Electroweak right-handed neutrino portal dark matter

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This talk is based on

WZF, Zi-Hui Zhang, "*Darker matter* generated from the dark," 2405.19431.
WZF, Zi-Hui Zhang, "*Annihilating to the darker*: a cure for WIMP," 2409.17217.

WZF, Ao Li, Zong-Huan Ye, Zi-Hui Zhang, "Electroweak right-handed neutrino portal dark matter," 2508.xxxxx.

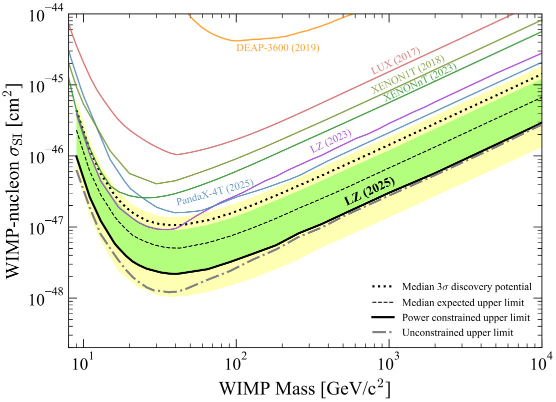
WZF, Jinzheng Li, Zong-Huan Ye, Pran Nath, "Gravitational waves from cogenesis in a $B - L$ conserving Universe," 2508.xxxxx. (gauge invariant approach, supercooling phase transition and PTA range GW signals) Sep, 2025 @Beijing

Overview

Explorations into hidden sectors

- The non-observation of WIMPs has substantially challenged a large number of traditional dark matter models.
- Direct, indirect detections as well as collider constraints significantly narrow down the parameter space for the majority of WIMP dark matter candidates.
- $\Omega h^2 = 0.12$ now becomes a constraint to the dark matter models rather than an ultimate goal to achieve (for model builders).

Nightmare direct detection constraints on WIMPs



[LZ, 2025]

Post-WIMP era

- Sub-GeV dark matter: lack of direct detection experiments for this mass range (experimental constraints not that strong), MeV-WIMP freeze-out cross-sections require weaker couplings (lower than the current experimental constraints) with the SM particles compared with the traditional $\mathcal{O}(100)$ GeV WIMPs, some of the $3 \to 2$ annihilation freeze-out dark matter models prefer a MeV mass range...
- Quark-phobic type of models: dark matter does not directly annihilate to quarks, which seems rather unnatural, at least for me.
- Resonance models (remain subject to strong constraints from colliders). In many cases, DM and mediators are all pushed to $\mathcal{O}(\text{TeV})$ or above.
- Right-handed neutrino portal dark matter, somehow lack of (traditional) direct detection detectability due to dark matter does not interact with quarks.
- What about the $1 - 200$ GeV traditional WIMP models?
- Shall we completely abandon these models?

Traditional WIMP models?

- Should we totally give up almost-excluded traditional WIMP models due to the more stringent constraints?
- In general, what can theorists offer to new physics studies?

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- In general, what can theorists offer to new physics studies?
- Lessons from String Pheno studies:
  - 20 years ago, string theorists were fascinated by finding some “generic” 6D internal space to compactify the 10D string theory. On these types of background, one can “naturally” obtain many required features of the SM (three generations, gauge groups, fermion spectrum, etc), such that people can have a lot of freedom to choose our Universe from the compactifications on these 6D background. Also, one expects these so-called generic backgrounds to be geometrically simple, natural, and with good symmetrical properties.

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  - It is unsuccessful. Such “generic” background hasn’t been found, or does not exist at all.
  - The SM itself is extremely peculiar, with all interactions and couplings difficult to be realized locally from bottom-up approach in string theory, not mentioning top-down.

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  - It is unsuccessful. Such “generic” background hasn’t been found, or does not exist at all.
  - The SM itself is extremely peculiar, with all interactions and couplings difficult to be realized locally from bottom-up approach in string theory, not mentioning top-down.
  - Even it was successful, the bottom-up approach (using the SM as an input to construct string models) cannot offer convincing (stringy) predictions to the SM.
  - If string theory cannot offer a “natural” realization of the SM, it seems meaningless.

Explore more possibilities beyond the SM

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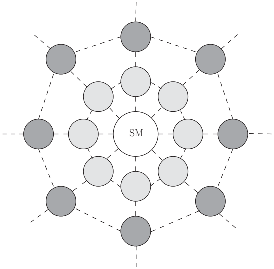
- Our Universe is strange and unique, and thus we need to explore more possibilities beyond the Standard Model.
- It is widely accepted that dark matter resides in one or multiple hidden sectors. Since dark matter hasn't been detected other than gravitational observations, it is possible that dark matter undergoes strong interactions across multiple hidden sectors, while only ultraweakly coupled to the Standard Model.
- It is interesting to explore interactions within multiple hidden sectors that may contain dark matter candidates.

Multiple hidden sectors beyond the SM

- Hidden sectors generally exist in string theory and GUT models.
- SM extensions with one or more hidden sectors is one possibility of our true world, and the importance of physics among multiple hidden sectors may have been underestimated and largely overlooked in the past.
- Evolutions of hidden sector particles and hidden sector temperature are important in determining new physics signals, in concordance with various experimental constraints and *dark matter relic density constraint.*
- YES WE CAN, although tedious, calculate the full evolutions of hidden sector particles as well as hidden sector temperatures.

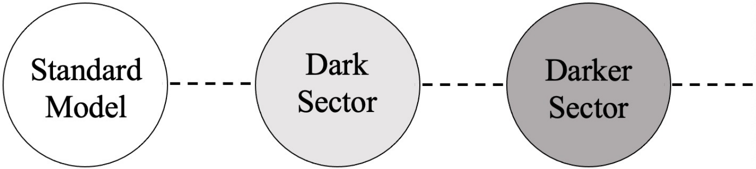
Multiple hidden sectors beyond the SM



The Standard Model is in general directly or indirectly connected with multiple hidden sectors, with either weak scale coupling or ultraweak coupling. A hidden sector feebly interacted with the SM will evolve almost independently with respect to the observed Universe, and it possesses its own temperature.

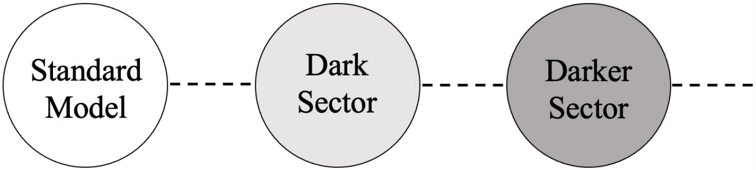
Among hidden sectors, however, they may exhibit rather strong interactions.

Exploring deeper into multiple hidden sectors



A graphic illustration of a darker sector which indirectly connected to the SM.

Exploring deeper into multiple hidden sectors



Connection of the dark sector with the SM: SUSY portal, Higgs portal, axion portal, fermion portal, right-handed neutrino portal, $(U(1))$ vector portal, gravity portal.

Connection of the darker sector with the dark sector can be also through these portals, but with less experimental constraints.

Freeze-out WIMPs are facing stringent experimental constraints

Why introducing the darker sector is important?

- Dark matter candidates from a single dark sector through portal interactions are now subject to stringent experimental constraints (on masses and couplings for both dark matter candidates and mediators):
  Higgs portal [Arcadi, Djouadi, Raidal, 2019], axion portal [Allen, Blackburn, Cardenas, Messenger, Nguyen, Shuve, 2024], fermion portal [Bœhm, Chu, Kuo, Pradler, 2020], vector portal [WZF, Zhang, 2024].

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- A fair conclusion: with the current sensitivities of both DM detectors and colliders, the usual WIMP dark matter candidates, which are subject to DM direct detection constraints (usually more important), cannot sufficiently annihilate into SM particles and will result in an overproduction of the relic dark matter through freeze-out.

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- A fair conclusion: with the current sensitivities of both DM detectors and colliders, the usual WIMP dark matter candidates, which are subject to DM direct detection constraints (usually more important), cannot sufficiently annihilate into SM particles and will result in an overproduction of the relic dark matter through freeze-out.
- This problem can be resolved with the assistant of additional darker sector [WZF, Zhang, 2024]: *annihilating to the darker*.

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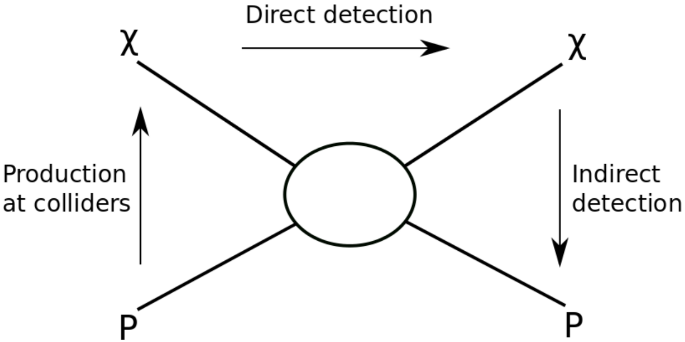
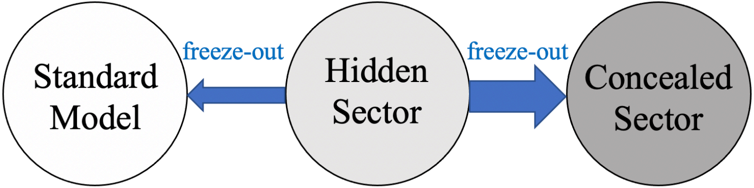
Dark matter detections



Freeze-out mechanism sets the coupling between WIMP and SM, which must inevitably be large. This leads to substantial elastic scattering cross-sections between WIMP and hadrons which have been already excluded by DM direct detections.

