Scrutinising Dirac neutrino in CMB:

An alternative road to Dark Matter

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Refs. **arXiv**:2103.05648 (JCAP), **arXiv**:2205.01144

Major unsolved issues in the ν-sector

- What is the exact mechanism behind neutrino mass generation?
- What is the absolute mass scale of neutrinos?
  - from cosmology $\sum m_i < 0.12$ eV Planck 2018 arXiv:1807.06209
  - from oscillation experiments only two mass square differences are known

  ($\Delta m^2_{12} \simeq 7.4 \times 10^{-5}$ eV^2 and $|\Delta m^2_{23}| \simeq 2.5 \times 10^{-3}$ eV^2) NuFIT arXiv:2007.14792
- What is the flavour symmetry that reproduces such a peculiar mixing pattern? $\left(\theta_{23} \simeq 42.1^\circ (49.0^\circ) > \theta_{12} \simeq 33.4^\circ >> \theta_{13} \simeq 8.6^\circ\right)$

  $\Rightarrow$ distinctly different from the quark mixing!

  $\left(\theta^q_{12} \simeq 13.1^\circ >> \theta^q_{23} \simeq 2.3^\circ >> \theta^q_{13} \simeq 0.22^\circ\right)$ PTEP 2020, 083C01 (PDG)
- What is the amount of CP violation in the ν-sector?
  - current data indicates nearly maximal CP violation $\delta_{CP} \sim 230^\circ (278^\circ)$ and disfavours CP conservation. No prediction is still there for the Majorana phases!

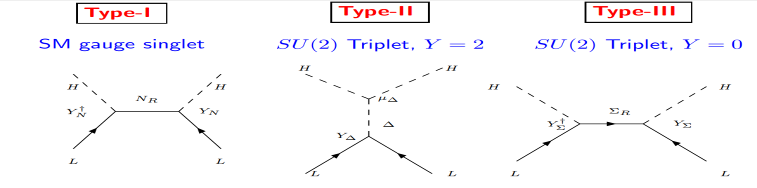
Dirac or Majorana fermion?

What happen if ν is Majorana

Two units of L violation is required

- Neutrino is its own anti-particle, $\nu_j^c = e^{i\alpha}\nu_j$, where $\nu_j^c = C\overline{\nu_j}^T$
- Lepton number (L), an accidental symmetry of the SM, does not remain conserved $\Rightarrow$ Majorana mass term $\overline{\nu_\alpha^c}\nu_\alpha$ violates L symmetry explicitly
- Seesaw mechanism is the most natural way to address tiny ν mass
  - Heavy fermionic or scalar degrees of freedom in the theory: $m_\nu \propto v^2/M$

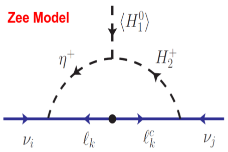
  $\Rightarrow$ high scale origin of neutrino mass, Minkowski (1977), Yanagida (1979), Mahapatra & Senjanovic (1980)

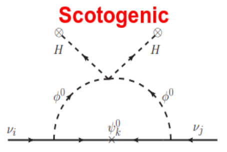


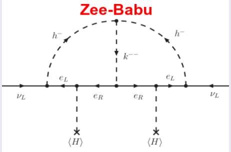
- Inverse seesaw $(m_\nu \propto \mu)$: adding another singlet fermion S_L with mass $\mu\overline{S_L}S_L^c$, only L violating term, $\mu \to 0$ re-establish L conservation Mahapatra & Valle (1986)

Majorana ν

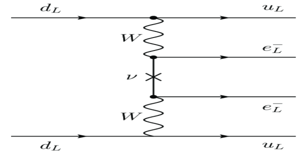
- Radiative generation of ν mass ($\Delta L = 2$ vertices are introduced): At one loop (Zee model PLB 1980, Scotogenic model PRD 2006), two loop (Zee-Babu model PLB 1988), three loop (cocktail model PRL 2012) etc.

