Sterile Neutrino Dark Matter in the Super-Weak Model

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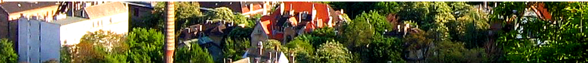

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This talk is based on the article [arXiv:2104.11248] by S. Iwamoto, K. Seller, and Z. Trócsányi.

Introduction to the Super-Weak Model

Extending the Standard Model

A possible way to solve a number of shortcomings of the SM is to extend the gauge group:

$$\boxed{\text{Super-weak gauge group:}\quad \mathrm{G}_{\mathrm{SW}} = \underbrace{\mathrm{SU}(3)_{\mathrm{c}} \otimes \mathrm{SU}(2)_{\mathrm{L}} \otimes \mathrm{U}(1)_{y}}_{\mathrm{G}_{\mathrm{SM}}} \otimes \mathrm{U}(1)_{z}}$$

Why an extra U(1)?

- Phenomenologically the simplest choice $\longrightarrow$ Avoid having many new parameters

What is the goal of the model?

- Simple model $\rightarrow$ simultaneous explanation of multiple observations beyond the SM possible?
- See today's poster session:
  - [1288] Z. Trócsányi – SWSM phenomenology
  - [1195] Z. Péli – Vacuum stability in SWSM
  - [518] T. Kärkkäinen – Neutrino physics in SWSM

Super-Weak Model Spectrum and Charges

We extend the spectrum of the Standard Model with

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

The lightest sterile neutrino N_1 is the dark matter candidate.

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

- The condition can be satisfied in many ways.
- The $\mathrm{U}(1)_z$ charges are linear combinations of the hypercharges and $B - L$ numbers.
- Simple choice: right-handed neutrinos have the opposite charge to left-handed ones.

Super-Weak Model Interactions

In the super-weak model only the neutral currents are modified.
Rotation (θ_W, θ_Z) of gauge eigenstates to mass eigenstates: $(B_\mu, B'_\mu, W^3_\mu) \to (A_\mu, Z_\mu, Z'_\mu)$
$(g_{Z^0} = g_L / \cos\theta_W)$

- Covariant derivative:

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

- Effective couplings:

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

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

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

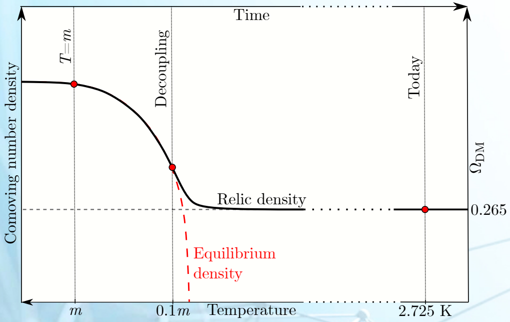
The Z–Z' mixing is small, and the weak neutral current is only modified at order $\mathcal{O}(g_z^2/g_{Z^0}^2)$.

Super-Weak Model Parameters

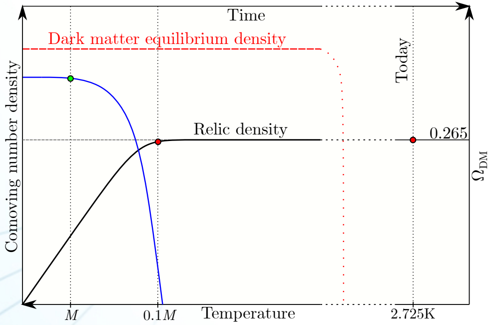
1. Gauge coupling, g_z
   - In order to avoid SM precision constraints, $\boxed{\mathcal{O}(g_z/g_{Z^0}) \ll 1}$.
2. Vacuum expectation value of χ singlet, w
   - We will use the mass of Z' instead. It is assumed that $\boxed{M_{Z'} \ll M_Z.}$
3. Z–Z' mixing angle, θ_Z
   - Given the above assumptions,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

Dark Matter production

Freeze-out and Freeze-in



(a) Freeze-out



(b) Freeze-in

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.