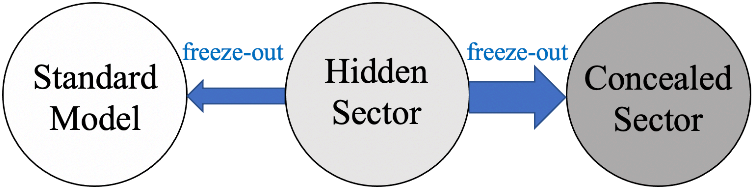
Annihilating to the darker



WZF, Zhang, "*Annihilating to the darker: a cure for WIMP*," 2409.17217.

In addition to freezing out into the SM with only a small fraction (which may still provide direct detection signals for future experiments), the thermal WIMP χ_x $(1 - 200\ \text{GeV})$ predominantly annihilate into a darker concealed sector.

Annihilating to the darker



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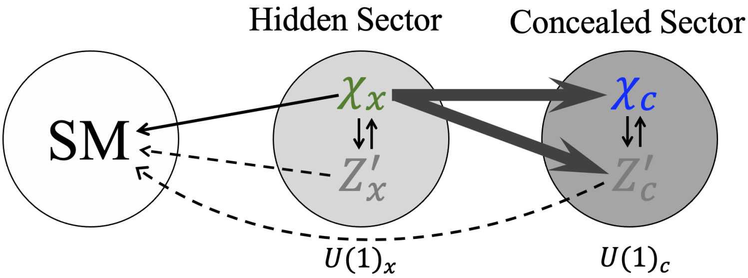
In addition to freezing out into the SM with only a small fraction (which may still provide direct detection signals for future experiments), the thermal WIMP χ_x $(1 - 200$ GeV$)$ predominantly annihilate into a darker concealed sector. The connections can be any portal interactions.

An illustration: a simple two-$U(1)$ model



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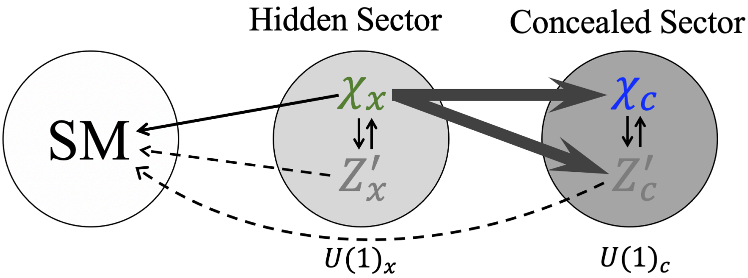
Investigation on two distinct possibilities



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Case 1: The WIMP annihilates efficiently and achieves the observed relic density with the assistance of the concealed sector.

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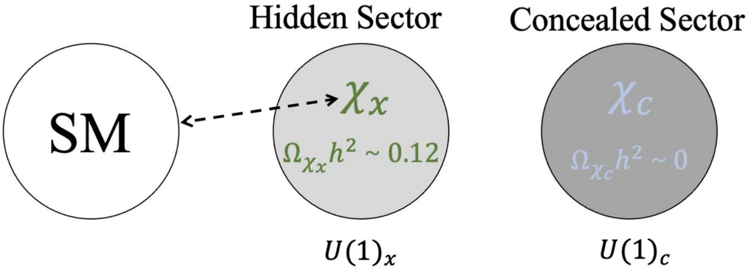

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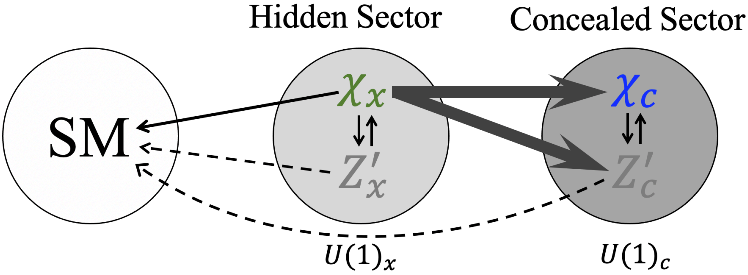

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Case 2: The WIMP transforms into another type of dark matter within the concealed sector and attains the observed relic density.

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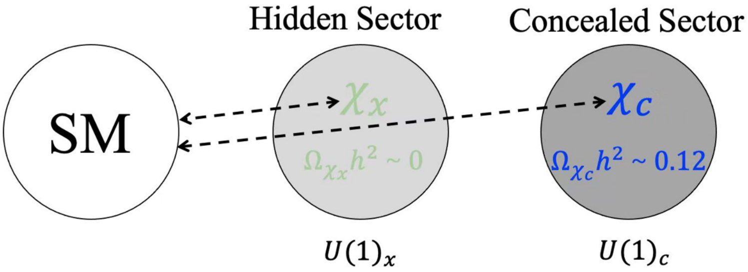

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Benchmark models

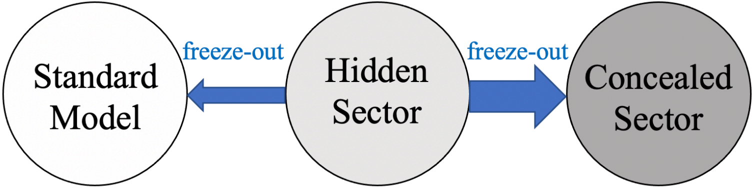
Model	m_x	m_c	M_x	M_c	M_m	$M_{Z'_x}$	$M_{Z'_c}$	δ_1	δ_2	g_x	g_c	$\Omega_{\chi_x} h^2$	$\Omega_{\chi_c} h^2$
$1a$	200	90	210	80	100	211	65	1×10^{-4}	0.15	0.525	0.6	0.12	7.5×10^{-3}
$1b$	100	70	120	60	60	121	51.5	3×10^{-5}	0.1	0.4	0.6	0.12	2.0×10^{-3}
$1c$	10	6	15	4	3	15	4	6×10^{-6}	0.05	0.14	0.6	0.12	7.7×10^{-4}
$1d$	1	0.5	1.6	0.3	0.3	1.6	0.3	1×10^{-4}	0.01	0.055	0.4	0.12	1.5×10^{-4}
$1d'$	1	0.5	1.6	0.3	0.3	1.6	0.3	1×10^{-4}	0.01	0.17	0.4	0.012	4.9×10^{-5}

Table: Case 1 benchmark models: The WIMP dark matter χ_x mainly freezes out into the concealed sector, and remains undetected. Model $1d'$ demonstrates that models with $\mathcal{O}(1)$ GeV asymmetric dark matter candidates can efficiently reduce the symmetric portion to less than 10% under the mechanism described in this letter.

Model	m_x	m_c	M_x	M_c	M_m	$M_{Z'_x}$	$M_{Z'_c}$	δ_1	δ_2	g_x	g_c	$\Omega_{\chi_x} h^2$	$\Omega_{\chi_c} h^2$
$2a$	200	165	210	160	160	221	103	4×10^{-5}	0.3	0.6	0.31	0.017	0.103
$2b$	100	90	110	80	70	112	67	2×10^{-5}	0.2	0.6	0.235	0.010	0.11
$2c$	10	7	12	6.5	5	12	6.3	1×10^{-6}	0.2	0.6	0.075	1.5×10^{-3}	0.12
$2d$	1	0.5	1.6	0.3	0.3	1.6	0.3	1×10^{-4}	0.1	0.6	0.02	6.3×10^{-4}	0.12
$2c'$	10	7	12	9	5.8	12.6	8.2	1×10^{-6}	0.005	0.6	0.6	8.5×10^{-4}	0.12
$2d'$	1	0.65	1.2	0.82	0.3	1.2	0.81	1×10^{-4}	0.001	0.5	0.46	3.0×10^{-4}	0.12

Table: Case 2 benchmark models: The WIMP dark matter χ_x primarily freezes out into the concealed sector, converting to χ_c, the dominant dark matter candidate, and leaving only a small fraction remaining in the Universe. Models $2c'$ and $2d'$ represent a specific type of models where the dark matter candidate χ_c is the lightest particle in the entire hidden sector.

Importance of the "Annihilating to the darker" scenario



WZF, Zhang, "*Annihilating to the darker: a cure for WIMP*," 2409.17217.

- Dark matter may exhibit complex interactions among multiple hidden sectors beyond the SM, which have been underestimated and largely overlooked in the past.
- Various WIMP models may still retain interest since the dark matter is primarily annihilating to the darker concealed sector and continue to hold potential for future dark matter detections.

