FROM DARK MATTER TO NEUTRINO MASSES

via a recent phase transition

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Based on 2306.XXXX

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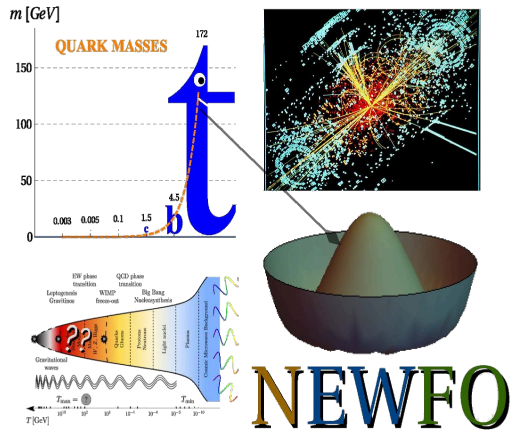
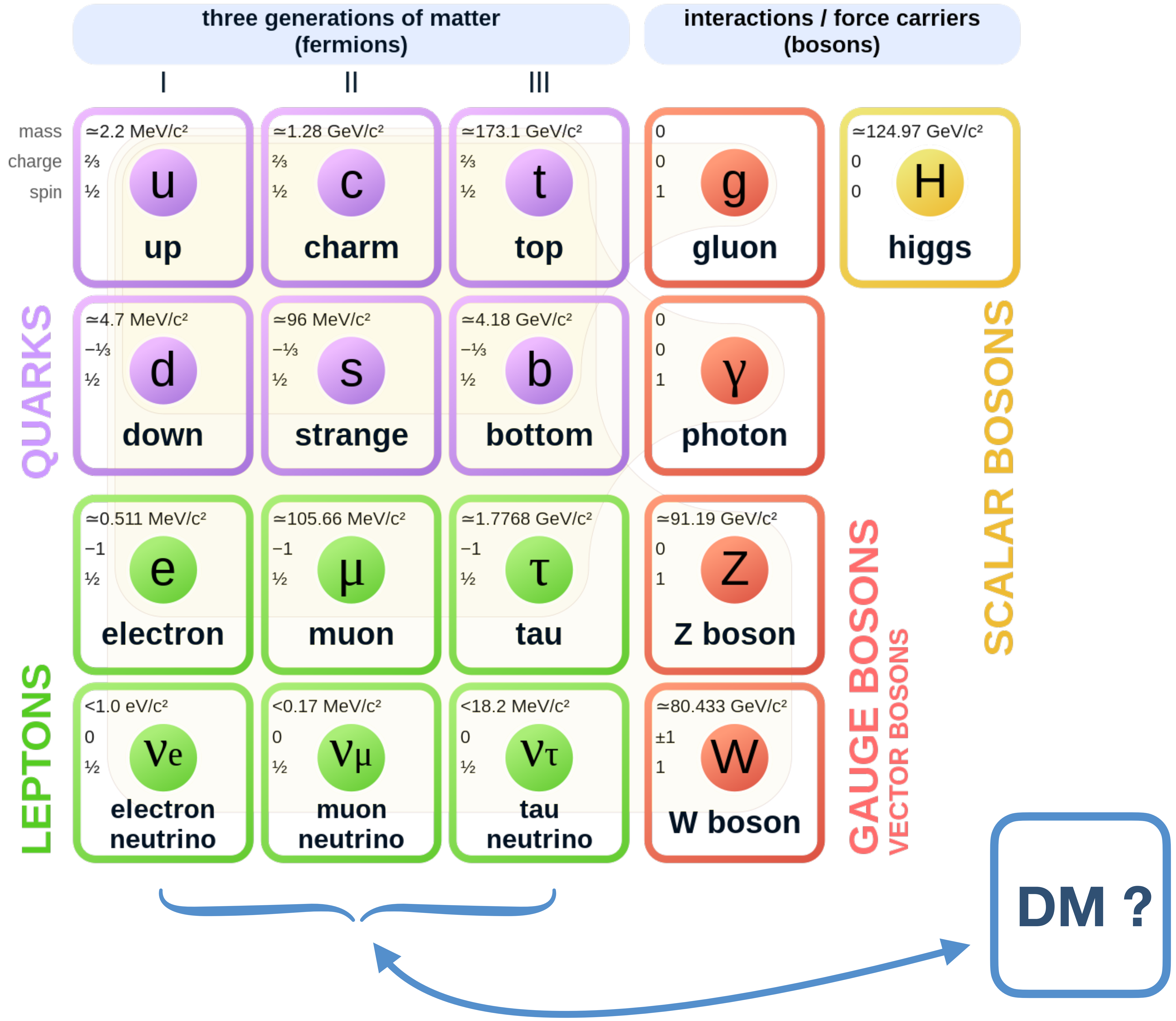


Content…

…of the talk:

- Motivation
- Model
- Neutrino Spectrum
- Revised Parameter Space
- Phase Transition
- Conclusion & Outlook

…of the Standard Model:



Open Questions of SM

Why are neutrinos massive?

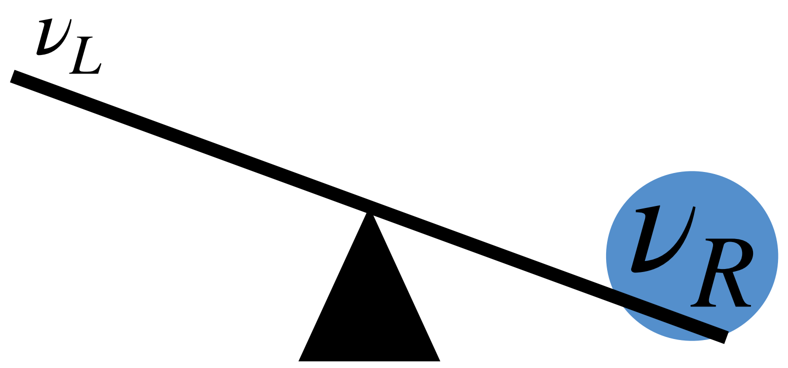
What is the nature of dark matter?

Seesaw Mechanism
(via heavy ν_R)

Sterile Neutrinos
(keV masses)

?

+ many more ideas…



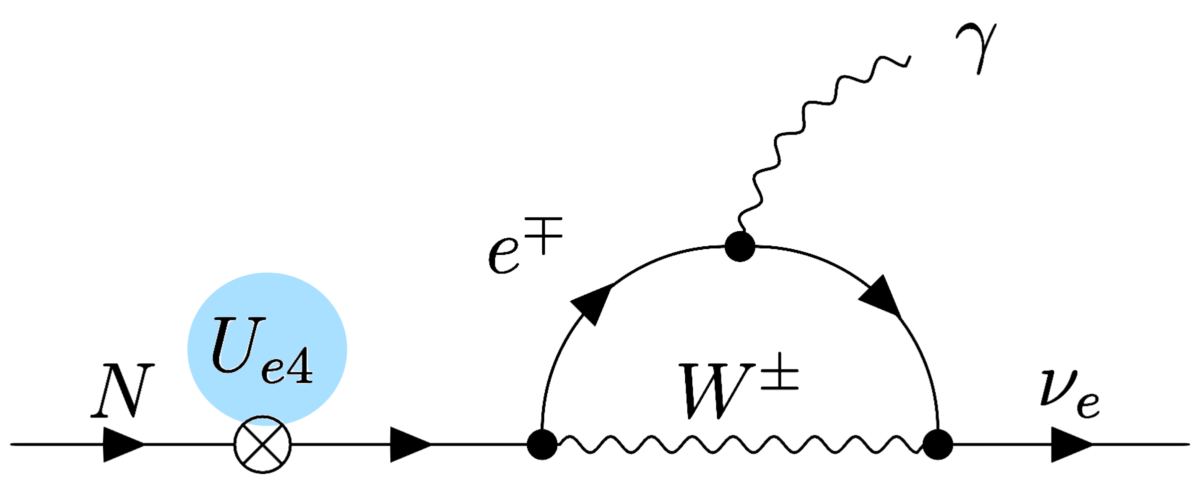
can they be one and the same?

