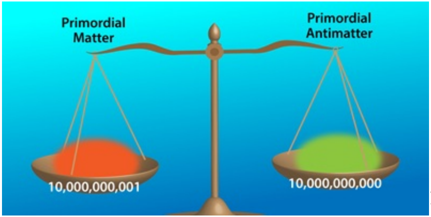
Low scale leptogenesis and dark matter in the presence of primordial black holes

based on arXiv : 2104.14496
(Suruj Jyoti Das, Devabrat Mahanta, Debasish Borah).

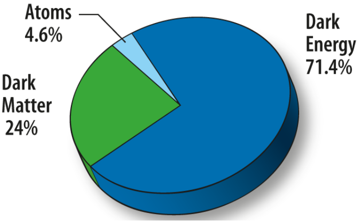
Suruj Jyoti Das
Department of Physics,
Indian Institute of Technology, Guwahati.

Plan of the talk

- Motivation.
- Primordial Black Holes.
- The Scotogenic model.
- Scotogenic leptogenesis and scalar DM in the presence of PBH.
- N_2 leptogenesis and fermion DM.
- Summary.
- Conclusion.



[1]



Baryon Asymmetry : $\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6.1 \times 10^{-10}$. **Dark Matter :** $\Omega_{\rm DM} h^2 \approx 0.12$.

- Some BSM physics : Leptogenesis, WIMP, FIMP...
- Cosmic history prior to BBN ?

A Universe dominated by **Primordial Black Holes (PBH)!**

[1] Alan Stonebraker

Primordial Black Holes (Hawking 1975)

- PBH formed in the very early universe (Carr et al. 2002.12778),

$$M_{\rm BH}(T_{\rm in}) \approx \frac{4\pi}{3}\frac{\rho_{\rm Rad}(T_{\rm in})}{H^3(T_{\rm in})}.$$

$$\boxed{\text{Lower bound}:\ H_I \leq 2.5\times 10^{-5} M_{\rm Pl} \implies M_{\rm in} \gtrsim 0.1\ g}$$

- Black hole temperature :

$$T_{\rm BH} = \frac{1}{8\pi G M_{\rm BH}} \approx 1.06\ \left(\frac{10^{13}\ \rm g}{M_{\rm BH}}\right)\ \rm GeV.$$

- Initial PBH fraction :

$$\beta = \frac{\rho_{\rm BH}(T_{\rm in})}{\rho_{\rm Rad}(T_{\rm in})}.$$

- Hawking evaporation :

$$\frac{dM_{\rm BH}}{da} = -\frac{\epsilon(M_{\rm BH})\kappa}{aH}\left(\frac{1\ \rm g}{M_{\rm BH}}\right)^2 \qquad T_{\rm ev} \approx \left(\frac{9g_*(T_{\rm BH})}{10240}\right)^{\frac{1}{4}}\left(\frac{M_{\rm Pl}^5}{M_{\rm in}^3}\right)^{\frac{1}{2}}.$$

$$\boxed{\text{Upper bound}:\ M_{\rm in} \lesssim 2\times 10^8\ \rm g\ (BBN) \quad M_{\rm in} \lesssim 2\times 10^5\ \rm g\ (Sphaleron).}$$

The Scotogenic model [E. Ma, Phys. Rev. D73 (2006) 077301].

BSM Particles	$SU(2)_L$	Z_2
$N_i (i = 1, 2, 3)$	0	$-$
$\eta = (\eta^{\pm} \quad H^0 + i A^0/\sqrt{2})$	1	$-$

$$\mathcal{L} \supset \frac{1}{2}(M_N)_{ij} N_i N_j + \left(Y_{ij} \bar{L}_i \tilde{\eta} N_j + \text{h.c.} \right)$$

$$V(\Phi_1, \eta) = \mu_1^2 |\Phi_1|^2 + \mu_2^2 |\eta|^2 + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\eta|^4 + \lambda_3 |\Phi_1|^2 |\eta|^2 + \lambda_4 |\Phi_1^\dagger \eta|^2 + \left[\frac{\lambda_5}{2} (\Phi_1^\dagger \eta)^2 + \text{h.c.} \right].$$

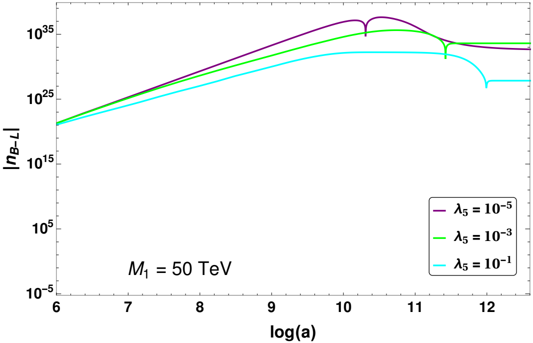
- Light neutrino mass at loop-level :

$$(m_\nu)_{ij} = \sum_k \frac{Y_{ik} Y_{jk} M_k}{32\pi^2} \left[L_k(m_{H^0}^2) - L_k(m_{A^0}^2) \right]$$