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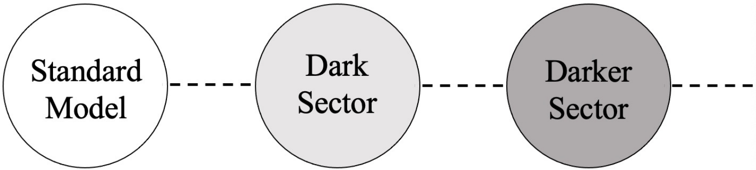
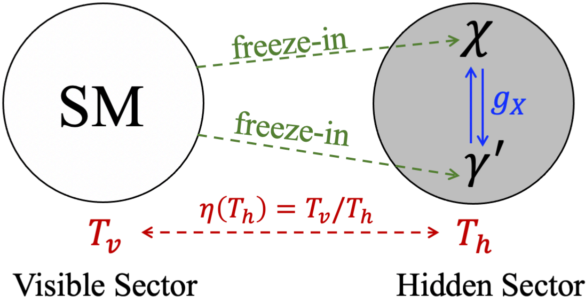
Explore multiple frozen-in hidden sectors



Freeze-in is an alternative mechanism to generate dark matter satisfying all current experimental constraints.

A graphic illustration of the simplest $U(1)_X$ model from freeze-in

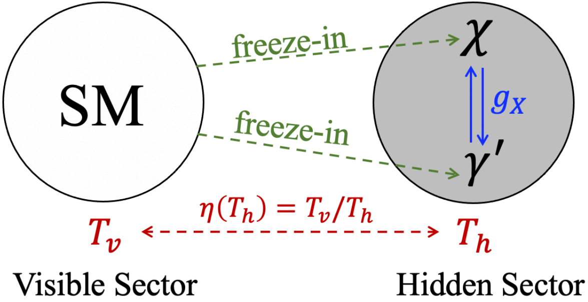


A graphic illustration of the freeze-in generation of the simplest $U(1)_X$ hidden sector generated through freeze-in mechanism.

Recent developments on $U(1)$ hidden sectors

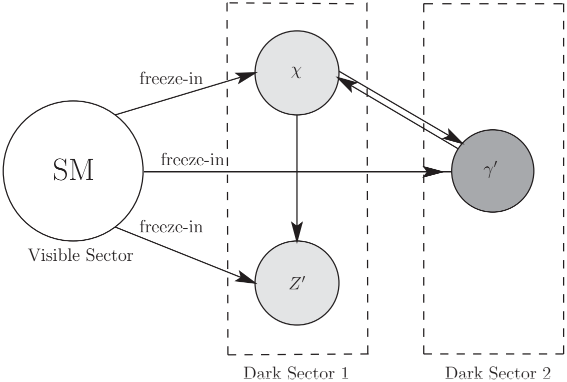
- We have developed a formalism to compute the evolution of hidden sector temperature as well as the hidden sector particles produced through freeze-in mechanism [Aboubrahim, WZF, Nath, Wang, 2008.00529].
- The strong interaction among dark matter, which might be the answer to various small scale structure issues, can be addressed in a $U(1)_X$ hidden sector produced via freeze-in beyond the SM.
- This formalism can be applied to any models with a freeze-in produced hidden sector involving hidden sector self-interactions, and compute the complete evolution of the hidden sector particles.

A graphic illustration of the simplest $U(1)_X$ model



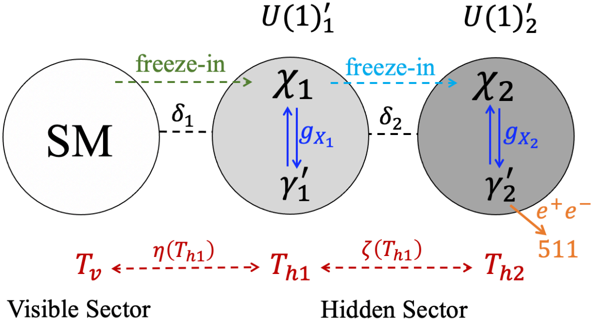
For a single $U(1)$ extension, a dark photon dark matter can occupy at most $\sim 5\%$ of the total dark matter relic density. $\Longrightarrow$ Extension with more $U(1)$'s.

Dark photon dark matter from $U(1)$ mixings



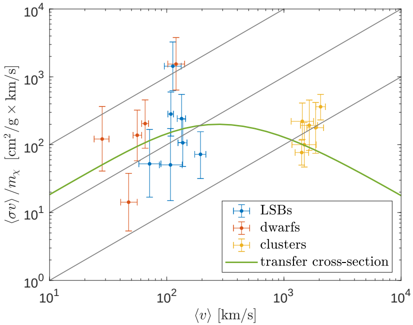
[Aboubrahim, WZF, Nath, Wang, 2103.15769]: dark photon dark matter from two $U(1)$'s can occupy almost 100% of the relic density.

A two-step freeze-in $U(1)$ model



[WZF, Zhang, 2405.19431]: a hidden sector produced through the freeze-in mechanism, can further generate an even more hidden sector via an additional freeze-in process. Such a two-step freeze-in process produces dark matter coupled weaker-than-ultraweakly to the standard model particles, and is thus referred to as the "darker matter".

Darker matter as the solution of the small scale structure problems



The strong self-interactions of the darker matter, residing in a darker hidden sector and coupling weaker-than-ultraweakly to the SM particles, could potentially resolve the problems associated with cosmic small-scale structures [WZF, Zhang, 2405.19431].

The 511 keV photon signal

Longstanding discovery and seen from many collaborations:

The galactic 511 keV photon line emission has been firstly observed for more than 50 years [Johnson, Harnden, Haymes, 1972], and confirmed by recent measurements including the SPI spectrometer on the INTEGRAL observatory [astro-ph/0309442, ...] and COSI balloon telescope [arXiv:1912.00110], see [arXiv:1009.4620] for an early review.

Basic interpretation

Low-energy positrons can annihilate with electrons and produce two 511 keV photons directly in a small fraction (faction $(1-f_p)$), or form a bound state known as positronium (fraction f_p) with two possible states.

The singlet state (para-positronium/p-Ps) with a zero total spin angular momentum $s=0$, which occupies 1/4 of the fraction of the total positronium can annihilate into two photons with energies equal to 511 keV.

Thus the total production rate of 511 keV photons is given by

$$\dot{n}_\gamma = 2\left[\left(1-f_p\right)+\frac{1}{4}f_p\right]\dot{n}_{e^+} = 2\left(1-\frac{3}{4}f_p\right)\dot{n}_{e^+}\,.$$

The dark matter interpretation

The positron production rates in the case of annihilation and decays are given by ($\rho(r)$ is the dark matter density)

$$\dot{n}_{e^+}^{\rm ann} = f_X \frac{\rho^2(r)}{4m_X^2} \langle \sigma v \rangle_{X\bar{X}\to e^+e^-} \,,$$

$$\dot{n}_{e^+}^{\rm dec} = f_X \frac{\rho(r)}{m_X} \Gamma_{X\to e^+e^-} {\rm Br}(X \to e^+e^-) \,,$$

Two types of dark matter density profiles widely adopted:

1. The Navarro-Frenk-White (NFW) profile [Navarro, Frenk, White 1996]

$$\rho_{\rm NFW}(r) = \rho_s \left(\frac{r}{r_s}\right)^{-\gamma} \left(1 + \frac{r}{r_s}\right)^{\gamma-3} .$$

2. The Einasto profile [Einasto, arXiv:0901.0632]

$$\rho_{\rm Einasto}(r) = \rho_s \exp\left\{-\left[\frac{2}{\alpha}\left(\frac{r}{r_s}\right)^{\alpha} - 1\right]\right\} .$$

Constraints on dark matter responsible for 511

- Internal bremsstrahlung $\chi\bar{\chi} \to e^+e^-\gamma$, constrains the dark matter mass $\lesssim 20$ MeV [Beacom, Bell, Bertone, 2004].
- Positron in-flight annihilation [Beacom, Yuksel, 2005]. Small fraction of energetic positrons will annihilate with electrons during their energy-loss, which sets constraint on annihilation dark matter mass $\lesssim 3$ MeV, and decaying dark matter mass $\lesssim 6$ MeV.
- Additional constraints on feebly interacting particles from supernova [Calore, Carenza, Giannotti, Jaeckel, Lucente, Mastrototaro, Mirizzi, 2021].

Dark matter annihilation

The light WIMP achieved their final relic abundance through the freeze-out mechanism with the (total) annihilation cross-section

$$\langle \sigma v \rangle_{\rm ann} \simeq 3 \times 10^{-26} \left(\frac{m_{\rm DM}}{\rm MeV} \right)^2 \ {\rm cm}^3/{\rm s}$$

at the freeze-out.

To explain the 511 keV signal the annihilation of dark matter at late times needs to be

$$\langle \sigma v \rangle^{511}_{e^+ e^-} \simeq 5 \times 10^{-31} \left(\frac{m_{\rm DM}}{\rm MeV} \right)^2 \ {\rm cm}^3/{\rm s} \, .$$

[Boehm, Hooper, Silk, Casse, Paul, 2003][Ascasibar, Jean, Boehm, Knoedlseder, 2005][Gunion, Hooper McElrath, 2005][Huh, Kim, Park, Park, 2007][Vincent, Martin Cline, 2012][Wilkinson, Vincent, Boehm, McCabe, 2016][Ema, Sala, Sato, 2020][Boehm, Chu, Kuo, Pradler, 2020][Drees, Zhao, 2021][De la Torre Luque, Balaji, Silk, 2021]

Annihilation DM from freeze-in is highly implausible

To explain the 511 keV signal, the effective coupling between $\chi\bar{\chi}$ and e^+e^- is too large for the freeze-in production (overproduction of the dark matter from freeze-in).