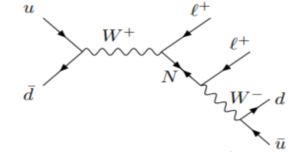






- Characteristic signature is $0\nu\beta\beta$, ${}^{76}\mathrm{Ge} \to {}^{76}\mathrm{Se} + 2e^-$, $\tau_{\mathrm{half}} > 5.3 \times 10^{25}$ yr $\Rightarrow m_{\beta\beta} < 0.15 - 0.33$ eV (GERDA II), and in collider $pp \to \ell^\pm \ell^\pm + 2j$ Keung & Senjanovic, PRL 1983, T. Han, PRL 2006





Dirac ν: new interactions are required!

- No experimental results till date have shown preference to Majorana over Dirac
- like other charged fermions, there will be ν_R as light as ν_L
- tiny ν mass via Dirac seesaw (Logan et. al. 2009, Ma et. al. 2015, Valle et. al. 2016, Baek 2019 ...) and loop induced processes (Babu et. al. 1989, Ma et. al. 2012 ...)
- ν_R can act as dark radiation and could be important from cosmological point of view
- effective number of relativistic DOF: $N_{\rm eff} = \dfrac{\rho_{\rm rad} - \rho_\gamma}{\rho_{\nu_L}}$; $\rho_{\rm rad}^{\rm SM} = \left(1 + n_\nu \dfrac{7}{8}\left(\dfrac{T_{\nu_L}}{T}\right)^4\right)\rho_\gamma$
- $N_{\rm eff} = 2.99^{+0.34}_{-0.33}$ (Planck 2018) and $N_{\rm eff}^{\rm SM} = 3.045$ (due to three active νs) Mangano et. al. 2005

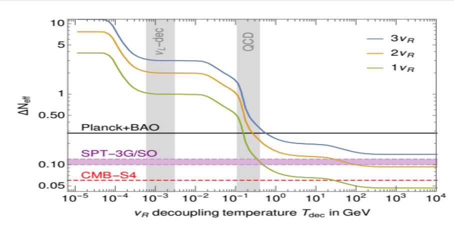
$\Delta N_{\rm eff}$ for thermalised ν_R:s Abazajian et. al. 2019

- $\Delta N_{\rm eff} = 3 \times 2 \times \dfrac{7}{8} \times 0.027 \left(\dfrac{106.75}{g_s(T_{\rm dec})}\right)^{4/3}$
- For one thermalised $\nu_R \Rightarrow \Delta N_{\rm eff}^{\rm min} = 0.0473$

CMB-S4: $\Delta N_{\rm eff} \equiv N_{\rm eff} - N_{\rm eff}^{\rm SM} = 0.054\ (2\sigma)$

- $T_{\rm dec} \gtrsim 600$ MeV for 3 ν_Rs
- for non-thermalised ν_R: $\Delta N_{\rm eff} \sim \mathcal{O}(10^{-12})$

