

1) MODEL

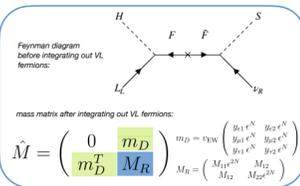


$$\mathcal{L}_{FN}^{\text{eff}} = -y_{iJ} \left(\frac{S}{\Lambda_S} \right)^{Q_{FN}(\nu_{R,i})} \bar{L}_i \tilde{H} \nu_{R,J} - \frac{M_{IJ}}{2} \left(\frac{S}{\Lambda_S} \right)^{Q_{FN}(\nu_{R,I}) + Q_{FN}(\nu_{R,J})} \bar{\nu}_{R,I}^c \nu_{R,J} + h.c.$$

RECIPE FOR FROGGATT-NIELSEN (FN) MECHANISM ONLY IN NEUTRINO SECTOR:

- $U(1)_{FN}$ **symmetry** under which Standard Model (SM) fields uncharged
- non-minimally coupled **scalar singlet field S** with tachyonic mass and FN charge -1
- **heavy vector-like FN fields F** → sets scale of new physics Λ_S
- **even number of RH neutrinos** → no massless sterile ν_s while $\langle S \rangle = 0$

- active neutrinos remain **massless until $\langle S \rangle \neq 0$**
- phase transition starts during **matter domination**
- **tiny Yukawa couplings** are induced $y \sim \mathcal{O}(1) \times (\langle S \rangle / \Lambda_S)^N$
- masses & mixings **carry time dependence**
- sterile neutrinos **long-lived DM candidate**
- scalar field potentially acts as **dynamical dark energy**



MINIMAL REALISATION:

- 2 RH neutrinos ν_R^1 and ν_R^2
- ν_R FN charges $\pm N = \pm 1$
- \mathcal{O} (keV) Majorana masses → ν_s as DM candidates
- relevant parameter: $\epsilon \equiv \langle S \rangle / \Lambda_S$

2) MASS AND MIXING

MASS GENERATION:

- $M_\nu = -m_D(M_R)^{-1}m_D$
- seesaw mechanism → suppression by $1/M_i$ (*subdominant effect*)
- late phase transition → suppression by $(\langle S \rangle / \Lambda_S)^N \ll 1$ (*dominant effect*)
- $M_{IJ} \in (0.4, 50) \text{ keV}$, $\epsilon^N \in (10^{-8} - 10^{-13})$, $y_{IJ} \in (10^{-2} - 1)$ correctly reproduce NO and IO

MIXING:

- mass eigenstates \neq flavour eigenstates
- mixing described by PMNS matrix U
- charged leptons do not carry $U(1)_{FN}$ charge → mass matrix diagonal
- **usual problem of a single FN field non-existent** (i.e. small atmospheric neutrino mixing due to cancellation in hierarchies of mass matrices)
- precise parameter space for two (four) sterile neutrinos → *ongoing work*

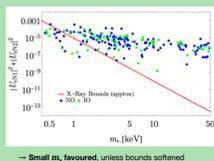
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3) ACTIVE - STERILE MIXING

LH neutrinos are a mixture of active and sterile mass eigenstates. The active-sterile mixing can be constrained both through astrophysical and direct detection bounds. In our model, the mixing carries a time-dependence due to the ongoing phase transition.

$$(\nu_L)_\alpha = U_{\alpha i} \nu_i + U_{\alpha j} N_j^c \text{ where active-sterile mixing } U_{\alpha i} \approx (m_D)_{\alpha i} / M_I$$



X-RAY BOUNDS:

- radiative decay $N \rightarrow \nu + \gamma$ → monochromatic X-ray signal (once $\langle S \rangle \neq 0$)
- range of sources: XRB, galaxy clusters, dSp galaxies, Milky Way halo
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DIRECT DETECTION:

- not sensitive to current neutrino-less double beta decay bounds due to small sterile mass splitting see Bolton, Deppisch, Dev (2020)
- **sensitive to future LNC measurements** → KATRIN upgrade TRISTAN will probe predicted parameter space see Mertens et al. (2018)

4) STERILE NEUTRINO DARK MATTER

The sterile neutrinos form a **2-component dark matter** candidate with mass $M_{1,2} \sim \mathcal{O}(\text{keV})$. Once S acquires an expectation value, an almost negligible mass splitting is introduced. We do not specify the production mechanism of the ν_s but assume that it's non-thermal and gives the correct DM relic density.

