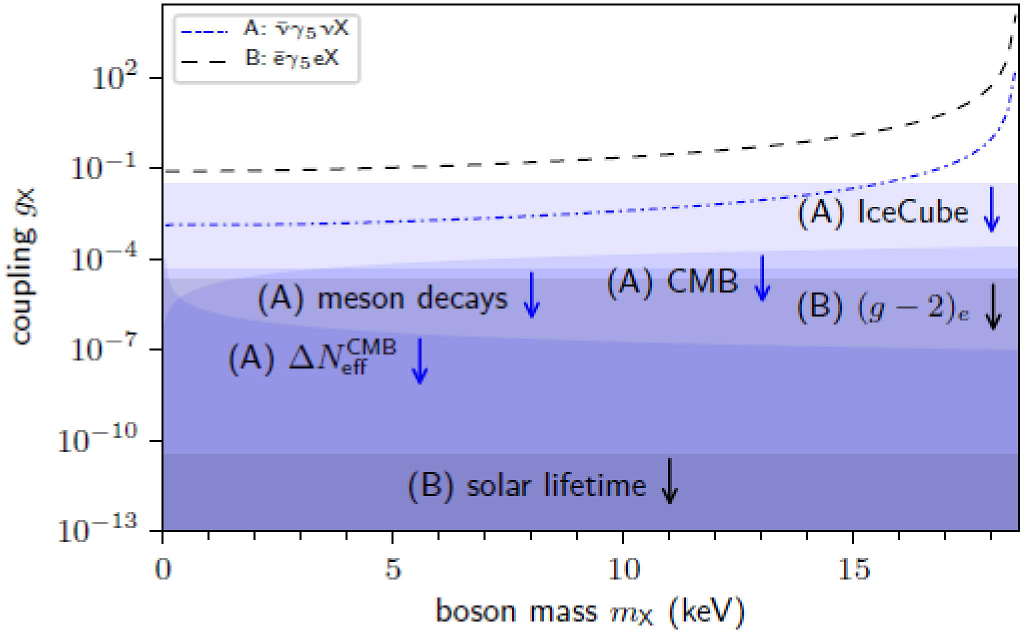
Model A: $i g_{\nu J}\, \bar\nu\gamma_5 \nu\, J$	
Double β decay (only LNV)	$g_{\nu J} \lesssim 10^{-(4\div 5)}$ [53, 54]
Meson decays	$g_{\nu J} \lesssim 4.4\times 10^{-5}$ [45]
CMB	$g_{\nu J} \lesssim 1.2\times 10^{-2}\left(\frac{m_J}{1\,\text{MeV}}\right)$ $(m_J \gg 1\,\text{eV})$ $g_{\nu J} \lesssim 1.2\times 10^{-7}$ $(m_J \ll 1\,\text{eV})$ [85]
Supernova 1987A	$g_{\nu J} \lesssim 10^{-3}$ $(m_J \leq \mathcal{O}(1\,\text{eV}))$ [58]
IceCube	$g_{\nu J} \lesssim 0.03$ [60]
$\Delta N_{\text{eff}}^{\text{CMB}}$	$g_{\nu J} \lesssim 1.6\times 10^{-6}\left(\frac{1\,\text{keV}}{m_J}\right)$ $(m_J\simeq \mathcal{O}(\text{keV}))$ $g_{\nu J} \lesssim 5\times 10^{-5}$ $(m_J\simeq \mathcal{O}(\text{eV}))$ [79, 80]
Model B: $i g_{eJ}\, \bar e\gamma_5 e\, J$	
Solar lifetime	$g_{eJ} \lesssim 3\times 10^{-11}$ [55]
$\Delta N_{\text{eff}}^{\text{BBN}}$	$g_{eJ} \lesssim 5\times 10^{-5}$ [79, 80]
$(g-2)_e$	$g_{eJ} \lesssim 1.8\times 10^{-5}$ [49, 51]

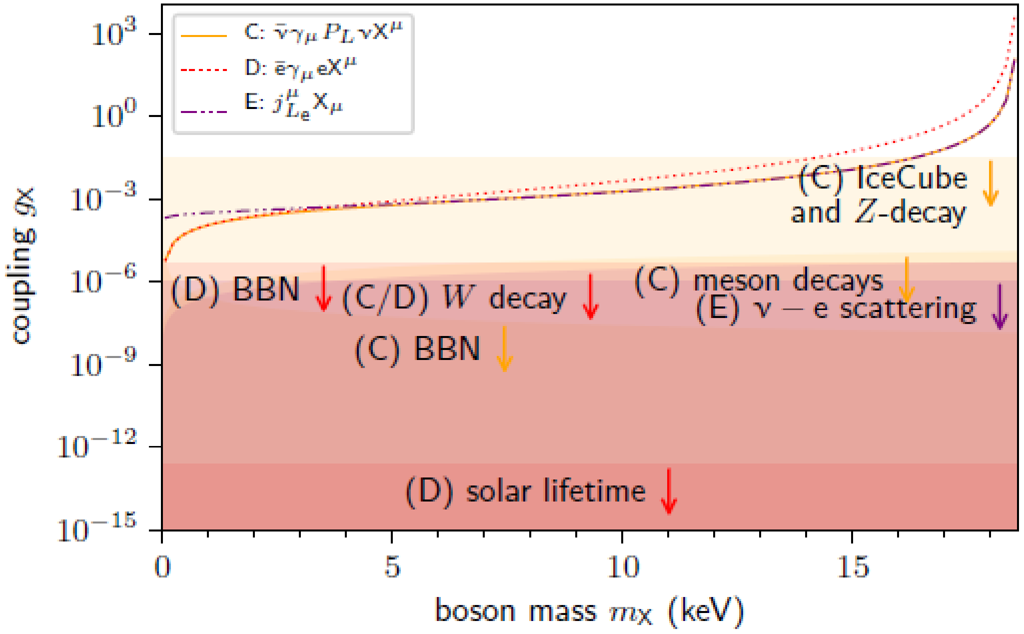
eV scale Bosons





KeV scale Bosons





Conclusions

We have investigated the capability of KATRIN of detecting light bosons.

The projected sensitivity regions are strongly constrained expecially from astro/cosmo constraints.

KATRIN measurements can nevertheless provide a good laboratory complement.