Sterile Neutrino Dark Matter in the Super-Weak Extension of the Standard Model

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Talk based on the paper [arXiv:2104.11248] by K. Seller, S. Iwamoto, and Z. Trócsányi.

Introduction to the Super-Weak Model

Shortcomings of the Standard Model

Particle physics	Cosmology
Neutrino masses & oscillation	Dark energy
Muon $g-2$	Dark matter
Electroweak vacuum stability	Big Bang
Hierarchy problem	Inflation
Quantum gravity	Lithium problem
...	...

The highlighted items were investigated in the super-weak model.

- Model introduction – Z. Trócsányi [arXiv:1812.11189]
- Inflation and vacuum stability – Z. Péli et al. [arXiv:1911.07082]
- Dark matter – K. Seller et al. [arXiv:2104.11248] (this talk)
- Neutrino phenomenology – T. Kärkkäinen et al. [arXiv:2104.14571]

Extending the Standard Model

A possible way to solve the issues is to extend the Standard Model gauge group:

$$\boxed{\text{Super-weak gauge group:} \quad G_{SW} = \underbrace{SU(3)_c \otimes SU(2)_L \otimes U(1)_y}_{G_{SM}} \otimes U(1)_z}$$

Why an extra U(1)?

- Phenomenologically the simplest choice
- Experiments do not point towards complicated extensions
- Avoid having many new parameters and particles
- Mixing in the $U(1)_y \otimes U(1)_z$ sector gives rise to exciting phenomenology

We do not assume any already existing global symmetry behind $U(1)_z$.

Super-Weak Model Spectrum and Charges

We extend the spectrum of the Standard Model with

- $N_i \quad \rightarrow \quad$ 3 right-handed sterile neutrinos,
- $Z' \quad \rightarrow \quad$ the gauge boson of $\mathrm{U}(1)_z$,
- $\chi \quad \rightarrow \quad$ complex scalar $\mathrm{SU}(2)_\mathrm{L}$ singlet.

The lightest sterile neutrino N_1 is the dark matter candidate.

- $N_{2,3}$ are considered to be heavy and near-degenerate, with masses around the EW scale.

Charge assignment for $\mathrm{U}(1)_z$ has to be anomaly-free.

- This can be done in infinitely many ways.
- The $\mathrm{U}(1)_z$ charges have to be linear combinations of the hypercharges and $B - L$ numbers.

Super-Weak Model Symmetry-breaking Pattern

The $\mathrm{SU}(2)_\mathrm{L}\otimes\mathrm{U}(1)_y\otimes\mathrm{U}(1)_z$ gauge symmetry is broken by the non-zero vacuum expectation value of the scalars,

$$\text{Spontaneous symmetry breaking: } \mathrm{SU}(2)_\mathrm{L}\otimes\mathrm{U}(1)_y\otimes\mathrm{U}(1)_z \to \mathrm{U}(1)_\mathrm{em}\,.$$

As usual the gauge bosons obtain masses through the Higgs mechanism,

$$\underbrace{\begin{pmatrix} B_\mu \\ W^3_\mu \\ B'_\mu \end{pmatrix}}_{\text{Gauge eigenstates}} \longrightarrow \underbrace{\begin{pmatrix} A_\mu \\ Z_\mu \\ Z'_\mu \end{pmatrix}}_{\text{Mass eigenstates}}$$

$\to$ 2 physical angles of rotation: θ_W, θ_Z .

(θ_W is the Weinberg angle, defined the same way as in the Standard Model.)

Super-Weak Model Interactions

In the super-weak model only the neutral currents are modified.

- Covariant derivative:

$$\to \mathcal{D}_\mu^{\text{neut.}} \supset -\mathrm{i}(\mathcal{Q}_A A_\mu + \mathcal{Q}_Z Z_\mu + \mathcal{Q}_{Z'} Z'_\mu)$$

- Effective couplings:

$$\to \mathcal{Q}_A = (T_3 + y)|e| \equiv \mathcal{Q}_A^{\text{SM}}$$

$$\to \mathcal{Q}_Z = \underbrace{(T_3 \cos^2\theta_W - y\sin^2\theta_W)g_{Z^0}}_{\mathcal{Q}_Z^{\text{SM}}} \cos\theta_Z - \zeta g_z \sin\theta_Z$$

$$\to \mathcal{Q}_{Z'} = (T_3 \cos^2\theta_W - y\sin^2\theta_W)g_{Z^0} \sin\theta_Z + \zeta g_z \cos\theta_Z$$

The Z–Z' mixing is small, and the weak neutral current is only modified at order $\mathcal{O}(g_z^2/g_{Z^0}^2)$.