Active Sterile Mixing

$(\nu_L)_\alpha = U_{\alpha i}\nu_i + U_{\alpha I} N_I^c$ where active-sterile mixing $U_{\alpha I} \approx \frac{m_D}{m_I}$

- neutrino masses
  constrained by oscillation measurements
  → lower bound on mixing

- radiative decay $N \to \nu\gamma$
  constrained by X-ray observations
  → upper bound on mixing



add heavier seesaw neutrinos
→ lowers allowed mixing

add additional DM candidate
→ increases allowed mixing

Active Sterile Mixing

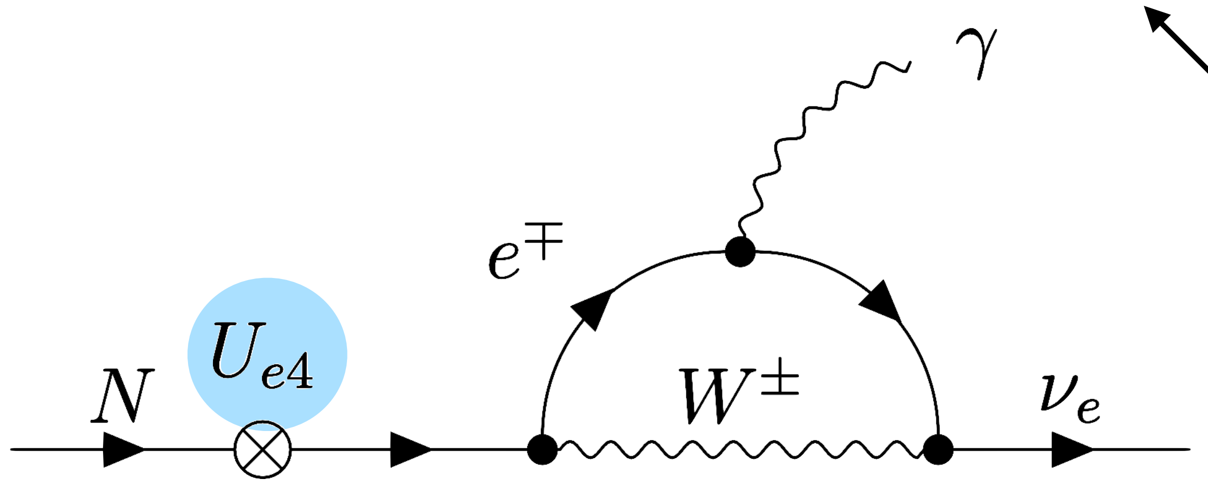
$$(\nu_L)_\alpha = U_{\alpha i}\,\nu_i + U_{\alpha I}\,N_I^c$$ where active-sterile mixing $U_{\alpha I} \approx \dfrac{v\,\epsilon\,Y_{\alpha I}}{m_I}$

- neutrino masses
  constrained by oscillation measurements
  → lower bound on mixing

today

- radiative decay $N \to \nu\,\gamma$
  constrained by X-ray observations
  → upper bound on mixing

from DM dense objects
(10^4 to 10^{10} ly away)



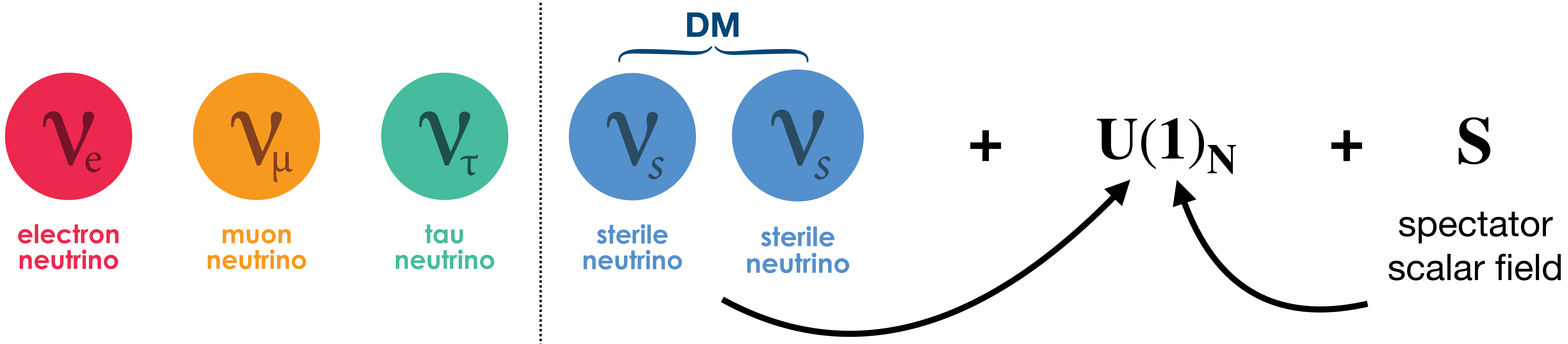
$\epsilon(t)$

add time dependence!

keep keV sterile neutrinos as DM candidate & as seesaw neutrinos

mass varying neutrinos e.g. in
Fardon, Nelson, Weiner (2004)
Brookfield et al. (2006)
Dvali, Funcke (2016)
Huang et al. (2022)
+ more…

Model



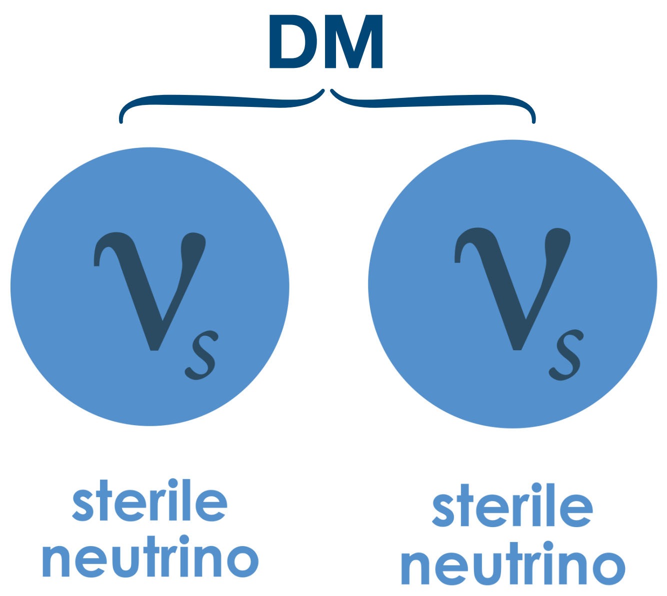
$Q_N(SM) = 0$ $Q_N(\nu_s) = \pm 1$ $Q_N(S) = -1$

- In the recent universe, the potential of the spectator scalar field becomes tachyonic ⇒ field starts rolling ⇒ expectation value $\langle S \rangle (t > t_{SB}) \neq 0$
- Active neutrino masses are induced via dim5-operator + seesaw type I

$$y_{\alpha 1} \frac{S^c}{\Lambda_S} \bar{L}_\alpha \tilde{H} \nu_{R1}$$

$$y_{\alpha 2} \frac{S}{\Lambda_S} \bar{L}_\alpha \tilde{H} \nu_{R2}$$

$$\hat{M} = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$



Dark Matter

- Majorana mass matrix: $M_R = \begin{pmatrix} \epsilon^2 M_{11} & M_{12} \\ M_{12} & \epsilon^2 M_{22} \end{pmatrix}$ with $\epsilon = \frac{\langle S \rangle}{\Lambda_S} \lll 1$ and $Q_N(\nu_{R1}) = -1$, $Q_N(\nu_{R2}) = +1$

- $m_{DM} = M_{12} = \mathcal{O}$(keV) mass effectively unchanged once $\langle S \rangle \neq 0$

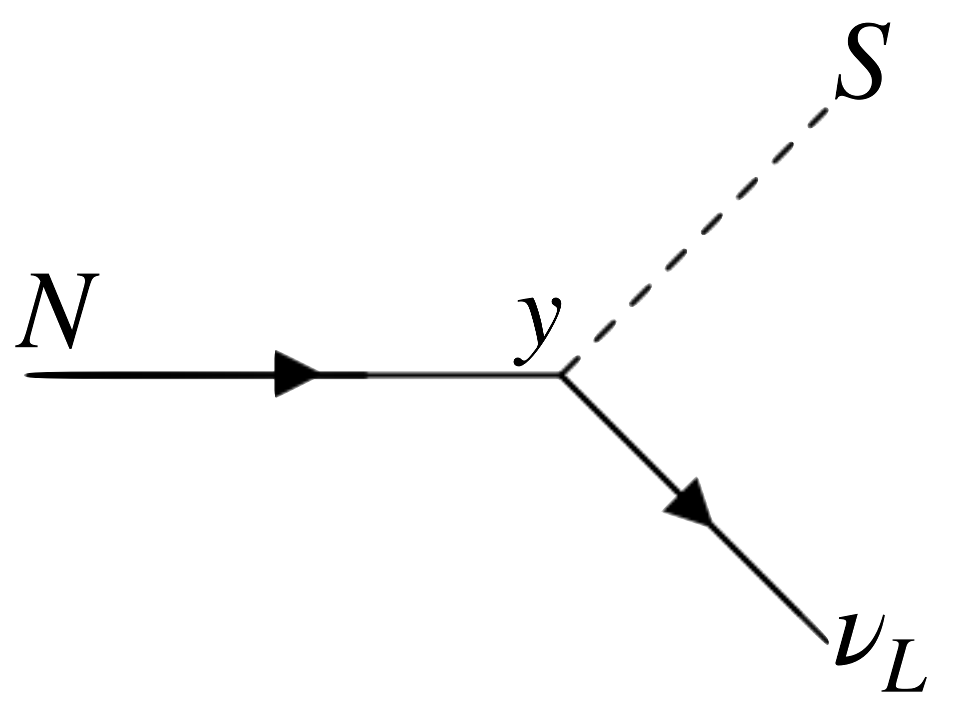
- production mechanism: not specified

- lifetime requires $\Lambda_S \gtrsim$ a few $\times 10^4$ GeV

$$y \sim \frac{v_{EW}}{\Lambda_S} \quad \text{and} \quad \Gamma \sim \frac{1}{16\pi} \frac{1}{m_{DM}} \left(\frac{v_{EW}}{\Lambda_S} \right)^2$$