Rodejohann et. al. JCAP 2021



minimal choice to thermalise ν_R

add a scalar field Φ

$\lambda_{H\Phi}\,(H^\dagger H)(\Phi^\dagger\Phi)$ → **Thermalize Φ.**

+

$y_\Phi\,\overline{\psi}\,\nu_R\,\Phi$ → **Thermalize ν_R and ψ.**

Charge assignment

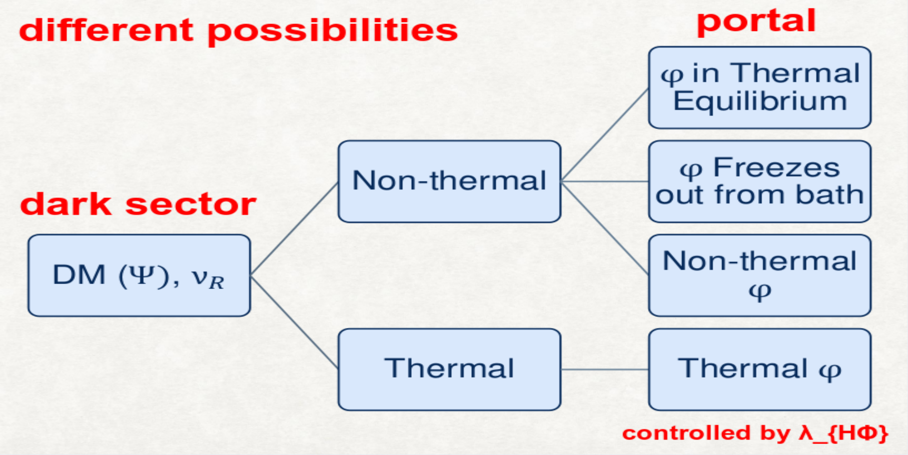
Particles	$SU(3)_c \times SU(2)_L \times U(1)_Y$	$\mathbb{Z}_4$
ℓ_L^α	$(1, 2, -\frac{1}{2})$	i
e_R^α	$(1, 1, -1)$	i
ν_R^α	$(1, 1, 0)$	i
ψ	$(1, 1, 0)$	-1
ϕ	$(1, 1, 0)$	i

primary requirements

- Dirac $\nu \Rightarrow$ ~~$\nu_R^c \nu_R$~~
- Stable DM $\Rightarrow$ ~~$\bar{L}_\alpha \tilde{H} \psi$~~

Refs. arXiv:2103.05648 (JCAP), ar

depending on $\lambda_{H\phi}$ & y_ϕ



- Thermal dark sector $y_\phi \sim 0.1$
- Non-thermal dark sector $y_\phi \lesssim 10^{-10}$

Thermal dark sector

Thermalisation & kinetic decoupling of portal ϕ

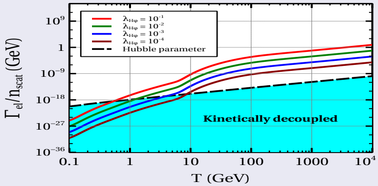
Chemical equilibrium: $\phi\phi^\dagger \to \mathrm{SM}\,\overline{\mathrm{SM}}$, **kinetic equilibrium:** $\phi(\phi^\dagger)\,\mathrm{SM} \to \phi(\phi^\dagger)\,\mathrm{SM}$

for kinetic decoupling

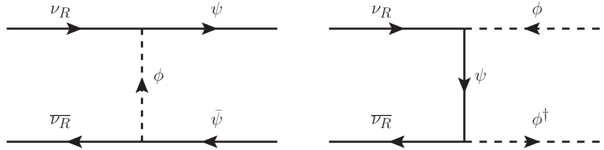
$$\frac{\sum_X n_X^{\rm eq} \times \langle\sigma \mathrm{v}\rangle_{\phi X\to\phi X}}{n_{\rm scat}} < \mathcal{H} \text{ at } T = T_{\rm dec}$$

- no. of scatterings required to transfer energy $\sim T$ is $n_{\rm scat}$
- weakly coupled ϕ decouples early
- massive ϕ decouples early

$T < T_{\rm dec} \Rightarrow T_{\rm dark} \neq T_{\rm SM}$



Thermalisation of ν_R & freeze-out of ψ



Contribution to $N_{\rm eff}$

$$N_{\rm eff} \equiv \frac{\varrho_{\rm rad} - \varrho_\gamma}{\varrho_{\nu_L}}$$

Mangano et. al.
NPB729(2005)221

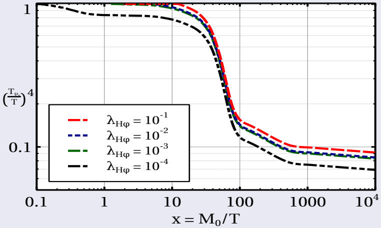
$$N_{\rm SM} = 3.046,\ \Delta N_{\rm eff} \leq 0.285\ (2\sigma)$$