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- $y_{\text{eff}} \sim \frac{y_{EW}}{\Lambda_S}$ and $\Gamma \sim \frac{1}{16\pi} \frac{1}{m_{DM}} \left(\frac{y_{EW}}{\Lambda_S} \right)^2$
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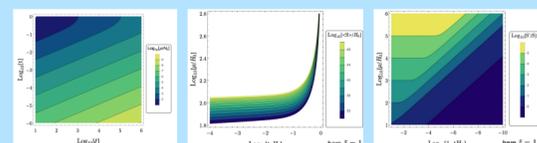
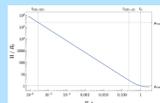
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- S can act as **thawing quintessence** field → *ongoing work*

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

Inflation: $R = 12H^2$, $H \approx \text{const.}$
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- effective coupling to LH neutrinos tiny
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- coupling Y to FN fields can be small
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FROM DARK MATTER TO NEUTRINO MASSES

A Late Phase Transition with a Non-Minimally Coupled Scalar Field

→ neutrinos become massive only in the late universe

Maya Hager

Max-Planck-Institut für Kernphysik Heidelberg

maya.hager@mpi-hd.mpg.de

in collaboration with

Florian Goertz, Giorgio Laverda & Javier Rubio

based on 2405.XXXX

April 22nd, 2024

Workshop „New Physics Directions“

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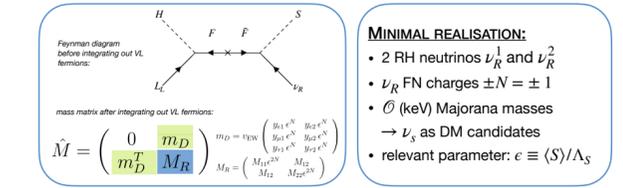


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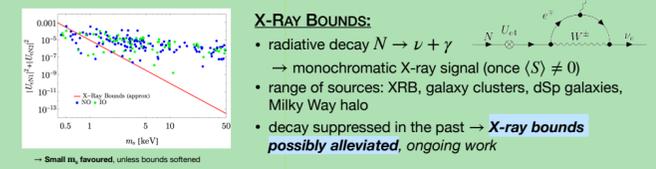
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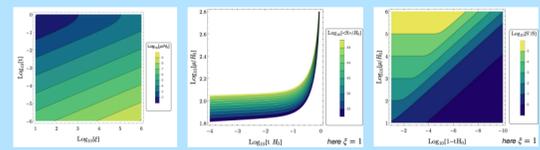
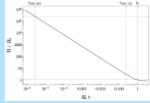
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MODEL:

- Extend SM by keV sterile neutrinos which are **DM candidates**
- **Froggatt-Nielsen mechanism (global U(1))** in right-handed neutrino sector (SM uncharged)
- scalar flavon-like field obtains expectation value only in the **late universe** and phase transition is **still ongoing**
- naturally tiny neutrino Yukawa couplings are induced, which are **dynamical** and increasing

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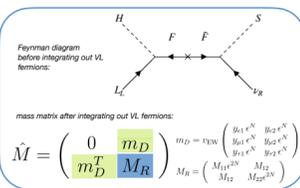


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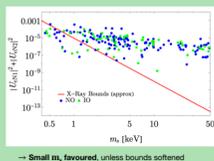
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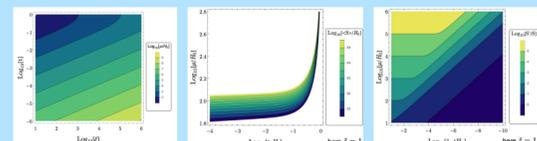
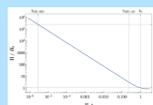
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PHENOMENOLOGY:

- throughout most of cosmological history: massless active neutrinos → **sensitive to future cosmological surveys**
- in the past smaller mixings → **potentially softens X-ray bounds**
- parameter space for active-sterile mixing sensitive to **future LNC experiments** (KATRIN upgrade TRISTAN)
- scalar field could be **dark energy field** (can act as thawing quintessence)

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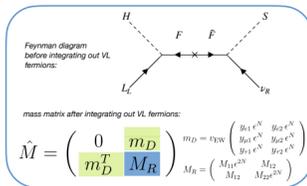


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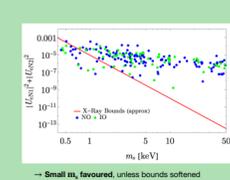
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4) STERILE NEUTRINO DARK MATTER

The sterile neutrinos form a **2-component dark matter** candidate with mass $M_{1,2} \sim \mathcal{O}$ (keV). Once S acquires an expectation value, an almost negligible mass splitting is introduced. We do not specify the production mechanism of the ν_s but assume that it's non-thermal and gives the correct DM relic density.

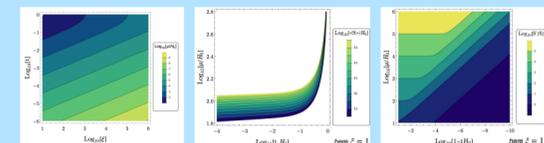
- #### LIFETIME BEFORE PHASE TRANSITION:
- $y_{eff} \sim \frac{y_{EW}}{\Lambda_S}$ and $\Gamma \sim \frac{1}{16\pi} \frac{1}{m_{DM}} \left(\frac{y_{EW}}{\Lambda_S} \right)^2$
 - $\tau = \Gamma^{-1}$ with $\tau_{universe} \sim 10^{10}$ yrs → $\Lambda_S \gtrsim \text{a few } \times 10^4 \text{ GeV}$

- #### LIFETIME AFTER PHASE TRANSITION:
- phase transition occurs during matter domination, i.e. when universe is $4.7 \times 10^3 - 9.8 \times 10^9$ yrs old
 - then, $N \rightarrow 3\nu$ decay with $\Gamma_{N \rightarrow 3\nu} = \frac{G_F^2 m_N^5}{96\pi^2} \sin^2 \theta$ → limits on mixing depend on t_{pt}

5) PHASE TRANSITION & SCALAR FIELD DYNAMICS

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

- #### PHASE TRANSITION:
- S is **spectator field** → no backreaction on cosmological evolution
 - once $\xi R \lesssim \mu^2$ → **tachyonic potential**
 - during radiation domination: Hubble friction keeps field frozen
 - the phase transition is not complete, $\langle S \rangle$ is **still changing**
 - S can act as **thawing quintessence** field → *ongoing work*



- #### CORRECTIONS TO SM PROCESSES
- $(S^c S)$ singlet under $U(1)_{FN}$
- Λ_S^3
 - can be added to any operator
 - corrections of $\mathcal{O}(10^{-18} - 10^{-22})$
 - negligible

- #### WHY S IS NOT IN THERMAL EQUILIBRIUM:
- no/negligible self-interaction
 - effective coupling to LH neutrinos tiny
 - Higgs portal can be neglected
 - coupling Y to FN fields can be small
 - due to degeneracy in $(\nu_{eff}^\nu)_{ij} \sim \frac{Y(S)}{M_F}$

FROM DARK MATTER TO NEUTRINO MASSES

A Late Phase Transition with a Non-Minimally Coupled Scalar Field

→ poster can be found outside the lecture hall, to the left

Maya Hager
Max-Planck-Institut für Kernphysik Heidelberg
maya.hager@mpi-hd.mpg.de