$\tau = \Gamma^{-1}$

$\tau_{\text{universe}} \sim 10^{10}$ yrs

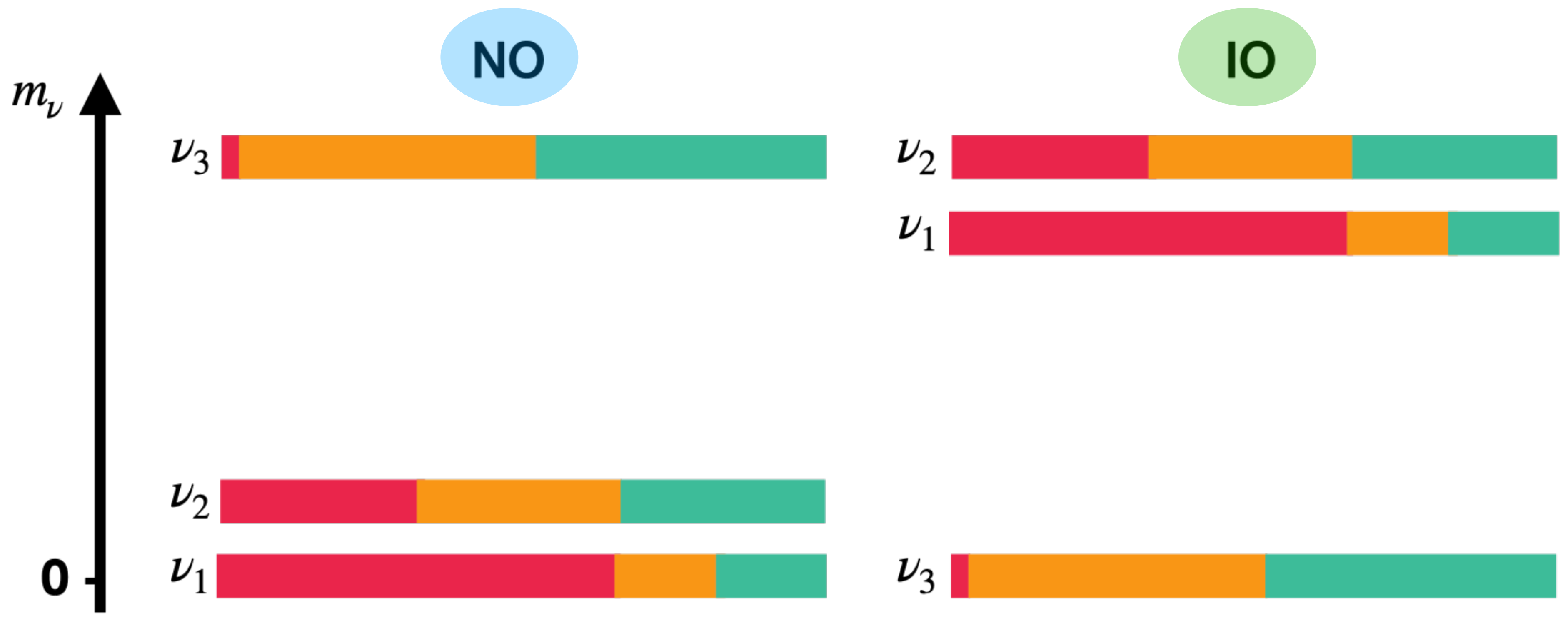


if $m_S > m_{DM}$ decay kinematically forbidden before onset of phase transition

Neutrino Spectrum

- Casas-Ibarra parametrisation with best-fit values & $m_s \in [0.4, 50]$ keV
  hep-ph/0103065, hep-ph/0511136
- Yukawa couplings $\mathcal{O}(10^{-2} - 10) \Longrightarrow$ correct spectrum for $\epsilon \sim 10^{-10}$ $\longleftarrow \frac{\langle S \rangle}{\Lambda_S}$

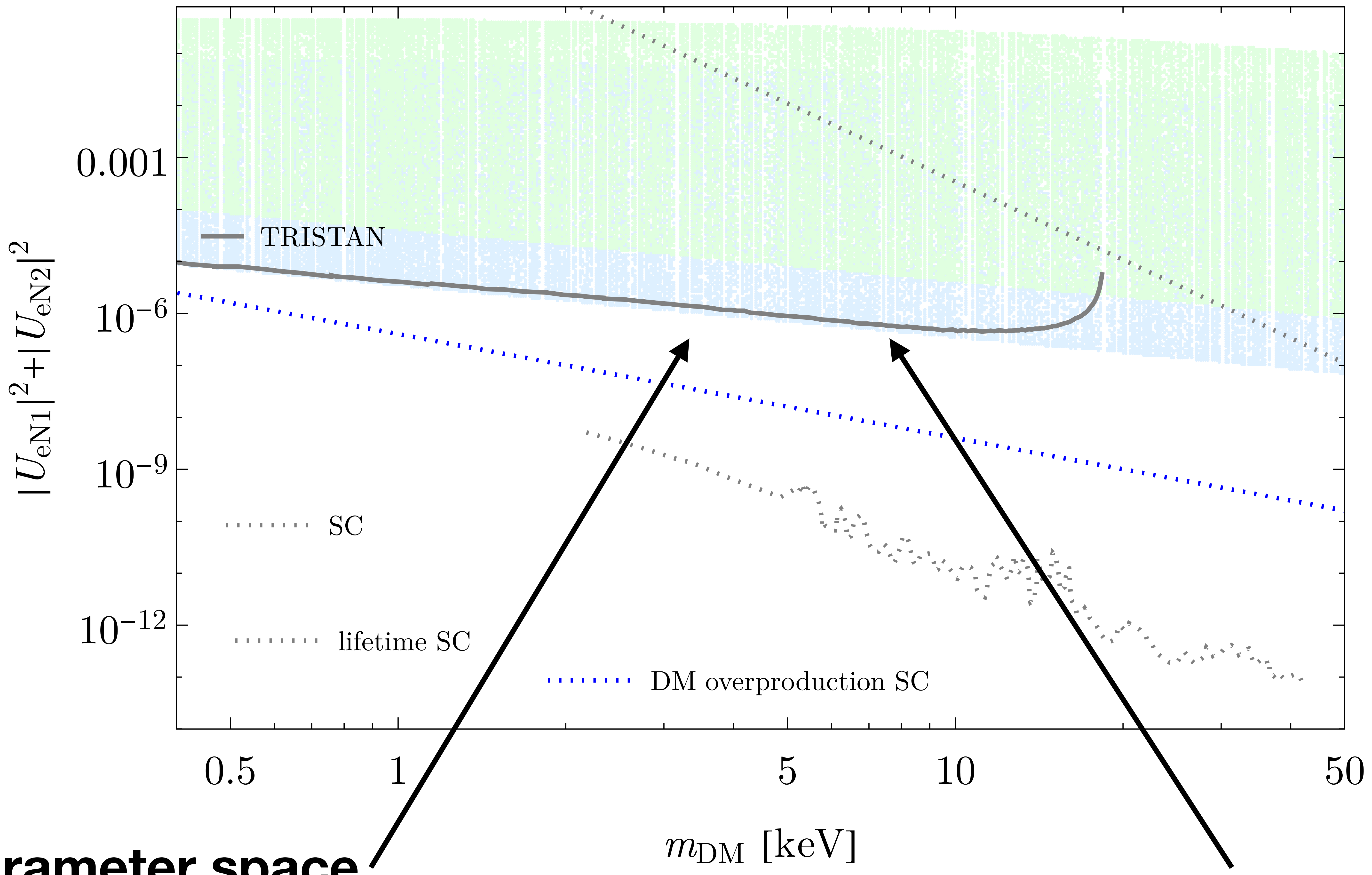
$y_{eff} = y\,\epsilon$



NuFIT 5.3 (2024)

without SK atmospheric data		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
	$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$
	$\theta_{12}/^\circ$	$33.66^{+0.73}_{-0.70}$	$31.60 \to 35.94$	$33.67^{+0.73}_{-0.71}$	$31.61 \to 35.94$
	$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.407 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
	$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
	$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00058}$	$0.02029 \to 0.02391$	$0.02219^{+0.00059}_{-0.00057}$	$0.02047 \to 0.02396$
	$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.11}$	$8.19 \to 8.89$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.90$
	$\delta_{CP}/^\circ$	197^{+41}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.511^{+0.027}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.024}$	$-2.581 \to -2.409$