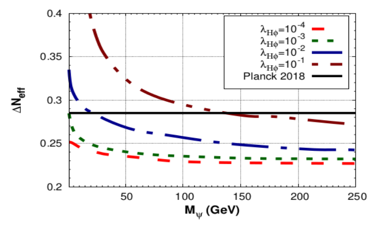
$$\Delta N_{\rm eff} = \frac{\sum_\alpha \varrho_{\nu_R^\alpha}}{\varrho_{\nu_L}} = 3 \times \frac{\varrho_{\nu_R}}{\varrho_{\nu_L}} = 3 \times \left(\frac{T_{\nu_R}}{T_{\nu_L}}\right)^4 \Bigg|_{T > T^{\rm dec}_{\nu_L}} = 3 \times \left(\frac{T_{\nu_R}}{T}\right)^4 \Bigg|_{T > T^{\rm dec}_{\nu_L}} = 3 \times \xi^4 \Big|_{T > T^{\rm dec}_{\nu_L}}$$

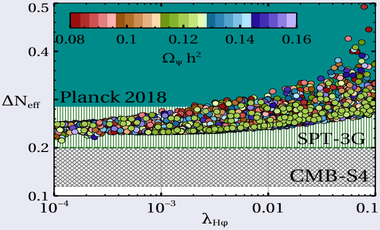
Few assumptions

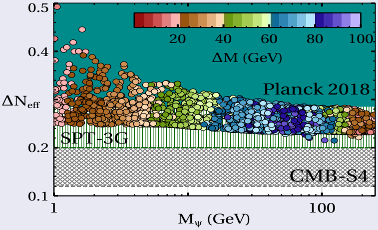
- All three right handed neutrinos have same couplings for the new Yukawa interaction.
- We have used the equilibrium distribution function for the right handed neutrinos throughout its cosmological evolution.

Numerical results for the thermal case





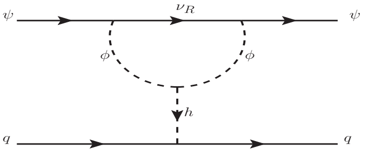


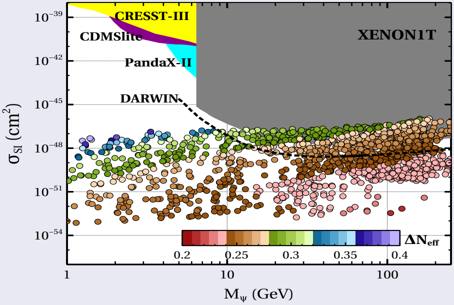


Direct detection (DD) of ψ

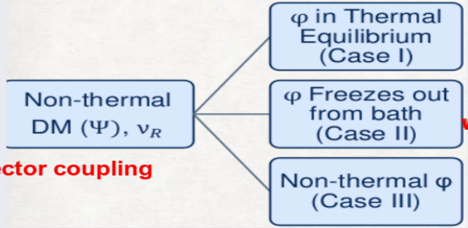
Indirect probe of secluded sector DM

- $\sigma_{\rm SI}$ is a loop induced process
- $\sigma_{\rm SI} \propto \frac{1}{mh^4}\left(\frac{\lambda_{H\phi} y_\phi^2}{M_\psi}\right)^2$
- Low mass region, beyond the reach of DD experiments, already excluded from Planck 2018 data
- future CMB experiments will probe the entire parameter space along with a fraction by DARWIN (high mass range)