$$L_k(m^2) = \frac{m^2}{m^2 - M_k^2} \ln \frac{m^2}{M_k^2}.$$

- CP asymmetry :

$$\epsilon_i = \frac{\sum_\alpha \Gamma(N_i \to l_\alpha \eta) - \Gamma(N_i \to \bar{l}_\alpha \bar{\eta})}{\sum_\alpha \Gamma(N_i \to l_\alpha \eta) + \Gamma(N_i \to \bar{l}_\alpha \bar{\eta})}$$
$$= \frac{1}{8\pi (Y^\dagger Y)_{ii}} \sum_{j \neq i} \mathrm{Im}[((Y^\dagger Y)_{ij})^2] \frac{1}{\sqrt{r_{ji}}} F(r_{ji}, \eta_i).$$



Scotogenic leptogenesis in the presence of PBH

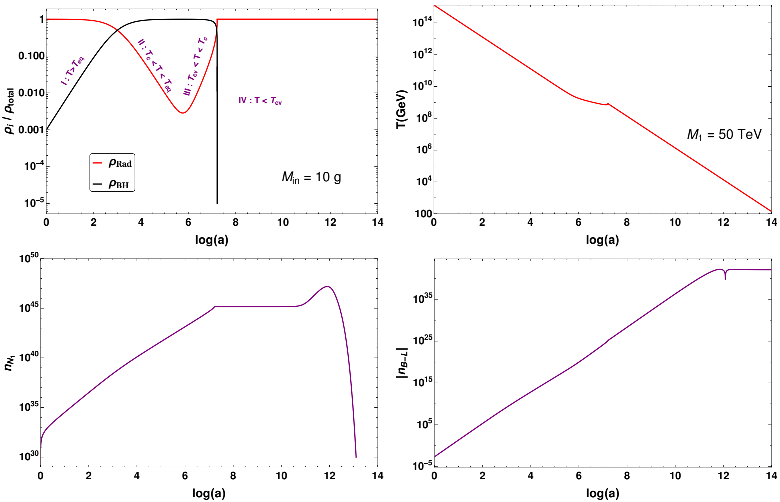
Boltzmann equations :

$$
\begin{aligned}
\frac{d\varrho_{\rm BH}}{da} &= \frac{1}{M_{\rm BH}}\frac{dM_{\rm BH}}{da}\varrho_{\rm BH}\,,\\
\frac{d\varrho_{\rm Rad}}{da} &= -\frac{\epsilon_{\rm SM}(M_{\rm BH})}{\epsilon(M_{\rm BH})}\frac{1}{M_{\rm BH}}\frac{dM_{\rm BH}}{da}a\varrho_{\rm BH}\,,\\
aH\frac{dn^T_{N_1}}{da} &= -\left(n^T_{N_1}-n^{\rm eq}_{N_1}\right)\Gamma^T_1\,,\\
aH\frac{dn^{\rm BH}_{N_1}}{da} &= -\left(n^{\rm BH}_{N_1}\right)\Gamma^{\rm BH}_1+n_{\rm BH}\Gamma_{{\rm BH}\to N_1}\,,\\
aH\frac{dn_{B-L}}{da} &= \epsilon_1\left[\left(n^T_{N_1}-n^{\rm eq}_{N_1}\right)\Gamma^T_1+n^{\rm BH}_{N_1}\Gamma^{\rm BH}_1\right]-(W_{ID}+\Delta W_{scattering})n_{B-L}\,,\\
\frac{dT}{da} &= -T\left(\frac{1}{a}+\frac{\epsilon_{SM}(M_{\rm BH})}{\epsilon(M_{\rm BH})}\frac{1}{M}\frac{dM_{BH}}{da}\frac{a\varrho_{\rm BH}}{4\varrho_{\rm Rad}}\right).
\end{aligned}
$$

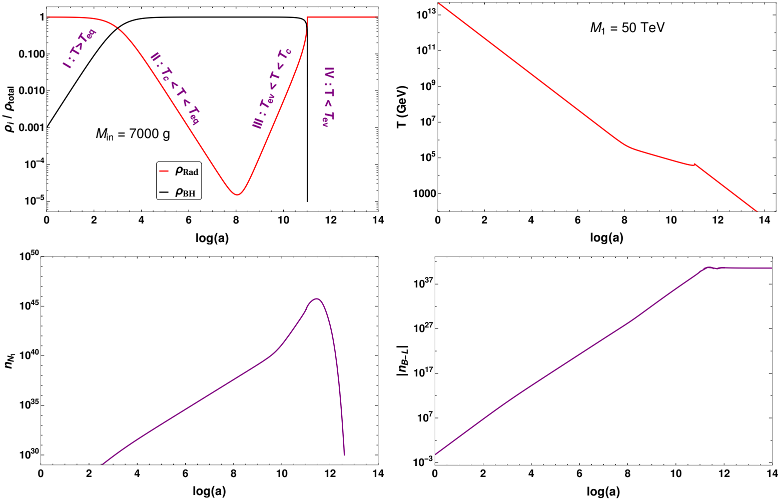
N_1 produced from PBH (J. Turner et al. 2010.03565) :

$$
\Gamma_{{\rm BH}\to N_1}=\frac{27\,T_{\rm BH}}{32\pi^2}\left(-z_{\rm BH}{\rm Li}_2(-e^{-z_{\rm BH}})-{\rm Li}_3(-e^{-z_{\rm BH}})\right).
$$