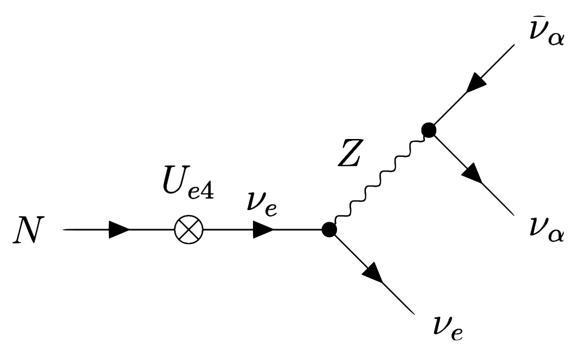
Parameter Space



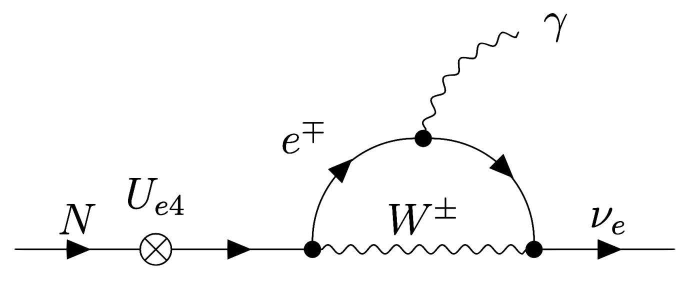
Parameter space for correct neutrino spectrum excluded!

TRISTAN regime excluded!

- NO: blue
- IO: green
- **SC: standard case**
- lifetime: $N \rightarrow 3\nu$



- X-ray: $N \rightarrow \gamma\,\nu$



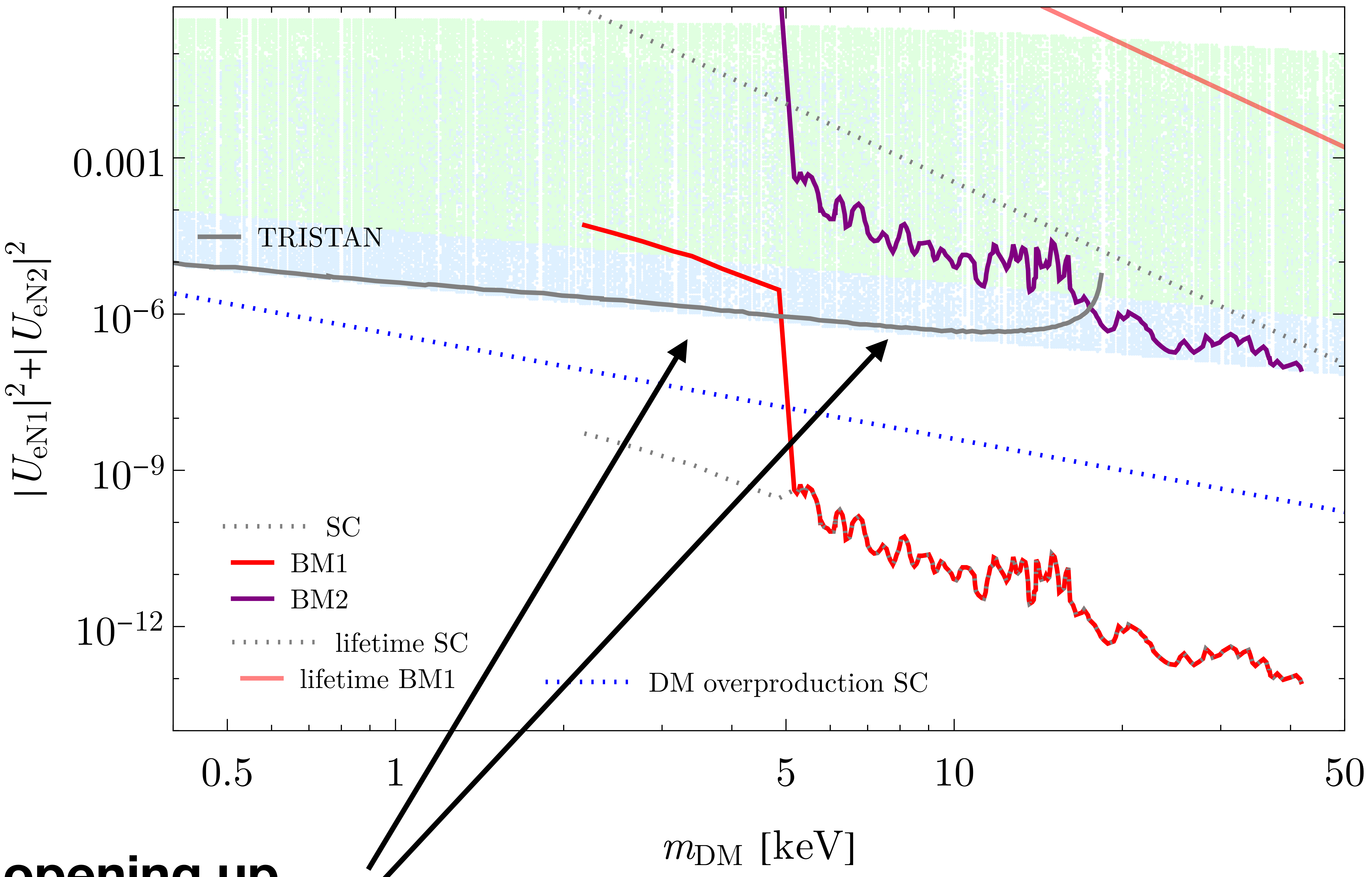
- TRISTAN: KATRIN upgrade

arXiv:1810.06711

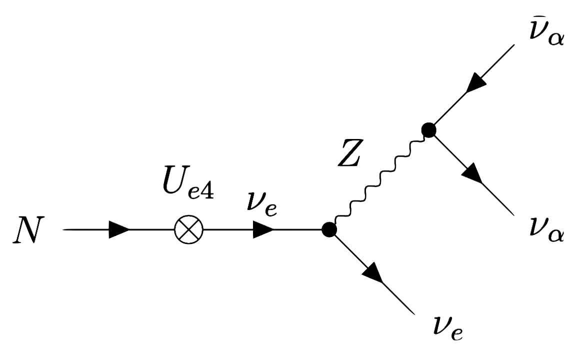
Preliminary

Parameter Space

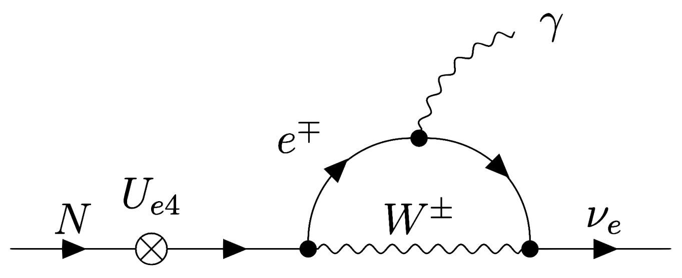
no problem with DM overproduction: $U_{eN} = 0$ in early universe



- NO: blue
- IO: green
- SC: standard case
- lifetime: $N \to 3\nu$



- X-ray: $N \to \gamma \nu$



- TRISTAN: KATRIN upgrade

arXiv:1810.06711

opening up of parameter space!