Non-thermal dark sector



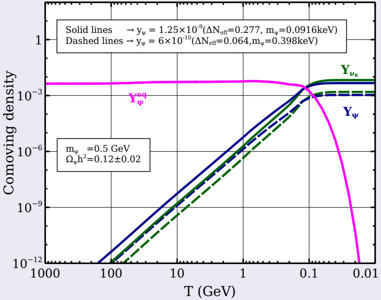
large portal coupling

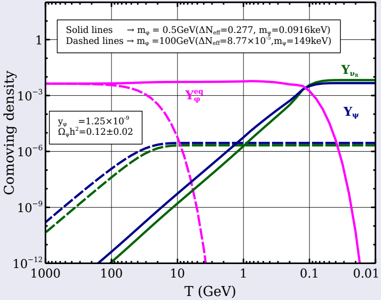
weak scale portal

feeble portal

feeble dark sector coupling

Case-I, ϕ in thermal equilibrium during DM production





$$Y_\psi \propto y_\phi^2 \qquad\qquad Y_\psi \propto 1/m_\phi$$

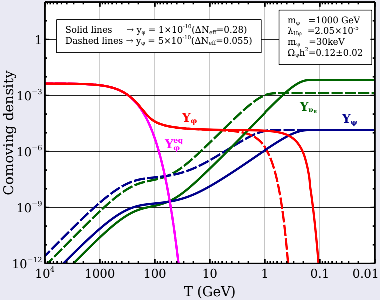
Hall et. al. JHEP 2010

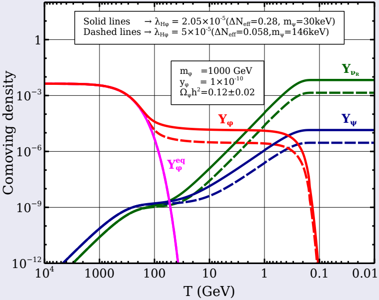
observations

- require $m_\psi < 1$ keV to satisfy relic density and sizeable $\Delta N_{\rm eff}$
- already excluded by Lyman α bound on free streaming length ($m_{\rm DM} \geq 7$ keV)

Ballesteros et. al. JCAP 2021

Case-II, ϕ freezes out during DM production



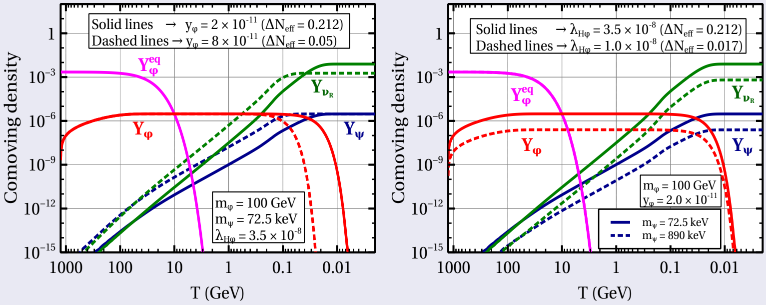


$Y_\psi \propto Y_\phi(T_F)$ $\qquad$ $Y_\psi \propto 1/\lambda^2_{H\phi}$

observations

- possible to produce correct relic density and sizeable $\Delta N_{\rm eff}$ and remain consistent with Lyman-α bound
- predicts low mass DM; $m_\psi \sim (\mathcal{O}(10))$ keV

Case-III, non-thermal ϕ



$Y_\psi \propto Y_\phi$ $\qquad$ $Y_\psi \propto \lambda_{H\phi}^2$

observations

- here also possible to produce correct relic density and sizeable $\Delta N_{\rm eff}$ and remain consistent with Lyman-α bound
- m_ψ can be as large as $\sim (\mathcal{O}(100))$ keV

Summary

• Precise measurement of $N_{\rm eff}$ will be a powerful tool to understand the existence of extra radiation in the early universe in general

• In particular, CMB-S4 will have the sensitivity to falsify the scenario of thermalised ν_R

• Current Planck measurement $N_{\rm eff} \leq 0.285$ has already probed some portion of low mass region ($\sim$ a few GeV) of secluded thermal DM model (where DD expts. are not sensitive enough)

• For non-thermal dark sector $\Delta N_{\rm eff}$, getting an observable $\Delta N_{\rm eff}$ requires light DM ($\mathcal{O}(1 \sim 100)$ keV) and some scenarios are already excluded from Lyman-α bound.