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

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

N_1 production channels:

1. Scattering via Z' exchange $(f\bar{f} \to Z' \to N_1 N_1) \longrightarrow$ FREEZE-OUT
2. Decays of Z' bosons $(Z' \to N_1 N_1) \longrightarrow$ FREEZE-IN

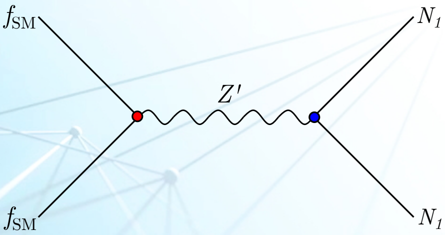
Dark Matter production: Freeze-out

Freeze-out in the Super-Weak Model: Processes

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 $\langle \sigma v_{\mathrm{Møl}} \rangle$ by exploiting resonance $(2M_1 \lesssim M_{Z'})$

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

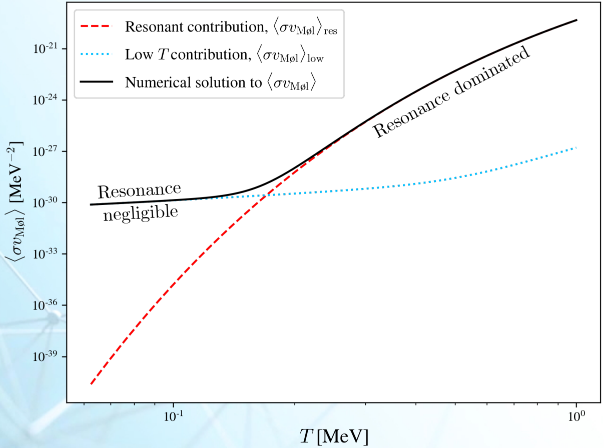
$\rightarrow$ Recall that $T_{\mathrm{dec}} \approx 0.1 M_1$, then at the resonance $s = M_{Z'}^2$
the Bessel function is $K_1(10 M_{Z'}/M_1)$

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

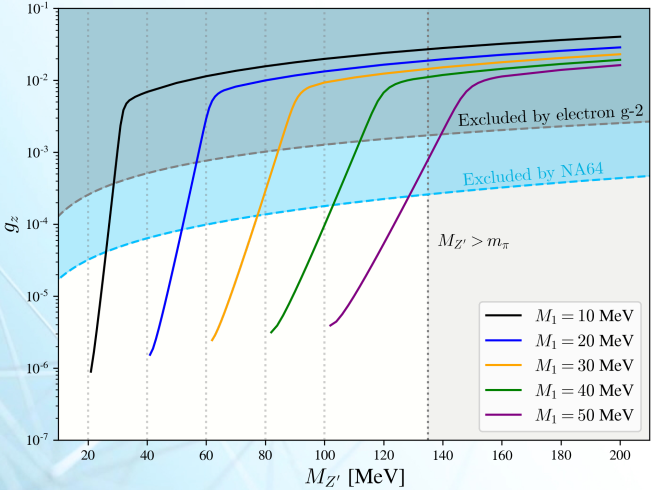
$\longrightarrow$ need $M_{Z'} \approx 2M_1$, i.e., resonance.

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



Experimental constraints

Experimental Constraints

1. Anomalous magnetic moment of electron and muon
   - Z' couples to leptons and appears in the triangle graph modifying the magnetic moment.
   - Constraints on $(g_\ell - 2)$ translate to upper bounds on the coupling as $g_z(M_{Z'})$.
2. NA64, search for missing energy events
   - Strict upper bounds on $g_z(M_{Z'})$ for any U(1) extension (dark photons).
3. Supernova constraints based on SN1987A
   - Constraints are based on comparing observed and calculated neutrino fluxes.
4. Big Bang Nucleosynthesis provides constraints on new particles
   - New particles should have negligible effects during BBN.
   - Meson production can be dangerous close to BBN.
5. Further constraints are due to CMB, solar cooling, beam dump experiments, etc.