BM1: $10^{-4}H_0$ ago : $V(S) \propto -\mu^2 S^2$ with $\mu = 5 \times 10^5 H_0$

BM2: $10^{-5}H_0$ ago : $V(S) \propto -\mu^2 S^2$ with $\mu = 10^7 H_0$

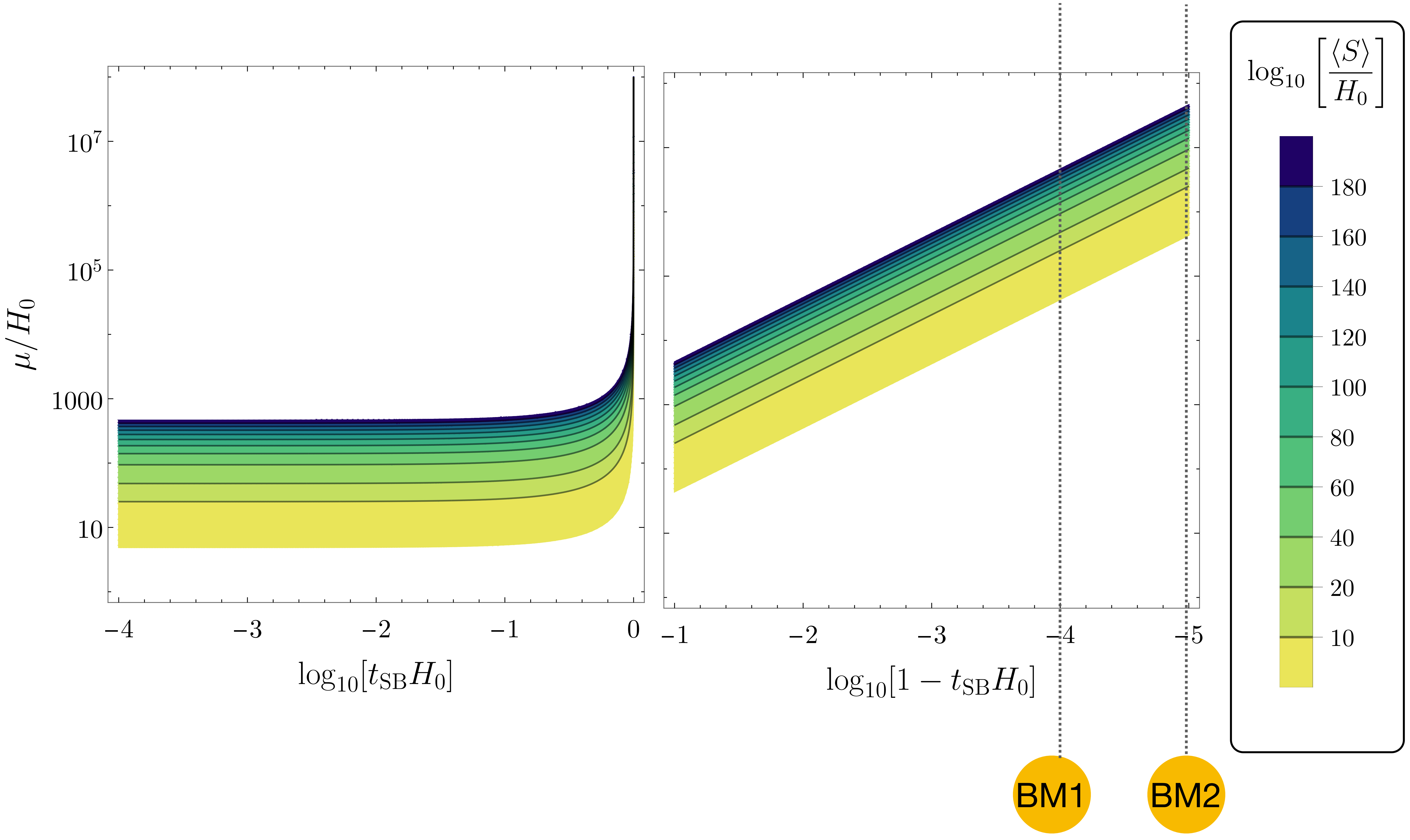
Phase Transition

$H_0 \sim 10^{-33}$ eV
BM1: $\sim 10^6$ years ago
BM2: $\sim 10^5$ years ago

effective description

$$V(S) = V_0 + \frac{1}{2}\mu^2(t)S^2 + V_{\rm HO}(S)$$

higher order operators



- from $t \geq t_{SB}$: $V(S) \propto -\mu_{SB}^2 S^2$
  $\Rightarrow$ field evolves as $S(t) \propto \exp(t)$
- $\log_{10}\frac{\langle S\rangle}{H_0} \in [36{,}50] \Rightarrow$ correct neutrino spectrum possible ✓

Non-Minimal Coupling

possible incarnation

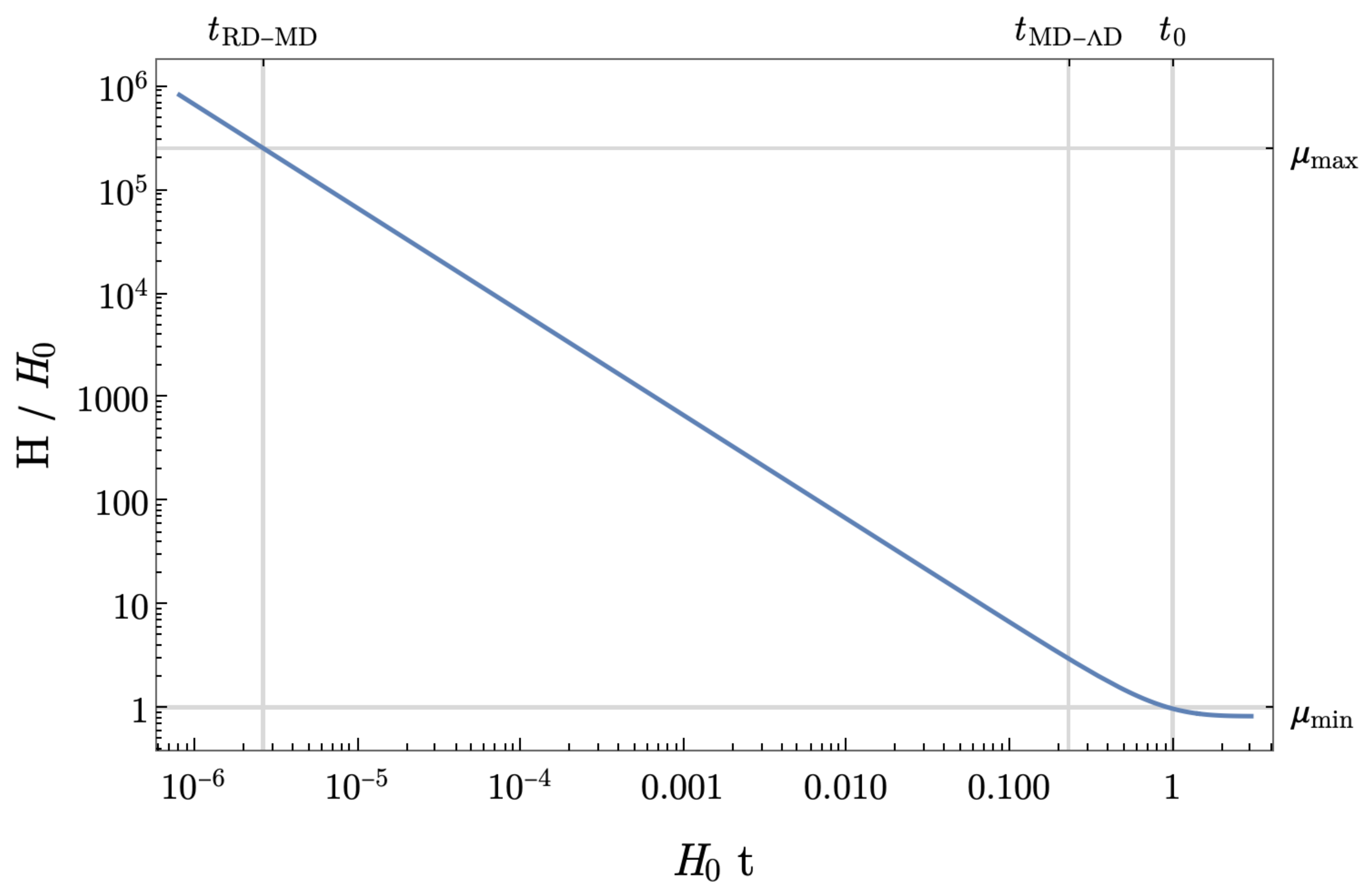
$$V(S) = V_0 - \frac{1}{2}\mu_{SB}^2 S^2 + \frac{1}{2}\xi S^2 R + V_{\mathrm{HO}}(S)$$

higher order operators

$$R = 3(1 - w_{\mathrm{eff}}(t))H^2(t)$$

Ricci Scalar

- prototypical cosmological phase transition
  → see talk by Javier Rubio on Thursday
- R tracks Hubble parameter and acts as „cosmological clock“
- maximal value for μ_{SB}^2 to remain stable during radiation domination → BM1
- open question: small scale effects?