One can introduce mediators (which can decay or annihilate into SM completely)

$$\chi\bar{\chi} \xrightarrow{\text{scalar } S,\,\text{dark photon } \gamma' \cdots} e^+e^-$$

such that one can arrange the interactions among the hidden sector

$$\chi\bar{\chi} \to SS,\ \gamma'\gamma' \to e^+e^- \text{ before BBN}$$

such that the overproduction of the dark matter χ can be depleted.

But now the mediators will receive stringent constraints from experiments and thus are already ruled out [Calore, Carenza, Giannotti, Jaeckel, Lucente, Mastrototaro, Mirizzi, 2021].

Dark matter decay

To explain the 511 keV signal, based on the dark matter profiles widely adopted, one needs

$$\frac{\tau_{X\to e^+e^-}(\text{sec}) \times M_X(\text{MeV})}{f_X \times \text{Br}(X \to e^+e^-)} \sim 10^{26} - 10^{29}\,,$$

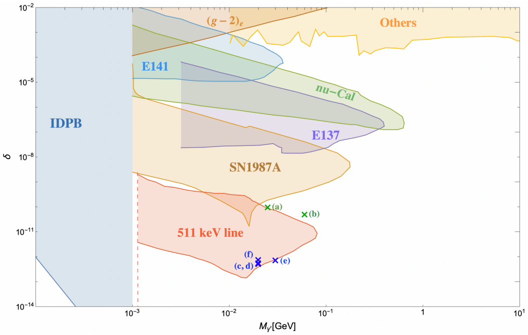
which can be also written as

$$g^2 \times f_X \times \text{Br}(X \to e^+e^-) \sim 10^{-50} - 10^{-47}\,,$$
$$\implies g \lesssim 10^{-16}$$

where g is the coupling of X with e^+e^-, f_X is the fraction of X in the total dark matter relic density, and $\text{Br}(X \to e^+e^-)$ is the branching fraction of X decay to e^+e^-. The coupling g is toooooo small even for the freeze-in production.

[Picciotto, Pospelov, 2004][Hooper, Wang, 2004][Takahashi, Yanagida, 2005][Finkbeiner, Weiner, 2007][Pospelov, Ritz, 2007][Cembranos, Strigari, 2008][Vincent, Martin Cline, 2012][Cai, Ding, Yang, Zhou, 2020][Lin, Yanagida, 2022][Cappiello, Jafs, Vincent, 2023][Cheng, Lin, Sheng, Yanagida, 2023]

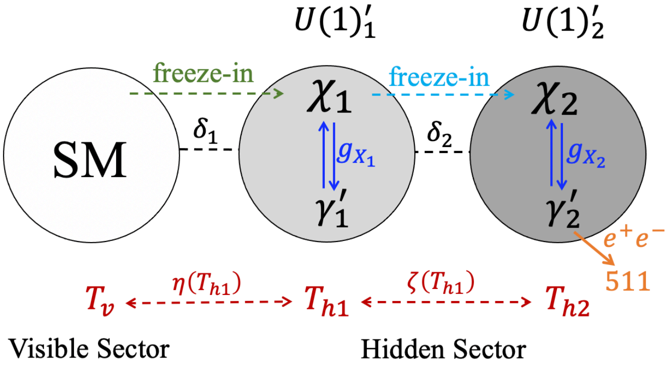
Two types of benchmark models



[WZF, Zhang, 2405.19431]

511 constraints for feebly interacting particles: [Calore, Carenza, Giannotti, Jaeckel, Lucente, Mastrototaro, Mirizzi, 2021]

A two-$U(1)$ model



[WZF, Zhang, 2405.19431]

The T-dependent Boltzmann equations

$$\frac{dY_{\chi_1}}{dT_{h_1}} = -s\frac{d\rho/dT_{h_1}}{4\rho H}\sum_{i\in SM}\Big\{(Y^{eq}_{\chi_1})^2\langle\sigma v\rangle^{T_{h_1}\eta}_{\chi_1\bar\chi_1\to i\bar i} - Y^2_{\chi_1}\langle\sigma v\rangle^{T_{h_1}}_{\chi_1\bar\chi_1\to\chi_2\bar\chi_2}$$
$$- Y^2_{\chi_1}\langle\sigma v\rangle^{T_{h_1}}_{\chi_1\bar\chi_1\to\gamma'_1\gamma'_1} + Y^2_{\gamma'_1}\langle\sigma v\rangle^{T_{h_1}}_{\gamma'_1\gamma'_1\to\chi_1\bar\chi_1} - Y^2_{\chi_1}\langle\sigma v\rangle^{T_{h_1}}_{\chi_1\bar\chi_1\to\gamma'_1\gamma'_2}$$
$$+\theta(M_{\gamma'_1}-2m_{\chi_1})\Big[-Y^2_{\chi_1}\langle\sigma v\rangle^{T_{h_1}}_{\chi_1\bar\chi_1\to\gamma'_1} + \frac{1}{s}Y_{\gamma'_1}\langle\Gamma\rangle^{T_{h_1}}_{\gamma'_1\to\chi_1\bar\chi_1}\Big]\Big\},$$

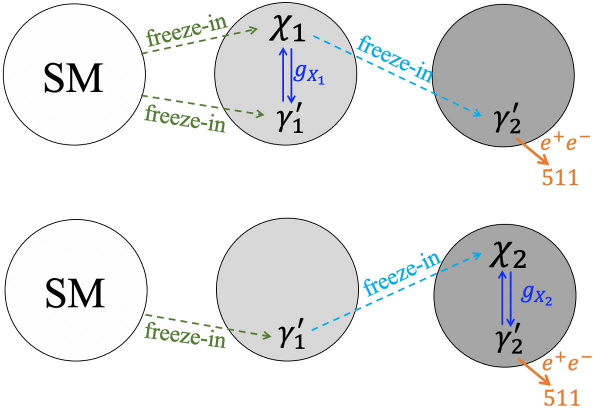
$$\frac{dY_{\gamma'_1}}{dT_{h_1}} = -s\frac{d\rho/dT_{h_1}}{4\rho H}\sum_{i\in SM}\Big\{Y^2_{\chi_1}\langle\sigma v\rangle^{T_{h_1}}_{\chi_1\bar\chi_1\to\gamma'_1\gamma'_1} - Y^2_{\gamma'_1}\langle\sigma v\rangle^{T_{h_1}}_{\gamma'_1\gamma'_1\to\chi_1\bar\chi_1} + Y^2_{\chi_1}\langle\sigma v\rangle^{T_{h_1}}_{\chi_1\bar\chi_1\to\gamma'_1\gamma'_2}$$
$$- Y^2_{\gamma'_1}\langle\sigma v\rangle^{T_{h_1}}_{\gamma'_1\gamma'_1\to\chi_2\bar\chi_2} + \theta(M_{\gamma'_1}-2m_i)\Big[Y^2_i\langle\sigma v\rangle^{T_{h_1}\eta}_{i\bar i\to\gamma'_1} - \frac{1}{s}Y_{\gamma'_1}\langle\Gamma\rangle^{T_{h_1}}_{\gamma'_1\to i\bar i}\Big]$$
$$+\theta(M_{\gamma'_1}-2m_{\chi_1})\Big[Y^2_{\chi_1}\langle\sigma v\rangle^{T_{h_1}}_{\chi_1\bar\chi_1\to\gamma'_1} - \frac{1}{s}Y_{\gamma'_1}\langle\Gamma\rangle^{T_{h_1}}_{\gamma'_1\to\chi_1\bar\chi_1}\Big]$$
$$+\theta(M_{\gamma'_1}-2m_{\chi_2})\Big[Y^2_{\chi_2}\langle\sigma v\rangle^{T_{h_1}\zeta}_{\chi_2\bar\chi_2\to\gamma'_1} - \frac{1}{s}Y_{\gamma'_1}\langle\Gamma\rangle^{T_{h_1}}_{\gamma'_1\to\chi_2\bar\chi_2}\Big]\Big\},$$

$$\frac{dY_{\chi_2}}{dT_{h_1}} = -s\frac{d\rho/dT_{h_1}}{4\rho H}\sum_{i\in SM}\Big\{Y^2_{\gamma'_1}\langle\sigma v\rangle^{T_{h_1}}_{\gamma'_1\gamma'_1\to\chi_2\bar\chi_2} + Y^2_{\chi_1}\langle\sigma v\rangle^{T_{h_1}}_{\chi_1\bar\chi_1\to\chi_2\bar\chi_2} - Y^2_{\chi_2}\langle\sigma v\rangle^{T_{h_1}\zeta}_{\chi_2\bar\chi_2\to\gamma'_2\gamma'_2}$$
$$+ Y^2_{\gamma'_2}\langle\sigma v\rangle^{T_{h_1}\zeta}_{\gamma'_2\gamma'_2\to\chi_2\bar\chi_2} + \theta(M_{\gamma'_1}-2m_{\chi_2})\Big[-Y^2_{\chi_2}\langle\sigma v\rangle^{T_{h_1}\zeta}_{\chi_2\bar\chi_2\to\gamma'_1} + \frac{1}{s}Y_{\gamma'_1}\langle\Gamma\rangle^{T_{h_1}}_{\gamma'_1\to\chi_2\bar\chi_2}\Big]\Big\},$$