(2) - NA64

NA64 experiment constists of an electron beam fired at a fix target of material with atomic number Z $\longrightarrow$ Bremsstrahlung process may produce a "dark photon".

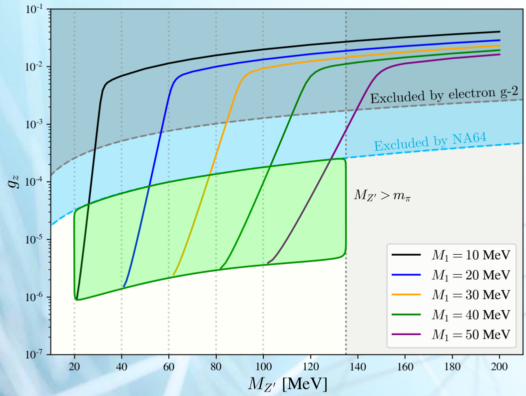
$$e + \mathrm{Z} \to e + \mathrm{Z} + A', \quad A' \to (\text{invisibles})$$

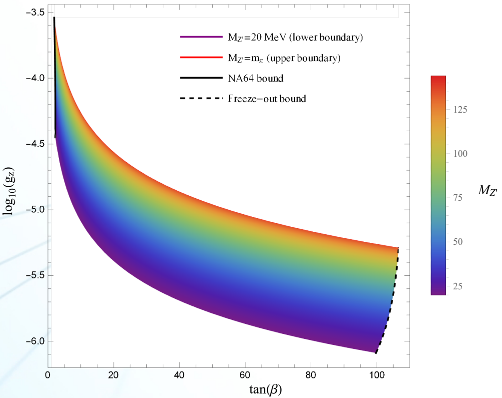
Look for missing energy events, i.e. when the dark photon decayed to invisible final states (sterile particles or SM neutrinos)

Non-observation of missing energy events $\longrightarrow$ constraints on kinetic mixing $\Longleftrightarrow$ Must be translated to the super-weak model!

$$(\text{Dark photon model}) \quad e\epsilon = |\tilde{g}_z|\sqrt{\mathcal{B}^{Z'}_{\text{inv.}}} \quad (\text{Super-weak model})$$

2 - NA64 BOUNDS





Conclusions

Conclusions

- The super-weak extension can provide a valid dark matter candidate, the lightest sterile neutrino
- Current experimental bounds 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 numerous sensitive parameters and feeble couplings

Backup slides

Super-Weak Model Spectrum and Charges

		Particle	$SU(3)_c$	$SU(2)_L$	$U(1)_y$	$U(1)_z$
Fermions	Quarks	Q_L	**3**	**2**	1/6	1/6
		U_R	**3**	**1**	2/3	7/6
		D_R	**3**	**1**	-1/3	-5/6
	Leptons	L_L	**1**	**2**	-1/2	-1/2
		N_R	**1**	**1**	0	1/2
		e_R	**1**	**1**	-1	-3/2
Scalars		ϕ	**1**	**2**	1/2	1
		χ	**1**	**1**	0	-1

Mixing of U(1) gauge symmetries

There are different ways to account for the mixing.

1. Kinetic mixing: $\mathcal{L}_{\text{km}} = -\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$ term is allowed by gauge symmetry.

2. Mixing in the couplings: $\mathcal{D}_\mu^{\mathrm{U}(1)} = -\mathrm{i} \underbrace{\begin{pmatrix} y & z \end{pmatrix}}_{\mathrm{U}(1)\ \text{charges}} \mathbf{g} \begin{pmatrix} B_\mu \\ B'_\mu \end{pmatrix}$

With non-diagonal coupling matrix, $\mathbf{g} = \begin{pmatrix} g_y & -\eta g_z \\ 0 & g_z \end{pmatrix} \times$ (Unphysical rotation).

