Seesaw determination of dark matter relic density

Be.HEP meeting in Brussels (UCLouvain ALMA), 2021.

Rupert Coy, Thomas Hambye, AG (ULB, Brussels)

Phys. Rev. D.104.083024 (2021)

Setting the stage

- Motivations:
  1. Two of the biggest unsolved mysteries: Origin of neutrino masses and Dark matter relic density $\Rightarrow$ Can they be interrelated?
  2. Can dark matter be detected (at least indirectly) in recent future, even if it is very *feebly* coupled to SM?
- Neutrino mass is very elegantly explained by Type-I seesaw mechanism:

$$\begin{aligned}\mathscr{L}_{\text{seesaw}} &= i\overline{N_R}\partial\!\!\!/ N_R - \frac{1}{2}m_N(\overline{N_R}N_R^c + \overline{N_R^c}N_R) \\ &\quad -(Y_\nu \overline{N_R}\tilde{H}^\dagger L + h.c.)\,,\end{aligned}$$

- The light neutrino masses are given by:

$$m_\nu = -\frac{v^2}{2} Y_\nu^T\, m_N^{-1} Y_\nu$$

- Note, we need at least three heavy neutrinos to explain the three light neutrino masses.
- Only one of the Yukawa couplings can be very small given $\Delta m^2_{\rm sol} \sim 10^{-5}$ eV and $\Delta m^2_{\rm atm} \sim 10^{-3}$.
- To explain the dark matter we next add a neutrino portal to the hidden sector:

$$\delta\mathscr{L} = -Y_\chi \overline{N} \phi \chi + h.c..$$

- Here both χ and ϕ are SM singlets.
- One or both of them can be dark matter candidates. χ is a Majorana fermion.
- Given the smallness of the Yukawa couplings dark matter is produced by freeze-in mechanism.

- Possible symmetries justifying the Lagrangian:
  - In absence of any kind of symmetries terms like $\phi H^\dagger H$ destabilizes the dark matter and hence we need to make them small by hand $\Rightarrow$ not a very attractive scenario.
  - Simplest way would be to impose a $\mathbb{Z}_2$ symmetry under which ϕ and χ are odd while all other fields are even.
  - Or a global U(1) under which only ϕ and χ is charged.
  - A gauged U(1) will have a corresponding massive Z' resulting in new decay channels of ϕ and χ. For example:
    - $\chi \to \nu Z' \propto \alpha' \underbrace{\frac{Y_\nu Y_\chi V V_\phi}{m_N m_\chi}}_{\sin\theta_{\nu\chi}} \Rightarrow$ The couplings need to be small.
    - $\chi \to \nu\gamma \propto \varepsilon \Rightarrow$ Kinetic mixing needs to be small.
  - Thus, the seesaw/DM relic density correspondence is viable but requires that quite a number of interactions are tiny.

Dark matter production

- We assume that $m_N < m_{Z,W,h}$ and $m_{N_{2,3}} > m_h$.
- N_2 and N_3 do not take part in DM production and is assumed to have very small neutrino portal interactions.
- DM is produced via freeze-in primarily from $N \to \phi\,\chi$ decay (controlled by y_χ).
- Because of this, the comoving number density $Y_N = Y_\phi = Y_\chi$.
- Hence it is sufficient to calculate Y_N (controlled by the seesaw couplings, Y_ν) and thereby establishing an one-to-one correspondence between the DM and seesaw parameters!
- Important: The relic density becomes independent of y_χ (hence giving rise to the correspondence) only if the two body decay is the dominant mode of production (more on this later).

- N is produced dominantly from decays: $h \to N\nu, W^{\pm} \to N l^{\pm}, Z \to N\nu$.
- The decay width of $V \to N f$ is given by:

$$\Gamma_{V \to N f} = \frac{1}{48\pi} m_V |Y_{\nu i}|^2 f(m_N^2/m_V^2).$$

where $f(x) = (1-x)^2(1+2/x)$ and V is $W^{\pm}$ or Z.