$$\frac{dY_{\gamma'_2}}{dT_{h_1}} = -s\frac{d\rho/dT_{h_1}}{4\rho H}\sum_{i\in SM}\Big[Y^2_{\chi_1}\langle\sigma v\rangle^{T_{h_1}}_{\chi_1\bar\chi_1\to\gamma'_1\gamma'_2} + Y^2_{\chi_2}\langle\sigma v\rangle^{T_{h_1}\zeta}_{\chi_2\bar\chi_2\to\gamma'_2\gamma'_2} - Y^2_{\gamma'_2}\langle\sigma v\rangle^{T_{h_1}\zeta}_{\gamma'_2\gamma'_2\to\chi_2\bar\chi_2}\Big],$$

$$\frac{d\eta}{dT_{h_1}} = -\frac{\eta}{T_{h_1}} + \frac{1}{T_{h_1}}\left(\frac{4H\rho_v + j_{h_1} + j_{h_2}}{4H\rho_{h_1} - j_{h_1}}\right)\frac{d\rho_{h_1}/dT_{h_1}}{d\rho_v/dT_v},\quad \frac{d\zeta}{dT_{h_1}} = -\frac{\zeta}{T_{h_1}} + \frac{1}{T_{h_1}}\left(\frac{4H\rho_{h_2} - j_{h_2}}{4H\rho_{h_1} - j_{h_1}}\right)\frac{d\rho_{h_1}/dT_{h_1}}{d\rho_{h_2}/dT_{h_2}}.$$

Two types of benchmark models



Type-I Seesaw mechanism revisited

The Type-I seesaw Lagrangian is given by

$$\mathcal{L} = -y_{ij}^{\nu}\, \overline{L_i}\tilde{H} P_R \mathbb{N}_j + h.c. - \frac{1}{2} M_i \,\overline{\mathbb{N}_i^c}\, \mathbb{N}_i \,.$$

Here N_i is the Majorana right-handed neutrino. The corresponding quantum numbers are

Fields	L	H	$\mathbb{N}$
$B-L$	-1	0	0

In this case, the term $\overline{L_i}\tilde{H} P_R \mathbb{N}_j$ explicitly violates the $B-L$ number. Therefore, under the given charge assignment, $B-L$ can not be (further) imposed as a symmetry, neither global nor local.
From this perspective, since the heavy Majorana fermions $\mathbb{N}$ carry no quantum numbers at all, it is natural to consider the possibility that multiple (potentially far more than three) such heavy states may exist at high energies, each with distinct couplings to LH operator.

Type-I Seesaw revisited: a broken $B-L$ symmetry

An alternative interpretation of the Type-I seesaw Lagrangian involves imposing $B-L$ as a gauge symmetry. In this case, the original Lagrangian takes the form

$$\mathcal{L} \supset -y^{\nu}_{ij}\,\overline{L_i}\tilde{H}P_R N_j + h.c. - y^N_i \Phi \overline{N^c_i} N_i \,,$$

where N_j are Dirac fermions carrying $B-L$ quantum number, and Φ is the $U(1)_{B-L}$ Higgs field responsible for spontaneously breaking the $B-L$ gauge symmetry at a high scale, commonly assumed to be near the GUT scale. In this scenario, the charge assignments under $U(1)_{B-L}$ are summarized as follows:

Fields	L	H	N	Φ
$B-L$	-1	0	-1	$+2$

From this perspective, the Yukawa interaction $\overline{L_i}\tilde{H}P_R N_j$ is $B-L$ invariant, while the Majorana mass term for N arises from the last term when Φ acquires its vacuum expectation value.

Majorana fermion in string theory

A string theory interpretation of the seesaw mechanism is particularly fruitful in the context of D-brane model building. In this framework, right-handed neutrinos can be realized either as

- bi-fundamental Dirac fermions originating from open strings stretched between different stacks of D-branes [Blumenhagen, Cvetic, Ibanez, Richter, Uranga, etc].
- chargeless Majorana fermions arising from closed string modes [WZF, Yi-Nan Wang, Yi Zhang, to appear].

In D-brane constructions, the $U(1)$ charges associated with individual D-branes can be consistently canceled through the inclusion of appropriate instantons localized at brane intersections.

As a result, in string theory it is often possible to construct a variety of gauge-invariant interactions without explicitly breaking the underlying symmetries.

Majorana fermions from Type-I Seesaw

In summary, the right-handed neutrino with a Majorana mass term can be interpreted in two distinct frameworks:

1. **As a truly neutral Majorana fermion** with no conserved charges. In this interpretation, no lepton-number-related symmetry, whether global or gauged, can be imposed, since $\overline{L_i}\tilde{H}P_R N_j$ explicitly violates both lepton number and $B-L$.
2. **As a $(B-L)$ -charged Dirac fermion** prior to the $B-L$ symmetry breaking. In this case, the $B-L$ gauge symmetry is preserved at very high energies, and the Majorana mass term for N arises only after spontaneous breaking of $U(1)_{B-L}$ symmetry, typically via the vacuum expectation value of a scalar field.

A theoretically inconsistent treatment found in parts of the literature involves introducing massive Majorana right-handed neutrinos with interactions of the form $\overline{L_i}\tilde{H}P_R N_j + h.c.$, which explicitly violate the $B-L$ symmetry, while simultaneously imposing a $U(1)_{B-L}$ gauge symmetry at low energies. This formulation is self-contradictory, as the Yukawa interactions break the very symmetry one attempts to preserve.

Type-I Seesaw, details

The full mass term for a one-generation neutrino is rewritten in terms of 2-component spinors, as

$$\mathcal{L}_{\text{mass}}^{\text{neutrino}} = -\frac{y_{ij}^{\nu} v}{\sqrt{2}}(\nu_i^\dagger N_j + N_j^\dagger \nu_i) - \frac{M_i}{2}\left[N_i^T(\mathrm{i}\sigma_2)N_i + (N_i^*)^T(-\mathrm{i}\sigma_2)N_i^*\right]$$
$$\to -\frac{m_D}{2}(\nu^\dagger N + N^\dagger \nu + N^{c\dagger}\nu^c + \nu^{c\dagger}N^c) - \frac{M_i}{2}(N^\dagger N^c + N^{c\dagger}N)$$

where in the second line we derive a one-generation model for illustration and we define $m_D = y_{ij}^{\nu} v/\sqrt{2} \to y^{\nu} v/\sqrt{2}$ and

$$\nu^c = +\mathrm{i}\sigma_2\nu^*\,, \qquad N^c = -\mathrm{i}\sigma_2 N^*\,.$$

Hence we can obtain the mass mixing matrix:

$$\mathcal{L}_{\text{mass}}^{\text{neutrino}} = -\frac{1}{2}\begin{pmatrix} \nu^{c\dagger} & N^\dagger \end{pmatrix}\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}\begin{pmatrix} \nu \\ N^c \end{pmatrix} - \frac{1}{2}\begin{pmatrix} \nu^\dagger & N^{c\dagger} \end{pmatrix}\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}\begin{pmatrix} \nu^c \\ N \end{pmatrix},$$

and these two terms are just the hermitian conjugate of each other.

Type-I Seesaw: matrix form

Regular Type-I Seesaw (Case-RS)
In the basis of two component spinors

$$\begin{pmatrix} \mathbf{V_0}^T & \mathbf{N}^T \end{pmatrix} = \begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau & \mathcal{N}_1 & \mathcal{N}_2 & \mathcal{N}_3 \end{pmatrix}$$

where $\mathbf{V_0} \equiv \begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \end{pmatrix}^T$ and $\mathbf{N} \equiv \begin{pmatrix} \mathcal{N}_1 & \mathcal{N}_2 & \mathcal{N}_3 \end{pmatrix}^T$ are 3×1 column matrices consisting of two-component spinors in the original flavor basis. The mass terms are

$$-\mathcal{L}_{\rm mass} = \frac{1}{2}(\mathbf{V_0}^\dagger \mathbf{M}_D \mathbf{N} + \mathbf{N}^\dagger \mathbf{M}_D^T \mathbf{V_0} + \mathbf{V_0}^{c\dagger} \mathbf{M}_D \mathbf{N}^c + \mathbf{N}^{c\dagger} \mathbf{M}_D^T \mathbf{V_0}^c) + \frac{1}{2}\mathbf{M}_N (\mathbf{N}^{c\dagger}\mathbf{N} + \mathbf{N}^\dagger \mathbf{N}^c) \,,$$

where the 3×3 mass matrix $\mathbf{M}_D$ is defined as $\mathbf{M}_{D\,ij} = \frac{1}{\sqrt{2}} y_{ij} v$, and $\mathbf{M}_N = \mathrm{diag}\{M_i\}$. The seesaw mixing matrix is thus written as

$$\begin{pmatrix} 0 & \mathbf{M}_D \\ \mathbf{M}_D^T & \mathbf{M}_N \end{pmatrix}_{6\times 6} .$$

Type-I Seesaw generalizations: Structure Cancellation (Case-SC)

The 3×3 mixing matrix as we relabeled as $\widetilde{\mathbf{M}_D}$, has a specific structure [Heusch, Minkowski]

$$\widetilde{\mathbf{M}_D} \equiv \frac{v}{\sqrt{2}}\mathbf{Y} + \epsilon\mathbf{X} = \frac{v}{\sqrt{2}} \begin{pmatrix} Y_1 & Y_2 & Y_3 \\ \alpha Y_1 & \alpha Y_2 & \alpha Y_3 \\ \beta Y_1 & \beta Y_2 & \beta Y_3 \end{pmatrix} + \epsilon\mathbf{X} \,,$$

where ϵ is a tiny real parameter, α, β are real numbers, and $\mathbf{X}$ is a 3×3 matrix with entry values within $[-1, 1]$. $Y_{i=1,2,3}$ are the neutrino Yukawa couplings which need to satisfy a further constraint: $\sum \frac{Y_i^2}{M_i} = 0$. With the above condition, the rank-1 Yukawa matrix $\mathbf{Y}$ will make the 6×6 seesaw mixing matrix rank-3, corresponding to three precisely massless neutrinos, if the $\epsilon\mathbf{X}$ term is not present. Thus the corrections from $\epsilon\mathbf{X}$ will generate tiny masses for the three light neutrinos.