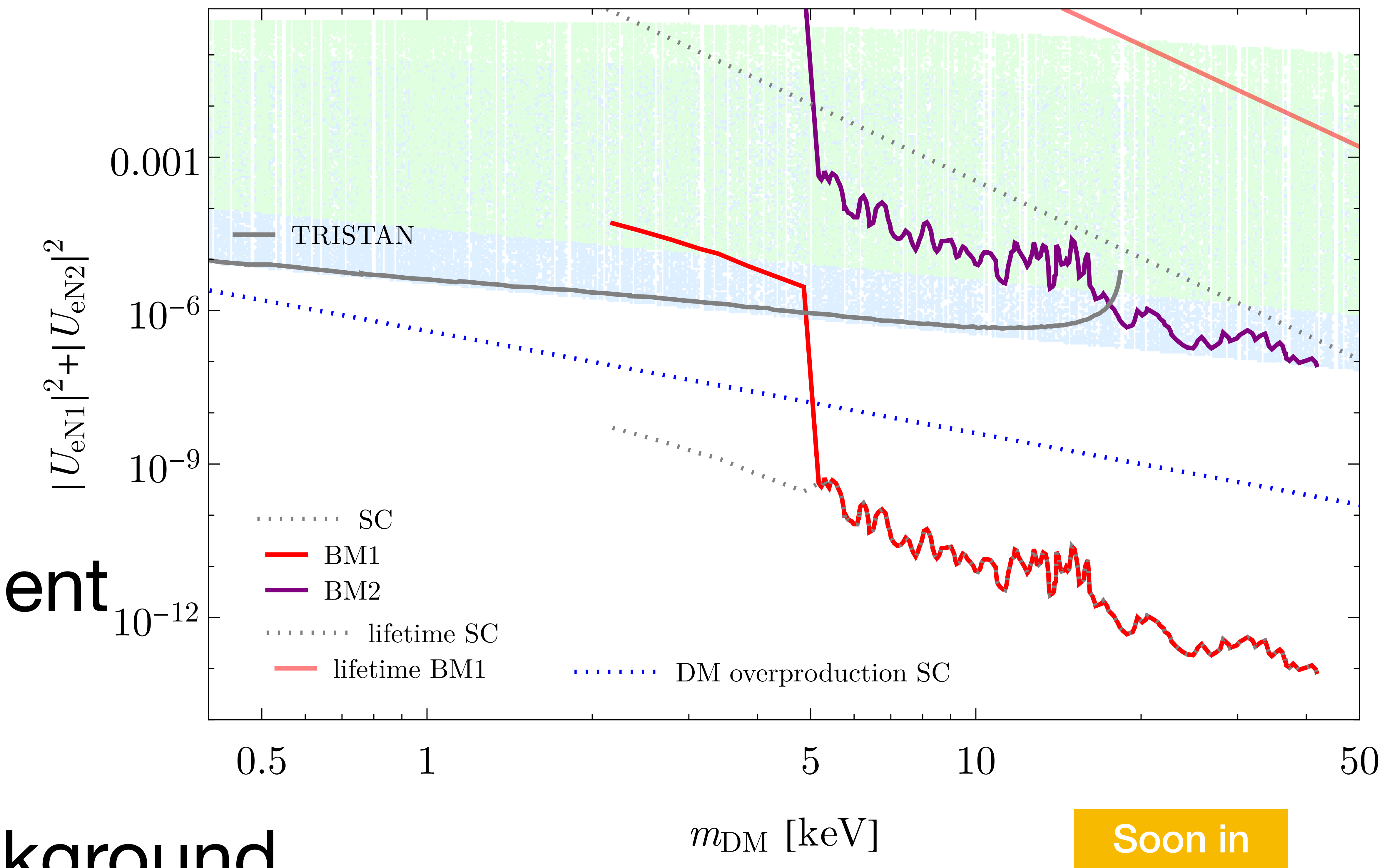
Conclusion & Outlook

- SM + 2 RH neutrinos + spectator scalar field to explain
  ⇒ keV sterile neutrino DM ✓
  ⇒ origin of neutrino masses ✓

- cosmologically massless neutrinos, gain time-dependent mass recently

- probable @ KATRIN/TRISTAN experiment & **not in conflict** with X-ray bounds

- future: diffuse supernova neutrino background
  (far) future: will observe DM decay

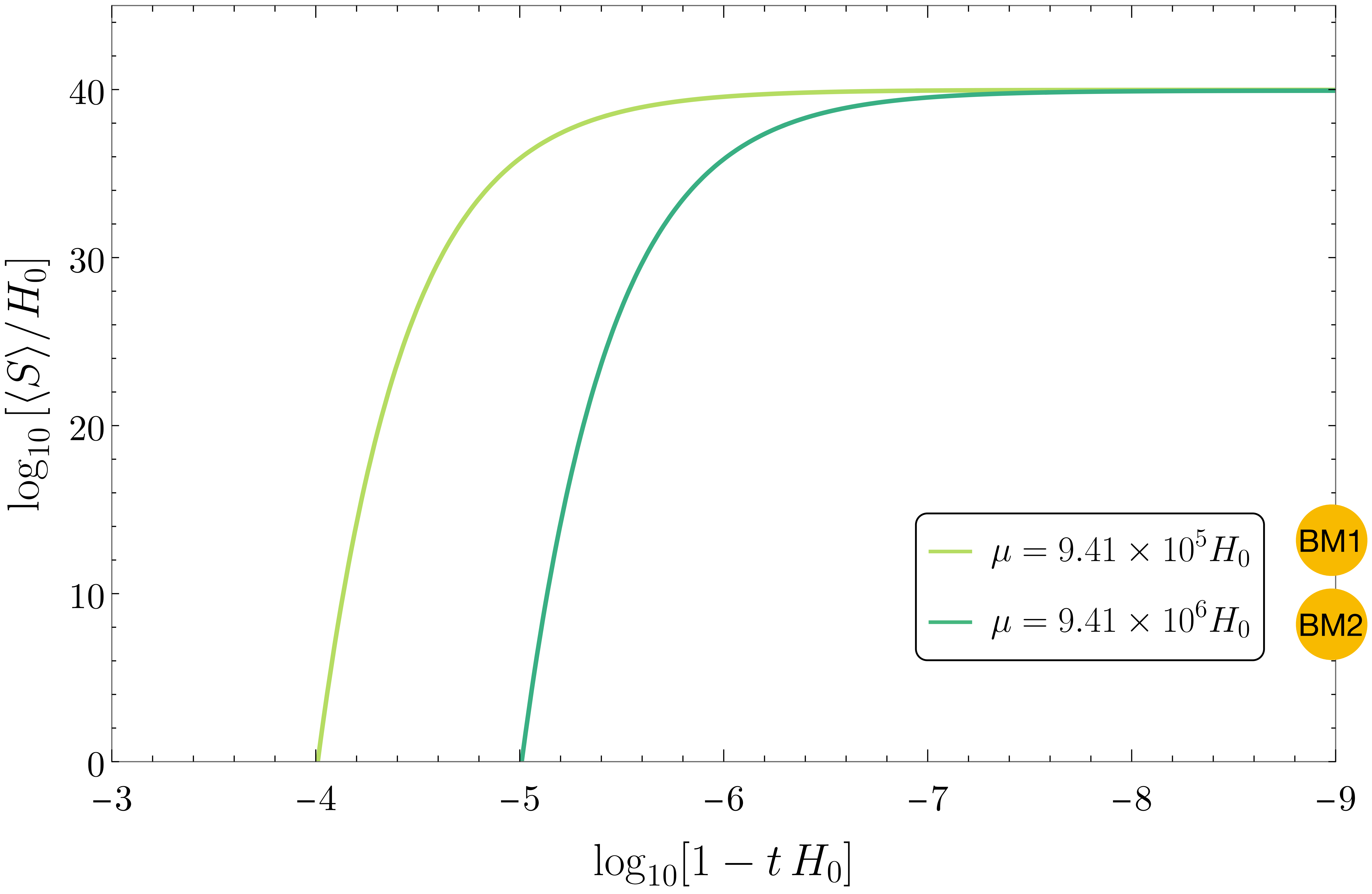


Soon in 2406.XXXX

de Gouvêa et al. (2022)

Back-Up Slides

Expectation Value of S



$\langle S\rangle = \mathcal{O}(10)$ MeV

$\implies \Lambda_S \sim \mathcal{O}(10^8)$ GeV

exemplary values, can change as long as $\epsilon \sim 10^{-10}$

Variation of Constants + 5th Forces

singlet: $\frac{S}{\Lambda_S}\,\frac{S^c}{\Lambda_S}$ can be added to any operator **today: $\epsilon^2 \sim 10^{-20}$**

$$\Rightarrow \begin{cases} m_f \to m_f\left(1 \pm \epsilon(t)^2\right) \\ m_V^2 \to m_V^2\left(1 \pm \epsilon(t)^2\right) \\ \alpha \to \dfrac{\alpha}{1 \mp \epsilon(t)^2} \end{cases}$$

$$\mathcal{L} \supset -\frac{1}{4e^2} F^{\mu\nu} F_{\mu\nu} \left(1 \pm \epsilon(t)^2\right)$$

natural nuclear reactor Oklo constrains

$$\boxed{\mathrm{d}\ln\alpha/\mathrm{d}\ln a \leq (2.5 \pm 3.5) \times 10^{-9}}$$ ✓

5th force searches more sensitive to terms linear in $S \Rightarrow$ here no problem ✓

Higgs portal assumed to be negligible ✓

Casas-Ibarra Parametrisation

hep-ph/0103065
hep-ph/0511136

here: slightly different conventions than original Casas-Ibarra.