Thank you

Backup Slides

Boltzmann equation for thermal dark sector

When $T > T_{\rm dec}$

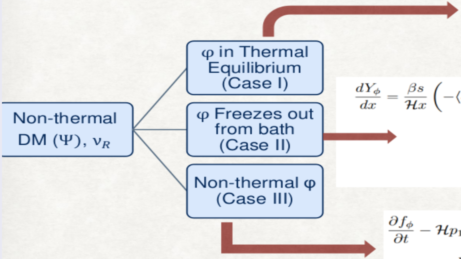
$$\frac{dY}{dx} = -\frac{1}{2}\frac{\beta\, s}{\mathcal{H}\, x}\langle \sigma v\rangle_{eff}\left[Y^2 - (Y^{eq})^2\right] \qquad \left(\beta(T) = \frac{g_\star^{1/2}(T)\sqrt{g_\rho(T)}}{g_s(T)}\right)$$

When $T < T_{\rm dec}$

$$\frac{dY}{dx} = -\frac{1}{2}\frac{\beta\, s}{\mathcal{H}\, x}\langle \sigma v\rangle_{eff}\left[Y^2 - (Y^{eq})^2\right] ,$$

$$x\,\frac{d\xi}{dx} + (\beta - 1)\xi = \frac{1}{2}\frac{\beta\, x^4\, s^2}{4\,\alpha\,\xi^3\,\mathcal{H}\, M_0^4}\langle E\sigma v\rangle_{eff}\left[Y^2 - (Y^{eq})^2\right] \qquad \left(\xi = \frac{T_{\nu_R}}{T}\right)$$

Boltzmann equation for non-thermal dark sector



$$\frac{dY_\psi}{dx} = \frac{\beta}{x\mathcal{H}}\Gamma_\phi \frac{K_1(x)}{K_2(x)} Y_\phi^{\rm eq},$$

$$\frac{dY_{\nu_R}}{dx} = \frac{\beta}{\mathcal{H}s^{1/3}x}\langle E\Gamma\rangle Y_\phi^{\rm eq},$$

$$\frac{dY_\phi}{dx} = \frac{\beta s}{\mathcal{H}x}\left(-\langle\sigma v\rangle\left((Y_\phi)^2-(Y_\phi^{\rm eq})^2\right) - \frac{\Gamma_\phi}{s}\frac{K_1(m_\phi/T)}{K_2(m_\phi/T)}Y_\phi\right),$$

$$\frac{dY_\psi}{dx} = \frac{\beta}{x\mathcal{H}}\Gamma_\phi \frac{K_1(x)}{K_2(x)} Y_\phi,$$

$$\frac{dY_{\nu R}}{dx} = \frac{\beta}{\mathcal{H}s^{1/3}x}\langle E\Gamma\rangle Y_\phi.$$

$$\frac{\partial f_\phi}{\partial t} - \mathcal{H}p_1\frac{\partial f_\phi}{\partial p_1} = C^{h\to\phi\phi^\dagger} + C^{hh\to\phi\phi^\dagger} + C^{\phi\to\bar{\nu}_R\psi},$$

$$\frac{dY_\psi}{dr} = \frac{g_\phi\beta}{r\mathcal{H}s}\frac{\Gamma_\phi m_\phi}{2\pi^2}\int \frac{\left(\mathcal{A}\frac{m_0}{r}\right)^3\xi^2 f_\phi(\xi,r)}{\sqrt{\left(\xi\mathcal{A}\frac{m_0}{r}\right)^2+m_\phi^2}}d\xi\,,$$

$$\frac{dY_{\nu_R}}{dr} = \frac{g_\phi\beta}{r\mathcal{H}s^{4/3}}\langle E\Gamma\rangle\frac{1}{2\pi^2}\int_0^\infty\left(\mathcal{A}\frac{m_0}{r}\right)^3\xi^2 f_\phi(\xi,r)d\xi\,,$$