Although fine-tune is required to obtain the sub-eV light neutrino masses, this is the only possibility that EW scale right-handed neutrinos can have a considerable size of couplings of order of $\mathcal{O}(10^{-2})$ with the SM sector.

Type-I Seesaw: From Minimal Seesaw to Split Seesaw

In the case of minimal seesaw [Xing, etc], there are only 2 Majorana right-handed neutrinos $\mathbb{N}_2, \mathbb{N}_3$ coupled with the SM.
All experimental constraints in the light neutrino sector can be fulfilled, although one of the three light neutrinos is exactly massless.

Split seesaw (Case-SS)

Based on the minimal seesaw, one can introduce a third Majorana right-handed fermion $\mathbb{N}_1$ but only minimally couples to the SM $(y_1^\nu \ll y_2^\nu, y_3^\nu)$. In this case, $\mathbb{N}_1$ is not responsible for the light neutrino mixings, and is only responsible for generating a non-zero tiny mass of the third light neutrino.

Minimal extended seesaw

This case is, indeed, equivalent to the "minimal extended seesaw" as some people refer [The Heidelberg group], that one adds an additional Majorana field $\mathbb{S}^T = \begin{pmatrix} -i\sigma_2 S^* & S \end{pmatrix}$ with m_S, motivated by that one can obtain a massive sterile neutrino in any mass range in addition to the 2 or 3 heavy Majorana right-handed neutrinos from the regular seesaw, but only minimally couple to the SM. In such case, one adds an additional Majorana field $\mathbb{S}^T = \begin{pmatrix} -i\sigma_2 S^* & S \end{pmatrix}$ with $m_S \neq 0$ (The original version of the minimal extended seesaw has $m_S = 0$), where $\mathbb{S}$ does not couple to the SM directly via $\overline{\mathbb{S}_1} LH$ term, but with non-trivial mixing mass terms with the seesaw right-handed neutrinos $\mathbb{N}_i$. Thus in addition to Eq. XX, one has additional terms

$$\mathcal{L}^{\rm ME}_{\rm mass} = -M_{S\,i}\overline{\mathbb{N}}_i\mathbb{S} - \frac{m_S}{2}\overline{\mathbb{S}}\mathbb{S} = -\frac{M_{Si}}{2}\overline{\mathbb{N}}_i\mathbb{S} - \frac{M_{Si}}{2}\overline{\mathbb{S}}\mathbb{N}_i - \frac{m_S}{2}\overline{\mathbb{S}}\mathbb{S}\,.$$

In the basis of two-component spinors

$$\begin{pmatrix} \mathbf{V_0}^T & \mathbf{N}^T & S \end{pmatrix} = \begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau & \mathcal{N}_1 & \mathcal{N}_2 & S \end{pmatrix}.$$

Minimal extended seesaw, continued

The mass terms are expressed as

$$-\mathcal{L}_{\rm mass}^{\rm ME} = \frac{1}{2}(S^\dagger \mathbf{M}_S^T \mathbf{N}^c + \mathbf{N}^\dagger \mathbf{M}_S S^c + S^{c\dagger} \mathbf{M}_S^T \mathbf{N} + \mathbf{N}^{c\dagger} \mathbf{M}_S S) + \frac{1}{2} m_S (S^{c\dagger} S + S^\dagger S^c)\,,$$

giving rise to the seesaw mixing matrix

$$\begin{pmatrix} 0 & \mathbf{M}_D & 0 \\ \mathbf{M}_D^T & \mathbf{M}_N & \mathbf{M}_S \\ 0 & \mathbf{M}_S^T & m_S \end{pmatrix}_{6\times 6}\,,$$

where $\mathbf{M}_S = \begin{pmatrix} M_{S1} & M_{S2} \end{pmatrix}^T$ is a 2×1 one column matrix.

Experiment constraints on light neutrinos

the diagonalization of the seesaw mixing matrix gives rise to the 6×6 rotation matrix U. The top-left 3×3 block of the rotation matrix U should fit the PMNS matrix obtained through experimentation:

$$\left|U^{\rm ex}_{\rm PMNS}\right| = \begin{pmatrix} 0.803 \sim 0.845 & 0.514 \sim 0.578 & 0.142 \sim 0.155 \\ 0.233 \sim 0.505 & 0.460 \sim 0.693 & 0.630 \sim 0.799 \\ 0.262 \sim 0.525 & 0.473 \sim 0.702 & 0.610 \sim 0.762 \end{pmatrix} .$$

The masses of the three light neutrinos should also satisfy: (1) the upper bound of neutrino mass sum, i.e.,

$$\sum_i m_{\nu i} \lesssim 0.12 \text{ eV}$$

(2) the experimental fitting values of the mass-square differences

$$\triangle m^2_{12} = m^2_{\nu 2} - m^2_{\nu 1} = 7.54 \times 10^{-5} \text{ eV}^2 ,$$
$$\triangle m^2_{13} = m^2_{\nu 3} - m^2_{\nu 1} = 2.47 \times 10^{-3} \text{ eV}^2 .$$

(3) the non-trivial Dirac phase.

PSO for UV parameters

We apply the Particle Swarm Optimization (PSO) algorithm to find the values of all the input parameters. The optimization is done by requiring the calculated values from seesaw mixing matrix matching all above mentioned experiment values.

To this end, we define 5 fitting functions, which capture the deviation of the calculated $|U_{\rm PMNS}|$, neutrino mass sum, two mass-square differences and Dirac phase, to the respective experimental values.

We also define a 6th fitting function for Case-SC, ensuring that the non-unitarity constraint is satisfied, which sets limits on the size of the mixing between the SM neutrinos and right-handed neutrinos. Such requirement is needed only for considerable large mixings between the SM neutrinos and the right-handed Majorana neutrinos, which is present only for Case-SC among the three cases we consider.

Right-handed portal dark matter

As discussed, the right-handed Majorana fermions can be regarded as either pure neutral Majorana fermion, or originally $B-L$ charged Dirac fermion N_i and becoming a Majorana after a $B-L$ symmetry breaking. In the latter viewpoint, the dark sector particles χ or ϕ may also carry $B-L$ quantum number to balanced the $B-L$ charge originally carried by N_i. The right-handed neutrino portal Lagrangian can be in general written as

$$\mathcal{L}_{\rm RHNP} = y_i^x \, \overline{\mathbb{N}_i^0} \chi \phi + y_i^{x*} \, \bar{\chi} \phi^* \mathbb{N}_i^0 \,, \tag{1}$$

where the Yukawa coupling y_i^x can be real or complex, $\mathbb{N}_i^0$ are the right-handed Majorana fermion in the original flavor basis of the Type-I seesaw interactions. The three Majorana fermions mixed with the three SM neutrinos and after the seesaw mixing, it becomes a linear combination of all six flavor neutrinos in the mass eigenbasis.

Right-handed portal dark matter

- We focus on right-handed neutrinos at electroweak scale.
- From a theoretical perspective, if the Majorana masses of right-handed neutrinos are close to the electroweak scale, it is possible that the origins of both scales are interconnected.
- From an experimental standpoint, EW-scale right-handed neutrinos are intriguing due to their relatively low mass, which increases the likelihood of detection at colliders.

Experiment constraints on electroweak sterile neutrinos

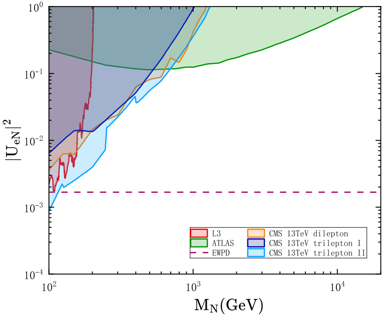


Figure: Exclusion limits at the 95% confidence level on the active-sterile mixing parameter $|U_{e\mathbb{N}}|^2$ are presented. The upper bounds are derived from various sources, including L3's search via $e^+e^- \to N\nu$, ATLAS same-sign WW scattering, and several CMS analyses at $\sqrt{s} = 13$ TeV: same-sign dilepton, trilepton I, and trilepton II, as well as global electroweak precision data (EWPD) constraints [J. de Blas, 2013].