Super-Weak Model Parameters

1. Gauge coupling, g_z
   - In order to avoid various constraints, $\boxed{\mathcal{O}(g_z/g_{Z^0}) \ll 1}$ where $g_{Z^0} = g_L/\cos\theta_W$.
2. Vacuum expectation value of χ singlet, w
   - We will use the mass of Z' instead. It is assumed that $\boxed{M_{Z'} \ll M_Z.}$
3. Z–Z' mixing angle, θ_Z
   - Given the above assumptions, $\boxed{\tan(2\theta_Z) = \frac{4\zeta_\phi g_z}{g_{Z^0}} + \mathcal{O}\left(\frac{g_z^3}{g_{Z^0}^3}\right) \ll 1.}$
4. $U(1)_y \otimes U(1)_z$ gauge mixing parameter, η
   - Its value can be determined from RGE, at relevant scales $0 \le \eta < 1$, but we use $\boxed{\eta = 0}$ for simplicity (no qualitative difference).
5. Neutrino masses, N_i
   - We assume N_1 to be light (keV-MeV scale), while $M_{2,3} = \mathcal{O}(M_{Z^0})$.

Dark Matter production

Portals to the Dark Sector

Portal: a weak interaction connecting the Standard Model and the sterile particles.

- There are three well-known portals in the literature:

1. Vector boson portal

   $\longrightarrow$ Popular option with gauge group extensions of the SM, e.g., kinetic mixing.
2. Higgs portal

   $\longrightarrow$ The Higgs field can couple to SM singlets with dimensionless coupling.

   $\longrightarrow$ See e.g., [arXiv:hep-ph/0605188]
3. Neutrino portal

   $\longrightarrow$ If dark matter is fermion, it can couple to the dimension 5/2 HL operator.

   $\longrightarrow$ See e.g., [arXiv:0908.1790]

Super-Weak Dark Matter Production

In the super-weak model the lightest sterile neutrino is the dark matter candidate.

Relevant particles: electrons, SM neutrinos, Z' bosons, and N_1 sterile neutrinos.

$$\boxed{\text{Vertex:} \quad \Gamma^\mu_{Z'ff} = -\mathrm{i} g_z \gamma^\mu \left[q_f \cos^2\theta_\mathrm{W}(2-\eta) + (z_f - 2y_f) + \mathcal{O}(g_z^2/g_{Z^0}^2) \right]}$$

- $\Gamma^\mu_{Z'\nu_i\nu_i} \simeq \Gamma^\mu_{Z'N_1N_1} \simeq -\mathrm{i}\dfrac{g_z}{2}\gamma^\mu$
- $\Gamma^\mu_{Z'ee} \simeq -\mathrm{i} g_z \gamma^\mu \left[(\eta - 2)\cos^2\theta_\mathrm{W} + \dfrac{1}{2} \right]$

N_1 production channels:

1. Scattering from electrons via Z' exchange $\longrightarrow$ FREEZE-OUT
2. Decays of Z' bosons $\longrightarrow$ FREEZE-IN

Boltzmann Equation

Describes the evolution of a particle abundance in presence of interactions.

It is convenient to define the comoving number density $\mathcal{Y}$ which factors out the expansion of the Universe.

$$\frac{\mathrm{d}\mathcal{Y}}{\mathrm{d}z} \propto \sum_{\text{particles}} \Big[(\text{rate of creation processes}) - (\text{rate of annihilation processes})\Big]$$

How do we get the process rates?

$$\text{Rate} = \underbrace{(\text{Cross section}/\text{Decay rate})}_{\text{Depends on the model}} \times (\text{Available phase space})$$

Important: everything depends on the temperature!

Thermally Averaged Rates

Decay rate

Decaying particle mass: M

$$z = M/T$$

$$\langle\Gamma\rangle = \Gamma\,\frac{K_1(z)}{K_2(z)}$$

Monotone increasing function of z.

$$\max(\langle\Gamma\rangle) = \lim_{z\to\infty}\langle\Gamma\rangle = \Gamma$$

Cross section

Incoming/Outgoing particle mass: $m_{\mathrm{in/out}}$

$$\mu = \max(m_{\mathrm{in}}, m_{\mathrm{out}})$$

$$\langle\sigma v_{\mathrm{Møl}}\rangle \propto \int_{4\mu^2}^{\infty} \mathrm{d}s\; \sigma(s)(s-4m_{\mathrm{in}}^2)\sqrt{s}K_1\left(\frac{\sqrt{s}}{T}\right)$$

Resonance can dominate the integral.