We can define

$$d_m^{-1} = \text{diag}(0, 1/m2, 1/m3)\ (\text{NO})\ /\ d_m^{-1} = \text{diag}(1/m1, 1/m2, 0)\ (\text{IO})$$

and use that

$$(\sqrt{d_m}\sqrt{d_m^{-1}})^T(\sqrt{d_m}\sqrt{d_m^{-1}}) = \text{diag}(0,1,1) \equiv R_{NO}^T R_{NO} \quad \text{for NO,}$$

$$(\sqrt{d_m}\sqrt{d_m^{-1}})^T(\sqrt{d_m}\sqrt{d_m^{-1}}) = \text{diag}(1,1,0) \equiv R_{IO}^T R_{IO} \quad \text{for IO,}$$

to find the Yukawa matrix Y[4]

$$Y = \frac{1}{\epsilon v}\left(U_R^*\sqrt{d_M}R\sqrt{d_m}U^\dagger\right)^T \tag{2.12}$$

in terms of known parameters, where we use the best fit values for masses, mixings, and CP violation from [27]. The matrices R have the form

$$R_{NO} = \begin{pmatrix} 0 & \cos z & \xi \sin z \\ 0 & -\sin z & \xi\cos z \end{pmatrix} \text{ and } R_{IO} = \begin{pmatrix} \cos z & \xi\sin z & 0 \\ -\sin z & \xi\cos z & 0 \end{pmatrix} \tag{2.13}$$

where z is complex, and $\xi = \pm 1$.

M_R can be diagonalised as

$$d_M = U_R^T M_R U_R\,,$$

which can be inverted to find

$$M_R^{-1} = U_R\, d_M^{-1}\, U_R^T = \left(\sqrt{d_M^{-1}}U_R^T\right)^T\left(\sqrt{d_M^{-1}}U_R^T\right).$$

with

$$U_R = \begin{pmatrix} i\cos\theta & \sin\theta \\ -i\sin\theta & \cos\theta \end{pmatrix}$$

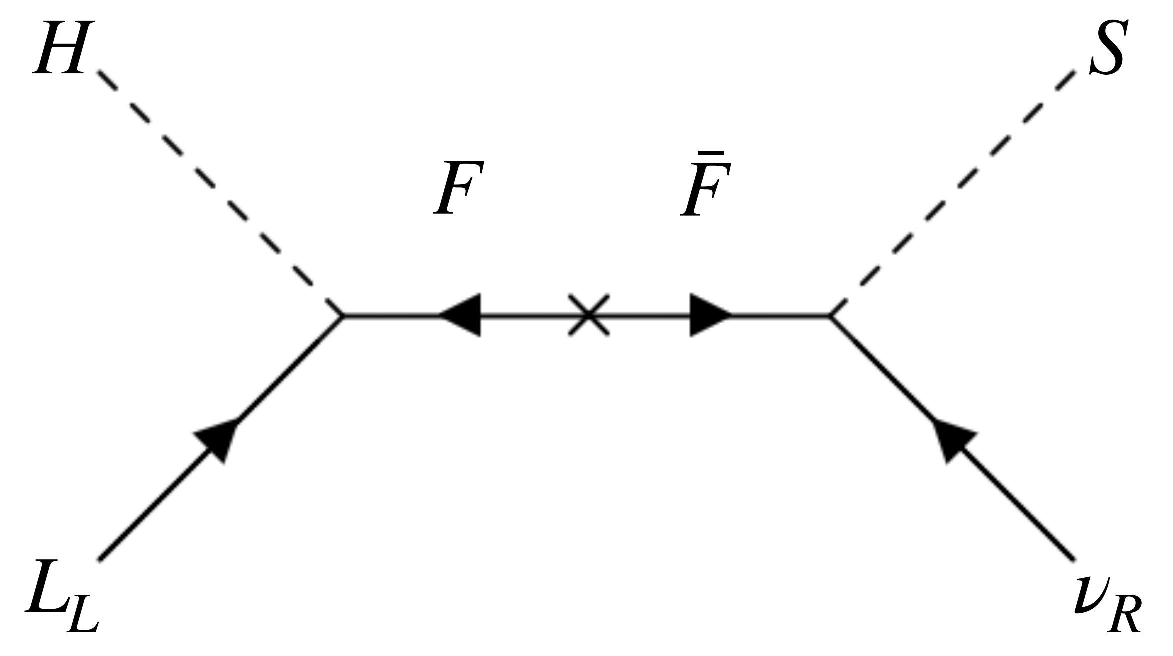
in the case of two RH neutrinos, where $\theta = \pi/4 + \mathcal{O}(\epsilon^2) \approx \pi/4$.

Possible UV-Completion

- like Froggatt-Nielsen mechanism (only for neutrinos)
- heavy vector-like messenger fermions F
- scale of new physics set by mass of F and coupling Y:

$$\boxed{\Lambda_S = \frac{M_F}{Y}}$$

Feynman diagram before integrating out VL fermions:



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X-Ray Bounds

Search	Object	Reason
[53]	Milky Way	40 keV $\leq m_s$
[54]	Milky Way	40 keV $\leq m_s$
[55]	dwarf Ursa Minor	$d \sim 2.3 \times 10^5$ lyrs
[56]	dwarf Draco	$d \sim 2.6 \times 10^5$ lyrs
[57]	dwarf satellite galaxies + M31	$d \gtrsim$ a few $\times 10^5$ lyrs
[58]	dwarf spheroidal galaxies	$d \gtrsim$ a few $\times 10^5$ lyrs
[59]	galaxy clusters	$d \gtrsim 5 \times 10^5$ lyrs
[60]	M31	$d \sim 2.5 \times 10^6$ lyrs
[61]	M31	$d \sim 2.5 \times 10^6$ lyrs
[62]	Coma & Virgo cluster	$d \gtrsim$ a few $\times 10^7$ lyrs
[63, 64]	Perseus cluster	$d \sim 2.4 \times 10^8$ lyrs
[65]	Bullet cluster	$d \sim 3.7 \times 10^9$ lyrs
[66]	XRB	see text
[67]	XRB	see text
[68]	XRB	see text
[69]	XRB	see text
[70]	XRB	see text
[71]	CXB	see text
[72]	CXB	see text
[73]	galactic center	model-dependent

Table 1: X-Ray limits that can be softened by BM1 and BM2.

Search	Object	Where
[74]	galactic center	$m_s = 5 - 16$ keV
[75]	Milky Way	$m_s = 6 - 40$ keV
[76]	galactic bulge	$m_s = 6 - 40$ keV
[77]	galactic bulge	$m_s = 10 - 40$ keV
[78]	galactic center & MW halo	$m_s = 20 - 50$ keV

Table 2: X-Ray limits that can be softened by BM2, but not by BM1.