Experiment constraints on electroweak sterile neutrinos

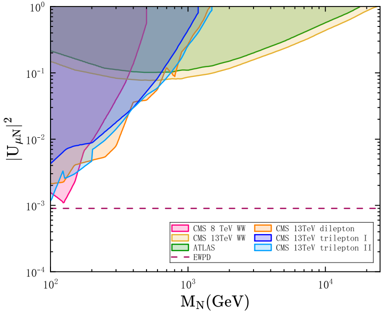


Figure: Exclusion limits at the 95% confidence level on the active-sterile mixing parameter $|U_{\mu\mathbb{N}}|^2$ are presented. The upper bounds are obtained from several sources, including ATLAS same-sign WW scattering, CMS same-sign dilepton I at $\sqrt{s} = 13$ TeV, CMS trilepton analysis, CMS trilepton II, CMS same-sign WW scattering, CMS same-sign dilepton at $\sqrt{s} = 8$ TeV, and electroweak precision data (EWPD) [J. de Blas, 2013].

Experiment constraints on electroweak sterile neutrinos

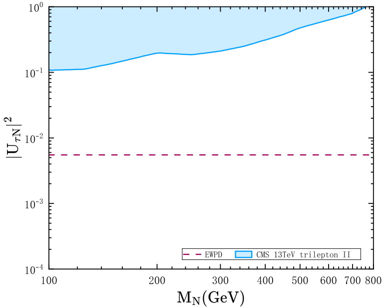
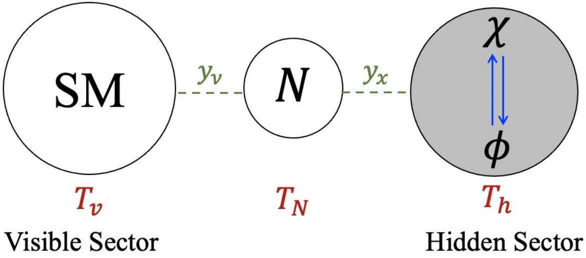


Figure: Exclusion limits at the 95% confidence level on the active-sterile mixing parameter $|U_{\tau\mathbb{N}}|^2$ are presented. The upper bounds are derived from the CMS trilepton II analysis at $\sqrt{s} = 13$ TeV and from electroweak precision data (EWPD) [Cheung, Chung, Ishida, Lu, 2020].

Right-handed portal dark matter



	y_ν	y_x	Evolution
RS	10^{-6}	$\mathcal{O}(1)$	freeze-out
SC	10^{-2}	$\mathcal{O}(1)$	freeze-out
SS	10^{-10}	–	–

The Boltzmann equations governing the full evolution

$$
\begin{aligned}
\frac{\mathrm{d}Y_\chi}{\mathrm{d}T} = &-\frac{s}{T\bar{H}}\Bigg\{\sum_{i,j=1}^{6}\Big[Y_{\mathbb{V}_i}Y_{\mathbb{V}_j}\langle\sigma v\rangle_{\mathbb{V}_i\mathbb{V}_j\to\chi\bar{\chi}} - Y_\chi^2\langle\sigma v\rangle_{\chi\bar{\chi}\to\mathbb{V}_i\mathbb{V}_j} \\
&+2\Big(Y_hY_{\mathbb{V}_i}\langle\sigma v\rangle_{h\mathbb{V}_i\to\chi\phi} - Y_\chi Y_\phi\langle\sigma v\rangle_{\chi\phi\to h\mathbb{V}_i}\Big) + \Big(h\to Z\Big) \\
&+\theta(m_\phi - m_\chi - m_i)\Big(\frac{1}{s}Y_\phi\langle\Gamma\rangle_{\phi\to\chi\mathbb{V}_i} - Y_\chi Y_{\mathbb{V}_i}\langle\sigma v\rangle_{\chi\mathbb{V}_i\to\phi}\Big)\Big] \\
&+2\sum_{i=1}^{3}\Big(Y_WY_{\ell_i}\langle\sigma v\rangle_{W\ell_i\to\chi\phi} - Y_\chi Y_\phi\langle\sigma v\rangle_{\chi\phi\to W\ell_i}\Big) \\
&+\sum_{i=4}^{6}\theta(m_\phi - m_\chi - m_i)\Big(\frac{1}{s}Y_{\mathbb{V}_i}\langle\Gamma\rangle_{\mathbb{V}_i\to\chi\phi} - Y_\chi Y_\phi\langle\sigma v\rangle_{\chi\phi\to\mathbb{V}_i}\Big) \\
&+Y_\phi^2\Big(2\langle\sigma v\rangle_{\phi\phi\to\chi\chi}\langle\sigma v\rangle_{\phi\bar{\phi}\to\chi\bar{\chi}}\Big) - Y_\chi^2\Big(2\langle\sigma v\rangle_{\chi\chi\to\phi\phi} + \langle\sigma v\rangle_{\chi\bar{\chi}\to\phi\bar{\phi}}\Big)\Bigg\}, \\
\frac{\mathrm{d}Y_\phi}{\mathrm{d}T} = &-\frac{s}{T\bar{H}}\Bigg\{\sum_{i,j=1}^{6}\Big[Y_{\mathbb{V}_i}Y_{\mathbb{V}_j}\langle\sigma v\rangle_{\mathbb{V}_i\mathbb{V}_j\to\phi\bar{\phi}} - Y_\phi^2\langle\sigma v\rangle_{\phi\bar{\phi}\to\mathbb{V}_i\mathbb{V}_j} \\
&+2\Big(Y_hY_{\mathbb{V}_i}\langle\sigma v\rangle_{h\mathbb{V}_i\to\chi\phi} - Y_\chi Y_\phi\langle\sigma v\rangle_{\chi\phi\to h\mathbb{V}_i}\Big) + \Big(h\to Z\Big) \\
&+\theta(m_\phi - m_\chi - m_i)\Big(-\frac{1}{s}Y_\phi\langle\Gamma\rangle_{\phi\to\chi\mathbb{V}_i} + Y_\chi Y_{\mathbb{V}_i}\langle\sigma v\rangle_{\chi\mathbb{V}_i\to\phi}\Big)\Big] \\
&+2\sum_{i=1}^{3}\Big(Y_WY_{\ell_i}\langle\sigma v\rangle_{W\ell_i\to\chi\phi} - Y_\chi Y_\phi\langle\sigma v\rangle_{\chi\phi\to W\ell_i}\Big) \\
&+\sum_{i=4}^{6}\theta(m_i - m_\chi - m_\phi)\Big(\frac{1}{s}Y_{\mathbb{V}_i}\langle\Gamma\rangle_{\mathbb{V}_i\to\chi\phi} - Y_\chi Y_\phi\langle\sigma v\rangle_{\chi\phi\to\mathbb{V}_i}\Big) \\
&-Y_\phi^2\Big(2\langle\sigma v\rangle_{\phi\phi\to\chi\chi} + \langle\sigma v\rangle_{\phi\bar{\phi}\to\chi\bar{\chi}}\Big) + Y_\chi^2\Big(2\langle\sigma v\rangle_{\chi\chi\to\phi\phi} + \langle\sigma v\rangle_{\chi\bar{\chi}\to\phi\bar{\phi}}\Big)\Bigg\}, \\
\frac{\mathrm{d}Y_{\mathbb{N}_i}}{\mathrm{d}T} = &-\frac{s}{T\bar{H}}\sum_{i,j=1}^{3}\Big[\mathcal{C}_{ij}\Big(Y_\chi^2\langle\sigma v\rangle_{\chi\bar{\chi}\to\mathbb{N}_i\mathbb{N}_j} + Y_\phi^2\langle\sigma v\rangle_{\phi\bar{\phi}\to\mathbb{N}_i\mathbb{N}_j}\Big) \\
&-\mathcal{C}_{ij}Y_{\mathbb{N}_i}Y_{\mathbb{N}_j}\Big(\langle\sigma v\rangle_{\mathbb{N}_i\mathbb{N}_j\to\chi\bar{\chi}} + \langle\sigma v\rangle_{\mathbb{N}_i\mathbb{N}_j\to\phi\bar{\phi}}\Big) \\
&+4\Big(Y_\chi Y_\phi\langle\sigma v\rangle_{\chi\phi\to h\mathbb{N}_i} - Y_hY_{\mathbb{N}_i}\langle\sigma v\rangle_{h\mathbb{N}_i\to\chi\phi}\Big) + 2\Big(h\to Z\Big) \\
&+2\,\theta(M_i - m_\chi - m_\phi)\Big(-\frac{1}{s}Y_{\mathbb{N}_i}\langle\Gamma\rangle_{\mathbb{N}_i\to\chi\phi} + Y_\chi Y_\phi\langle\sigma v\rangle_{\chi\phi\to\mathbb{N}_i}\Big) \\
&+2\,\theta(m_\phi - m_\chi - M_i)\Big(\frac{1}{s}Y_\phi\langle\Gamma\rangle_{\phi\to\chi\mathbb{N}_i} - Y_\chi Y_{\mathbb{N}_i}\langle\sigma v\rangle_{\chi\mathbb{N}_i\to\phi}\Big) \\
&+2\,\theta(M_i - m_W - m_{\ell_j})\Big(-\frac{1}{s}Y_{\mathbb{N}_i}\langle\Gamma\rangle_{\mathbb{N}_i\to W\ell_j} + Y_WY_{\ell_j}\langle\sigma v\rangle_{W\ell_j\to\mathbb{N}_i}\Big) \\
&+2\,\theta(M_i - m_h - m_j)\Big(-\frac{1}{s}Y_{\mathbb{N}_i}\langle\Gamma\rangle_{\mathbb{N}_i\to h\mathbb{V}_j} + Y_hY_{\mathbb{V}_j}\langle\sigma v\rangle_{h\mathbb{V}_j\to\mathbb{N}_i}\Big) + \Big(h\to Z\Big)\Big].
\end{aligned}
$$