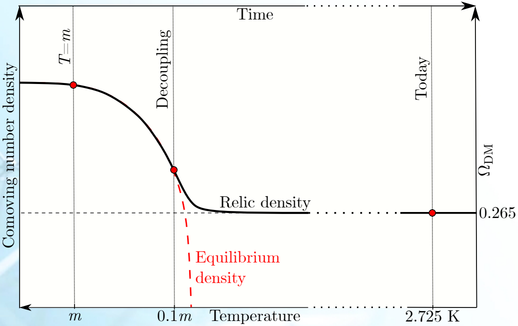
Decoupling: $\langle\sigma v_{\mathrm{Møl}}\rangle(T \ll m_{\mathrm{in}}) \to 0.$

Dark Matter production: Freeze-out

Freeze-out Mechanism

Freeze-out mechanism for a particle with mass m:

1. The particle species was in equilibrium at high temperatures ($T > m$),
2. Decoupling is a result of scattering processes becoming slow compared to Hubble expansion,
3. Decoupling happens at temperatures comparable to the mass of the particle, $T_{\text{dec}} \simeq 0.1m$.



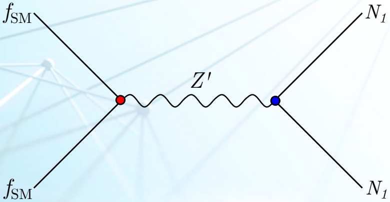
Freeze-out in the Super-Weak Model: Processes

Freeze-out requires decoupling $\longrightarrow$ scattering processes are important.

We consider $M_1 = \mathcal{O}(10)$ MeV $\longrightarrow$ decoupling happens at $T_{\text{dec}} = \mathcal{O}(1)$ MeV.

At this temperature range electrons and SM neutrinos are abundant, negligible amounts of heavier fermions.

$$N_1 N_1 \to f_{\text{SM}} f_{\text{SM}} : \quad \sigma_{\text{t}} \propto g_z^4 \sqrt{1 - \frac{4M_1^2}{s}} \frac{s}{(s - M_{Z'}^2)^2 + M_{Z'}^2 \Gamma_{Z'}^2}$$



Resonant Amplification

In the freeze-out mechanism increasing the interaction rate decreases the relic density.

- But large couplings are ruled out by experiments!
- Need another way out: increase $\langle \sigma v_{\text{Møl}} \rangle$ by exploiting resonance $(2M_1 \lesssim M_{Z'})$

$$\text{Resonance: } \langle \sigma v_{\text{Møl}} \rangle = (\dots) \int_{4M_1^2}^{\infty} \mathrm{d}s \underbrace{\frac{(\dots)}{(s - M_{Z'}^2)^2 + M_{Z'}^2 \Gamma_{Z'}^2}}_{\text{strongly peaked around } s = M_{Z'}^2} \times K_1\left(\frac{\sqrt{s}}{T}\right)$$

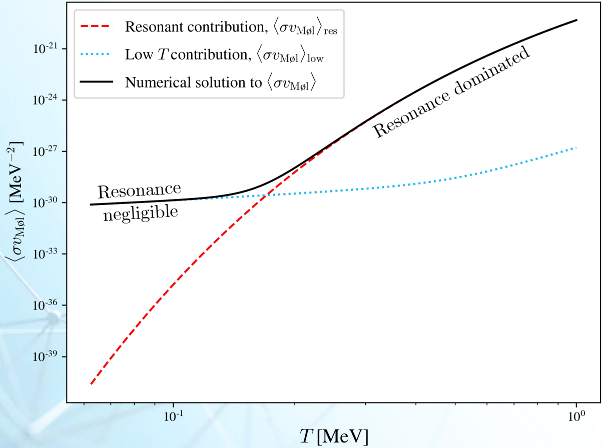
$\to$ Recall that $T_{\text{dec}} \approx 0.1 M_1$, then at the resonance $s = M_{Z'}^2$ the Bessel function is $K_1(10 M_{Z'}/M_1)$

$\to$ The Bessel function is exponentially small if its argument is large

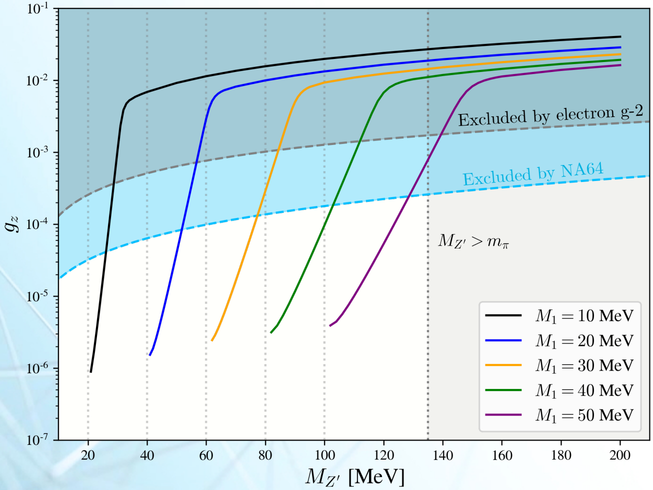
$\longrightarrow$ need $M_{Z'} \approx M_1$, i.e., resonance.