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TRISTAN Detector

$$\frac{d\Gamma}{dE} = \cos^2\Theta \frac{d\Gamma}{dE}\left(m_\beta^2\right) + \sin^2\Theta \frac{d\Gamma}{dE}\left(m_s^2\right)$$

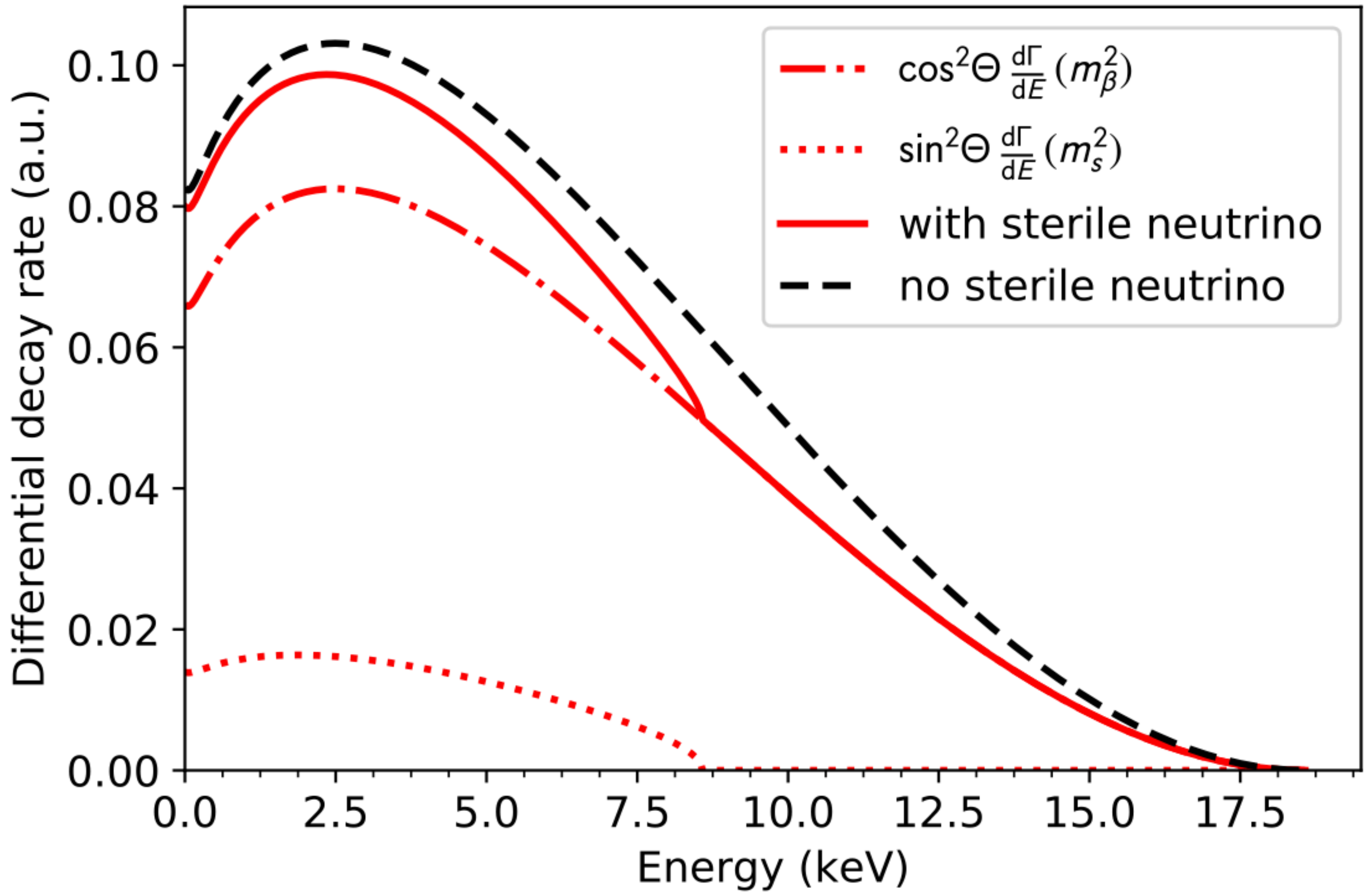

FIG. 1. Imprint of a heavy, mostly sterile, neutrino with a mass of $m_s = 10\,\mathrm{keV}$ and an unphysical large mixing angle of $\sin^2\Theta = 0.2$ on the tritium β-decay spectrum.

- KATRIN Collaboration
  Mertens et al. (2019)
- tritium-beta decay
- electron-flavor neutrino emitted along with electron
- spectrum related to superposition of mass eigenstates

Neutrinoless Double Beta Decay

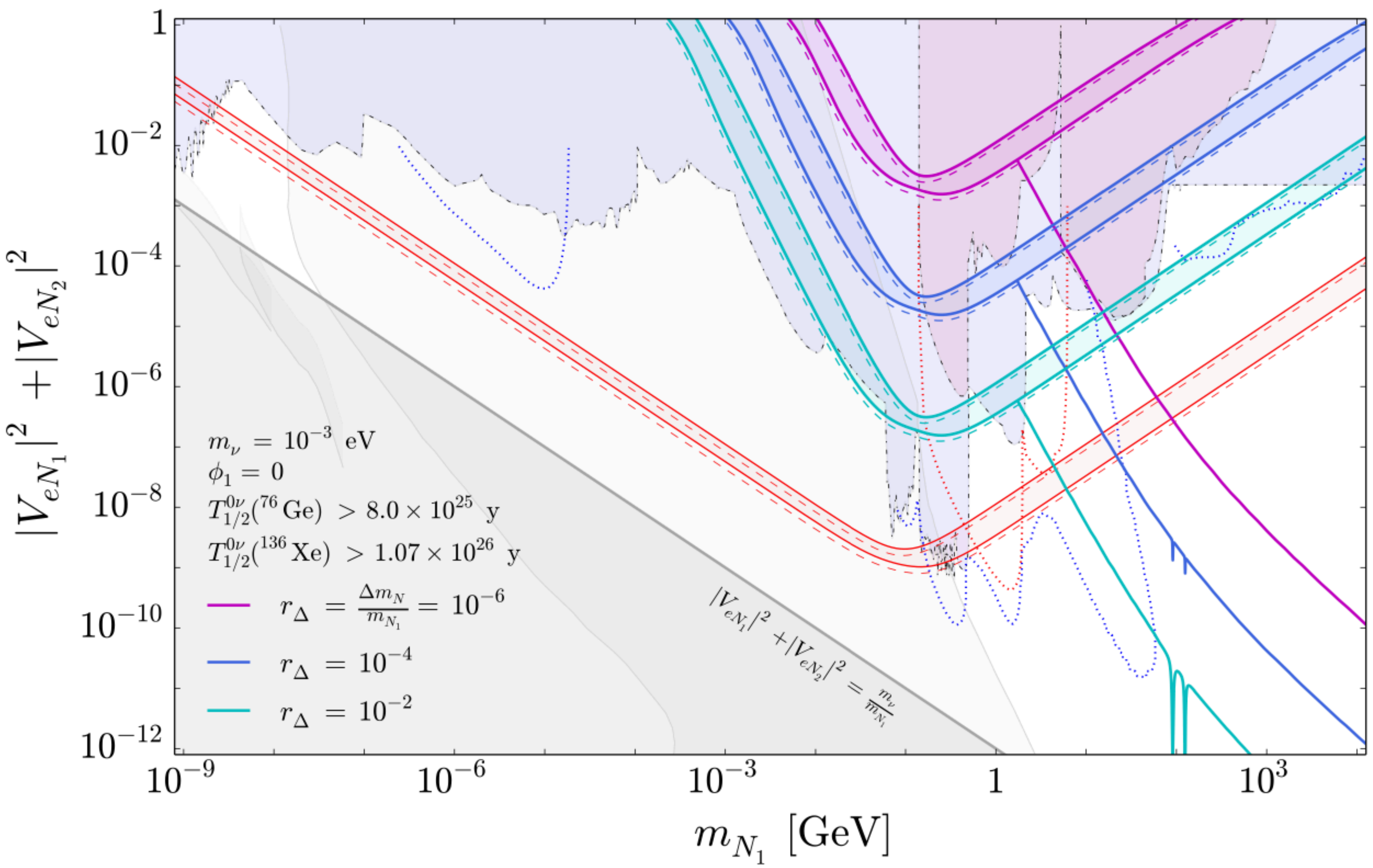

Figure 9: Upper limits on the sum of squared active-sterile mixings for three values of the sterile neutrino mass splitting ratio $r_\Delta = \frac{\Delta m_N}{m_{N_1}} \ll 1$. We show the limits from ^{136}Xe (solid) and ^{76}Ge (dashed) experiments with the bands indicating the respective uncertainties. The red curves highlight the limit in which $0\nu\beta\beta$ decay is driven by a single sterile neutrino. The curves sloping down to the lower right indicate the upper bounds by enforcing $|\delta m_\nu^{1-\text{loop}}| < 0.1 m_\nu$. These constraints are compared with the current and future sensitivities of LNC (blue shaded/dotted) and LNV (red shaded/dotted) searches, cf. Figs. 6 and 7.

- Bolton, Deppisch, Bhupal Dev (2020)
- interference effects between two sterile neutrinos with small mass splitting
- ⇒ constraints negligible for sterile neutrino masses in our model!