It is convenient to define the effective $\mathrm{U}(1)_z$ charge $\zeta = z - \eta y$:

$$\mathcal{D}_\mu^{\mathrm{U}(1)} = -\mathrm{i} \begin{pmatrix} y g_y & \zeta g_z \end{pmatrix} \times (\text{Unphysical rotation}) \times \begin{pmatrix} B_\mu \\ B'_\mu \end{pmatrix}$$

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,

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

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

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

Basis rotation has 3 free parameters: θ_W, θ_Z, and ϵ'.
However, only 2 are physical: ϵ' is cancelled by the mixing in the coupling matrix.

Super-Weak Model Gauge Sector

After spontaneous symmetry breaking, the gauge bosons acquire masses.
$(g_{Z^0} = g_\mathrm{L}/\cos\theta_\mathrm{W})$

$$M_Z = \frac{g_{Z^0} v}{2}\sqrt{1+\frac{2\zeta_\phi g_z}{g_{Z^0}}\tan\theta_z} = \underbrace{\frac{g_{Z^0} v}{2}}_{M_Z^{(\mathrm{SM})}} + \mathcal{O}\left(\frac{g_z^2}{g_{Z^0}^2}\right)$$

$$M_{Z'} = \frac{g_z w}{\sqrt{1+\frac{2\zeta_\phi g_z}{g_{Z0}}\tan\theta_z}} = g_z w - \mathcal{O}\left(\frac{g_z^2}{g_{Z^0}^2}\right)$$

$$M_W = \frac{g_\mathrm{L} v}{2} \qquad \longleftarrow \qquad \text{(Unchanged!)}$$

Note: $M_{Z'} \ll M_Z$ if $w \gtrsim v$ and $g_z \ll g_{Z^0} \longrightarrow$ "super-weak" coupling

Freeze-in in the Super-Weak Model: Processes

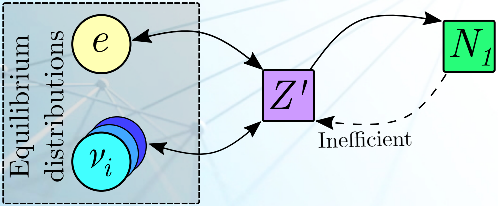
Main processes to consider are decays.

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

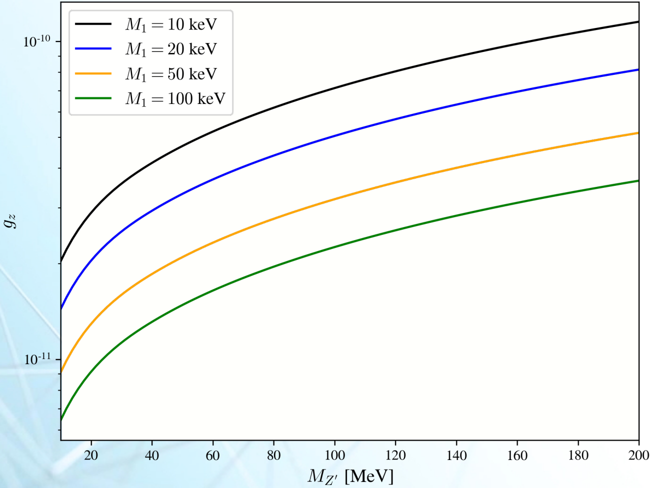
We have no reason to assume anything special about the initial abundance of Z':

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

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



1 - Anomalous magnetic moment

The coupling strength between Z' and the fermion:

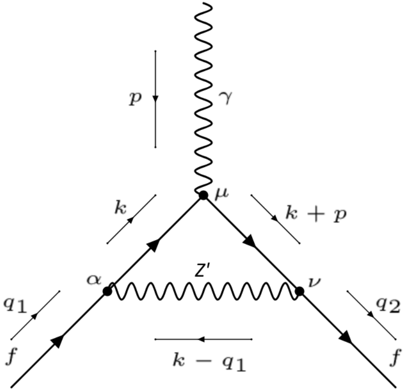
$$\tilde{g}_z = g_z \left[(\eta - 2) \cos^2 \theta_W + \frac{1}{2} \right]$$

$U(1)_z$ contribution to the magnetic moment:

$$\Delta a_f^{(\text{th.})} = \frac{\tilde{g}_z^2}{8\pi^2} \int_0^1 \mathrm{d}x \, \frac{2x(1-x)^2}{(1-x)^2 + \rho x},$$

where $\rho = \dfrac{M_{Z'}^2}{m_f^2}$

For a given $M_{Z'}$ find $g_z^{\max}$ for which $\Delta a_f^{(\text{th.})} = \Delta a_f^{(\text{exp.})}$.