Freeze-out: Non-EQ behavior of $\mathbb{N}$ and ϕ

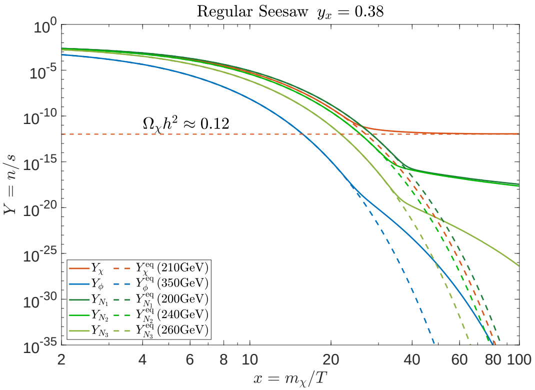
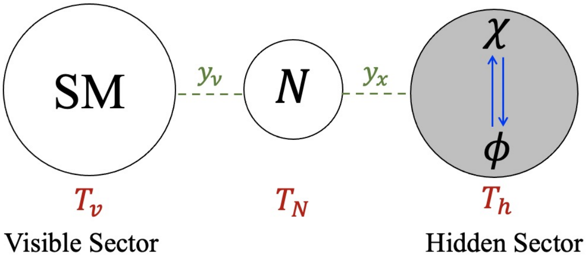


Figure: Full evolution of all dark sector particles for a selected benchmark:
$m_\chi = 210$ GeV, $m_\phi = 300$ GeV, $M_1 = 200$ GeV, $M_2 = 220$ GeV, $M_3 = 260$ GeV.

Freeze-out: Discussion

- The non-EQ behaviors of $\mathbb{N}$ and ϕ have significant impact on the dark matter evolution. More specifically, the departure from equilibrium of $\mathbb{N}$ and particularly ϕ, during the stage of dark matter freeze-out, acts to catalyze the freeze-out process. Although the major freeze-out process is $\chi\chi \to \mathbb{N}_1\mathbb{N}_1$, the dark sector internal interactions such as $\chi\chi \leftrightarrow \phi\phi$ and $\phi \leftrightarrow \chi\nu$, play important roles in determining the dark matter evolution.
- In Case-SC, where right-handed neutrinos have rather large couplings with the SM sector, the light-heavy neutrino mixing $\sim \mathcal{O}(10^{-2})$. Such large mixings should not be neglected in the calculation. Instead, the light and heavy neutrinos in the flavor eigenbasis must be expressed as linear combinations of six Majorana neutrinos in the mass eigenbasis. This treatment can lead to differences in the results of up to 2%.

Right-handed portal dark matter



Freeze-in case: Two scenarios

Since $m_\phi > m_\chi$, the decay $\phi \to \chi + \nu$ is always possible. For a consistent model, we require the lifetime of ϕ either

1. greater than the age of the Universe (both χ and ϕ are DM candidates). In this case, the effective Yukawa term is $y_x^\nu \bar{\nu}\chi\phi$ and $y_x^\nu \sim y_x U_{N\nu} \sim 10^{-22}$.
2. less than 1s (χ is the only DM candidate in the model, ϕ decays before BBN). In this case, $y_x^\nu \sim y_x U_{N\nu} \sim 10^{-12}$.

Freeze-in case: Case-RS

In RS type models, $y^\nu \sim 10^{-6}$ resulting in a mixing $U_{N\nu} \sim 10^{-8} - 10^{-7}$, the Majorana fermion N will become EQ at about EW scale.

(1) Both χ, ϕ are DM. In this case, $y_x^\nu \sim y_x U_{N\nu} \sim 10^{-22}$ and thus $y_x \to 10^{-15} - 10^{-14}$

- $M_N > m_\chi + m_\phi$. The major FI process is $N \to \chi + \phi$. Given $y_x \sim 10^{-15} - 10^{-14}$, the FI production is not sufficient.
- $M_N < m_\chi + m_\phi$. The major FI process is $NN \to \chi\chi$ and $NN \to \phi\phi$. Given $y_x \sim 10^{-15} - 10^{-14}$, the 4pt FI productions are not sufficient. The strength of the process $LH \to \chi\phi$ is $\sim y^\nu y_x \sim 10^{-22}$ is even smaller.

(2) Only χ is DM. In this case $y_x^\nu \sim y_x U_{N\nu} \sim 10^{-12}$ and thus $y_x \to 10^{-6} - 10^{-7}$

- $M_N > m_\chi + m_\phi$. The major FI process is $N \to \chi + \phi$. Given $y_x \sim 10^{-6} - 10^{-7}$, the FI production is too large.
- $M_N < m_\chi + m_\phi$. The major FI process is $NN \to \chi\chi$, $NN \to \phi\phi$ and $LH \to \chi\phi$. This case is possible.

Freeze-in case: Case-SC

In SC type models, $y^\nu \sim 0.1$ resulting in a mixing $U_{N\nu} \sim 0.01$, the Majorana fermion N will be always EQ. (1) Both χ, ϕ are DM. In this case $y_x^\nu \bar{\nu}\chi\phi$ where $y_x^\nu \sim y_x U_{N\nu} \sim 10^{-22}$ and thus $y_x \to 10^{-20}$

- $M_N > m_\chi + m_\phi$. The major FI process is $N \to \chi + \phi$. Given $y_x \sim 10^{-20}$, the FI production is not sufficient.
- $M_N < m_\chi + m_\phi$. The major FI process is $NN \to \chi\chi$ and $NN \to \phi\phi$. Given $y_x \sim 10^{-20}$, the 4pt FI production is not sufficient. The strength of the process $LH \to \chi\phi$ is $\sim y^\nu y_x \sim 10^{-22}$ is even smaller.

(2) Only χ is DM. In this case $y_x^\nu \bar{\nu}\chi\phi$ where $y_x^\nu \sim y_x U_{N\nu} \sim 10^{-12}$ and thus $y_x \to 10^{-10}$

- $M_N > m_\chi + m_\phi$. The major FI process is $N \to \chi + \phi$. This case is possible.
- $M_N < m_\chi + m_\phi$. The major FI process is $NN \to \chi\chi$, $NN \to \phi\phi$ and $LH \to \chi\phi$. This case is possible.

Freeze-in case: Case-SS

In SS type models, $y^\nu \sim 10^{-10}$ resulting in a mixing $U_{N\nu} \sim 10^{-10}$, the Majorana fermion N_1 never achieves EQ. (1) Both χ, ϕ are DM. In this case $y_x^\nu \sim y_x U_{N\nu} \sim 10^{-22}$ and thus $y_x \to 10^{-12}$.

- $M_N > m_\chi + m_\phi$. The major FI process is $N \to \chi + \phi$. This case is possible.
- $M_N < m_\chi + m_\phi$. The major FI process is $NN \to \chi\chi$, $NN \to \phi\phi$, the FI production is not sufficient.

(2) Only χ is DM. In this case $y_x^\nu \sim y_x U_{N\nu} \sim 10^{-12}$ and thus $y_x \to \mathcal{O}(1)$

- $M_N > m_\chi + m_\phi$. The major FI process is $N \to \chi + \phi$. This case is possible.
- $M_N < m_\chi + m_\phi$. The major FI process is $NN \to \chi\chi$, $NN \to \phi\phi$ and $LH \to \chi\phi$. This case is possible.

Conclusion

The exploration into the dark side of the Universe may continue to reveal the deeper mysteries of our cosmos.

- Annihilating to the darker: A possible explanation of the non-observation of WIMP is presented [WZF, Zhang, 2409.17217].
- Darker matter candidates freeze-in from a frozen-in hidden sector, couple weaker-than-ultraweakly to the SM particles, possess intriguing physical properties and have the potential to explain many unresolved problems in the Universe [Aboubrahim, WZF, Nath, Wang, 2103.15769][WZF, Zhang, 2405.19431].
- EW scale right-handed portal neutrino dark matter is discussed [to appear soon]:
    1. The analysis requires finding real benchmark models leading to light neutrino data.
    2. Once a specific type of Seesaw is taken, the Yukawa y_ν and masses of the heavy Majorana neutrinos are determined.
    3. For a specific type of RHN portal dark matter via freeze-in, the dark sector coupling y_x is fully determined by requiring the heavier state (in our case ϕ) either decay before BBN, or not decay within the age of the Universe.
    4. The dark sector internal interactions are important both for freeze-in and freeze-out mechanism.