Resonant Amplification: Example

Example calculated within the super-weak model for $M_1 = 10$ MeV and $M_{Z'} = 30$ MeV.



Freeze-out in the Super-Weak Model

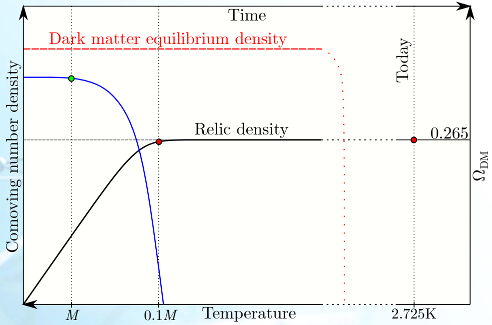


Dark Matter production: Freeze-in

Freeze-in Mechanism

Freeze-in with a particle with mass M decaying to a dark matter candidate with mass m.

1. The mother particle does not have to be in equilibrium at high ($T > M$) temperatures.
2. Freeze-in happens due to the Boltzmann-suppression of the mother particles.
3. Final relic abundance of **dark matter particles** is $\mathcal{Y}_\infty \simeq \max(\mathcal{Y}_{\text{mother}}) \times \text{Br}(\text{mother} \to \text{DM})$



Freeze-in in the Super-Weak Model: Processes

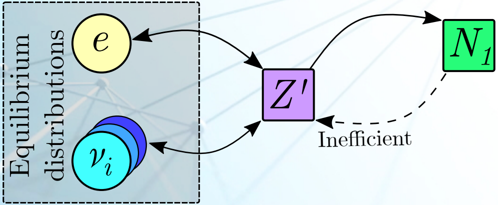
Main processes to consider are decays.

- Only Z' has a vertex with N_1, thus $Z' \to N_1 N_1$ is the only process creating DM

We have no reason to assume anything special about the initial abundance of Z':

$$\text{Simplest choice:} \quad \mathcal{Y}_{Z'}(T_0) = \mathcal{Y}_1(T_0) = 0\,, \;\text{ where } T_0 \gg M\,.$$

We have to solve for both Z' and N_1 abundances as both will be out of equilibrium.



Freeze-in in the Super-Weak Model: Parameters

Many parameters $\longrightarrow$ choose ones that are relevant

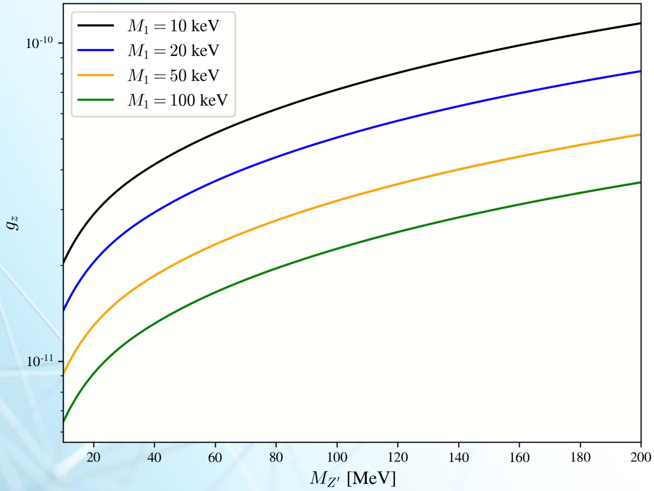
$$\text{Parameters} = \begin{cases} T_0 & \text{Initial condition: temperature} \\ \mathcal{Y}(T_0) & \text{Initial condition: abundance} \\ M_{Z'} & Z' \text{ boson mass} \\ M_1 & N_1 \text{ lightest sterile neutrino mass} \\ g_z & \mathrm{U}(1)_z \text{ gauge coupling} \\ \eta & \mathrm{U}(1)_y \otimes \mathrm{U}(1)_z \text{ gauge mixing} \end{cases}$$

Initial conditions are irrelevant as long as

$$\mathcal{Y}(T_0) \ll \mathcal{Y}_\infty \quad \text{and} \quad T_0 \gtrsim 10M.$$

Not using these assumptions leads to fine tuning problems.

Freeze-in in the Super-Weak Model



Conclusions

Conclusions

- The super-weak extension can provide a valid dark matter candidate, the lightest sterile neutrino
- Current experiments allow for both freeze-in and freeze-out scenarios
- Future experiments will probe the parameter space of the freeze-out case
- Freeze-in is difficult to completely rule out due to the many parameters and feeble couplings

• Thank You for Your Attention! •