3 - Supernova constraints

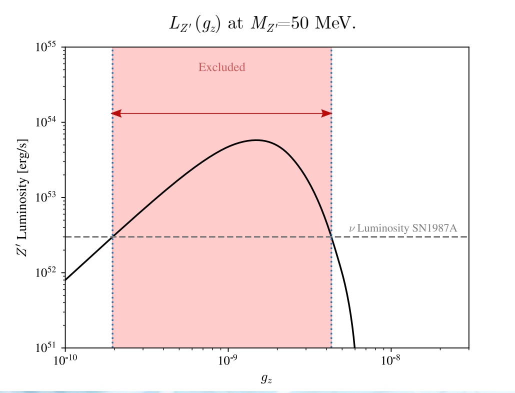
Supernova cooling: SN1987A measurement consistent with only neutrinos as cooling mechanism

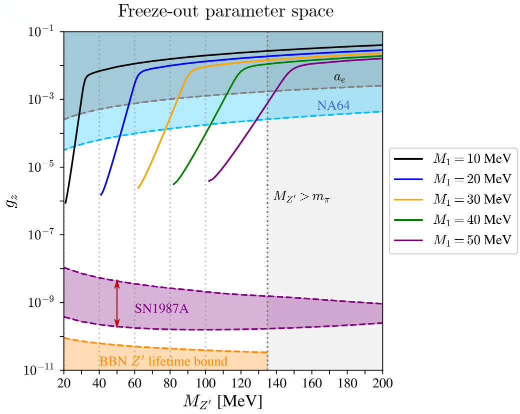
Constraint $\longrightarrow$ energy loss due to invisible channels cannot exceed that of the neutrino flux

$$Z' \text{ Luminosity:} \quad L_{Z'} = \int_0^{R_1} \mathrm{d}^3 r \int \frac{\mathrm{d}^3 k}{(2\pi)^3}\, \omega_k \Gamma_{\text{prod}}(\omega_k, r) \underbrace{\exp\left(-\int_r^{R_2} \mathrm{d}r'\, \Gamma_{\text{abs}}(\omega_k, r')\right)}_{\text{opacity}}$$

- For small couplings opacity is negligible ($\exp(-g_z^2) \approx 1$) and the luminosity is proportional to the production rate, i.e. $L_{Z'} \propto g_z^2$
- For large couplings opacity dominates over production and the luminosity is exponentially decreasing, i.e. $L_{Z'} \propto \exp(-g_z^2)$

3 - Supernova luminosity example





4 - BBN constraints

Experiments confirm that the standard model describes BBN very well (with the exception of the Li problem)

$\longrightarrow$ New physics cannot have large effects around BBN!

a.) Effective degrees of freedom (effective number of neutrinos) should not be drastically altered

- For freeze-out the change is negligible
- For freeze-in the change is $\Delta N_{\text{eff}} \sim 0.1$–$0.01$ depending on the ratio $M_{Z'}/M_1$ which is below current experimental bounds

b.) Production of pions is dangerous due to pion-enhanced proton-neutron conversion

- Simple solution: exclude $M_{Z'} > m_\pi$
- Z' lifetime constraints are present even below the pion mass, however they are negligible

5 - Other constraints

- γ ray production during and after supernova explosions
- Solar cooling can constrain models with very light particles (useful to constrain models with e.g. axions)
- Beam dump experiments can directly look for missing energy signatures
- The cosmic microwave background is very well understood and should not be disturbed by new physics (constraints on lifetimes of new particles, late-time ionisation)
- Simulations of structure formation and galaxy dynamics
- etc.