- For $m_N < m_V$ the gauge boson decay width is enhanced by a factor of m_V^2/m_N^2 wrt that of h.
- Freeze-in condition entails: $\Gamma_V/H|_{T \simeq m_Z} \lesssim 1 \Rightarrow$ $\sum_i |Y_{\nu i}|^2 \lesssim 1 \cdot 10^{-16} \cdot \left(\frac{m_N}{10\,\mathrm{GeV}}\right)^2$
- After solving a simple Boltzmann Eq. we get $Y_N^{\mathrm{today}} = 3 \times 10^{-4} \sum_{i=h,Z,W} \frac{g_i \Gamma_i}{M_i^2}$

- Hence, one finally obtains

$$\Omega_{DM}h^2 \simeq 10^{23} \sum_i |Y_{\nu i}|^2 \left(\frac{m_\chi + m_\phi}{1\,\mathrm{GeV}}\right) \left(\frac{10\,\mathrm{GeV}}{m_N}\right)^2 .$$

- Equating this to 0.12 we get:

$$\sum_i |Y_{\nu i}|^2 \simeq 10^{-24} \cdot \left(\frac{m_N}{10\,\mathrm{GeV}}\right)^2 \left(\frac{1\,\mathrm{GeV}}{m_\chi + m_\phi}\right). \tag{1}$$

- Using $m_{\nu_1} < \sum_i |Y_{\nu i}|^2 v^2/(2m_N)$ we get

$$m_{\nu_1} < 4 \cdot 10^{-12}\,\mathrm{eV} \cdot \frac{10\ \mathrm{GeV}}{m_N} \cdot \left(\frac{1\,\mathrm{GeV}}{m_\chi + m_\phi}\right). \tag{2}$$

- $f\bar{f} \to NL$: only 20% of the total N number density.
- The one-to-one correspondence holds iff:
  $\Gamma_{N\to\phi\chi} > \sum_f \Gamma_{N\to\nu f\bar{f}} + \Gamma_{N\to l f\bar{f}'}$

Three-body decays, neutrino line ...

- The two body decay width is given by:

$$\Gamma_{N\to\chi\phi} \simeq \frac{1}{16\pi} m_N |Y_\chi|^2 \left(1 + \frac{2m_\chi}{m_N}\right)$$

- The three body width is given by:

$$\Gamma_{N\to\nu f\bar{f}} = \frac{N_c}{1536\,\pi^3} |Y_{\nu i}|^2 \frac{g_2^2}{\cos\theta_W^2} (g_L^2 + g_R^2) \frac{m_N^3}{m_Z^2}\,,$$

and similarly for $N \to \ell f \bar{f}'$.

- Therefore $\Gamma_{N\to\phi\chi} > \sum_f \Gamma_{N\to\nu f\bar{f}} + \Gamma_{N\to l f\bar{f}'}$ implies a lower limit on y_χ:

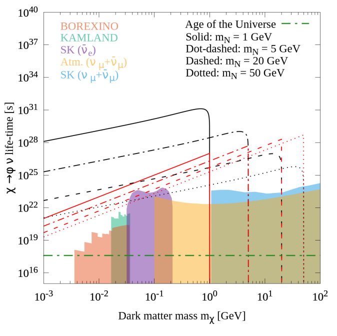
$$|Y_\chi|^2\Big|_{\rm min} \simeq 10^{-4} \sum_i |Y_{\nu i}|^2 \,(m_N/10\,\mathrm{GeV})^2 \qquad (3)$$

- Further, if $m_\chi > m_\phi$ then it can dominantly decay (with life-time $>$ age of the Universe) to produced a neutrino line.

- The decay width is given by:

$$\Gamma_{\chi\to\phi\nu} = \frac{1}{32\pi}|Y_\chi|^2 \frac{\sum_i |Y_{\nu i}|^2 v^2}{m_N^2} m_\chi \left(1 - \frac{m_\phi^2}{m_\chi^2}\right)^2 \qquad (4)$$

- This life-time has a lower limit as dictated by several neutrino experiments[1] $\Rightarrow y_\chi^2|_{\max}$. Thus, Using (1) and (3) in (4) we get the black lines as upper-limit on τ_χ:



1 JHEP05 (2021) 101 (Coy, Hambye)

Constraints

- BBN: Constraints from BBN is not a matter of concern because the number of N particles decaying is very limited, and they negligibly contribute to the total energy density at this time (hence to the Hubble expansion rate) even if N decays into two particles which are relativistic.
- Moreover, the decay is into χ and ϕ, which do not cause any photo-disintegration of nuclei since they do not produce any electromagnetic or hadronic material.
- Structure Formation: Imposing that DM, which has kinetic energy $\sim m_N/2$ when produced from N decay, redshifts enough so that it is non-relativistic when $T \sim$ keV gives an upper bound on the χ lifetime (the red lines in the plot)

$$\tau_\chi \lesssim 10^{28}\,\text{sec}\left(\frac{m_{DM}}{m_N}\right)^2\left(\frac{m_N}{10\,\text{GeV}}\right). \tag{5}$$

A second scenario: Relativistic Freeze-out

- Consider that the heaviest particle among χ and ϕ has a lifetime $<$ the age of the universe $\Rightarrow$ much larger values of y_χ.
- In this case, DM is made of only the lightest species and no neutrino line can be observed.
- A large y_χ coupling $\Rightarrow$ thermalisation of N, χ and ϕ.
- The thermalised hidden sector is characterized by a temperature, $T' < T$.
- The one-to-one connection is lost ?
  - Yes, if DM undergoes a non-relativistic, secluded freeze-out in the hidden sector.
  - But here, since $m_\phi < m_N, m_\chi$, the ν-portal annihilation processes ($\phi\phi \leftrightarrow \chi\chi$ etc) will not decouple when DM is non-relativistic but when DM is relativistic.

$\Rightarrow$ DM relic doesn't depend on the annihilation cross section but only on T'/T.

- T'/T is set by the $SM \to N$ freeze-in induced by the Y_ν coupling, here one also finds a one-to-one relation between seesaw parameters and DM relic density.

- T'/T can be estimated by considering that at the peak of N freeze-in production, when $T \simeq m_Z$, each N has an energy $\simeq m_Z$, so that the dark sector energy density is

$$\rho_{DS}|_{T\simeq m_Z} \simeq n_N|_{T\simeq m_Z} m_Z = (\pi^2/30) g^\star_{HS} T'^4 , \tag{6}$$

with n_N given by $Y_N = n_N/s$ found earlier.

- Knowing T'/T we can find the relic density by[2]:

$$\Omega_{DM} = 1.74 \times 10^{11} \left(\frac{m_\phi}{1\,TeV}\right) \left(\frac{T'}{T}\right)^3 \left(\frac{g_{\mathrm{DM}}}{g^s_\star}\right) \tag{7}$$

where $n_\phi \sim T'^3$ and entropy conservation at decoupling time is used.

[2] Phys.Lett.B 807 (2020) 135553, Hambye, Lucca, Vanderheyden.

- Using (6) in (7) we get:

$$\Omega_{DM}h^2 \simeq 2.5\times 10^{18}\left(\sum_i |Y_{\nu i}|^2\right)^{3/4} \cdot g_{DM}\left(\frac{1\,\mathrm{GeV}}{m_N}\right)^{3/2}\left(\frac{m_{DM}}{100\text{ MeV}}\right), \qquad (8)$$

- Note that this requires slightly smaller values of Y_ν couplings than the first scenario, because the dark sector thermalisation process increases the number of DM particles.
- T'/T can be more accurately calculated using [3]:

$$\frac{d\rho_{\rm DS}}{dt} + 4H\rho_{\rm DS} = \frac{1}{a^4}\frac{d(\rho_{\rm DS}\,a^4)}{dt} = -\sum_{i=Z,h,W}\frac{g_i}{2\pi^2}m_i^3\,T\,\Gamma_i K_2(m_i/T)$$

- The results are in good agreement with Eq.(7).

[3] JCAP05(2012)034, Chu, Hambye, Tytgat

Summary

- Seesaw-induced W, Z and h decays could be at the origin of the DM relic density, even though DM is not a seesaw sterile neutrino.
- the usual type-I seesaw model turns out to have sufficient flexibility to allow freeze-in production of DM from these decays in a way which is determined only by the seesaw parameters and the mass of the DM particle.
- As always for freeze-in, these scenarios are not easily testable because they are based upon the existence of tiny interactions.
- The first scenario predicts a neutrino-line within reach of existing or near-future neutrino telescopes.
- Moreover, both scenarios are falsifiable as they predict a small mass for the lightest neutrino.

THANK YOU