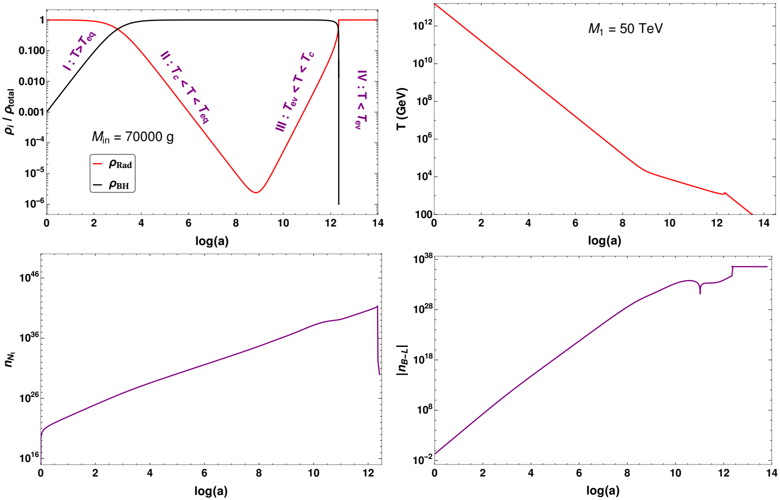
PBH evaporate before leptogenesis scale :

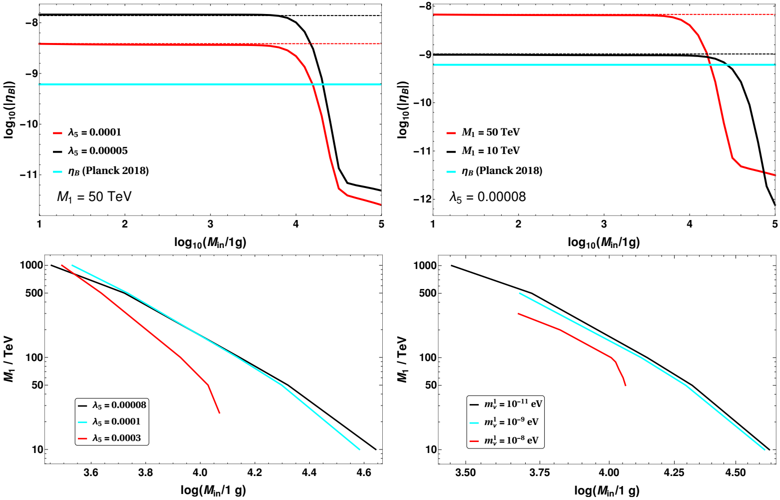


PBH evaporate during leptogenesis scale :



PBH evaporate after leptogenesis scale :



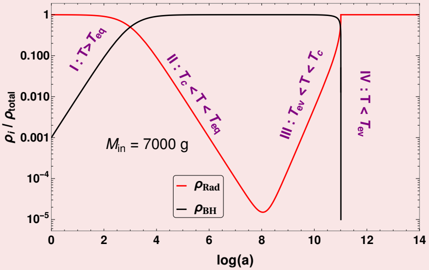


$\log_{10}(|\eta_B|)$
$\lambda_5 = 0.0001$
$\lambda_5 = 0.00005$
η_B (Planck 2018)
M_1 = 50 TeV
$\log_{10}(M_{in}/1g)$
$M_1 = 50$ TeV
$M_1 = 10$ TeV
η_B (Planck 2018)
λ_5 = 0.00008
$\log_{10}(M_{in}/1g)$
M_1 / TeV
$\lambda_5 = 0.00008$
$\lambda_5 = 0.0001$
$\lambda_5 = 0.0003$
$\log(M_{in}/1\text{ g})$
M_1 / TeV
$m_\nu^1 = 10^{-11}$ eV
$m_\nu^1 = 10^{-9}$ eV
$m_\nu^1 = 10^{-8}$ eV
$\log(M_{in}/1\text{ g})$

- DM candidate : Lightest scalar of inert doublet.

In the presence of PBH (N. Bernal et al. 2011.12306) :

1. $T_{fo} > T_{eq}$: Usual WIMP DM in a RD universe, with PBH dilution.
2. $T_c < T_{fo} < T_{eq}$: PBH dominate (for $\beta > \beta_c$), $\rho_{Rad} \propto a^{-4}$.
3. $T_{ev} < T_{fo} < T_c$: $\rho_{Rad} \propto a^{-3/2}$.
4. $T_{fo} < T_{ev}$: RD universe again, no PBH dilution.



Dark Matter in the presence of PBH

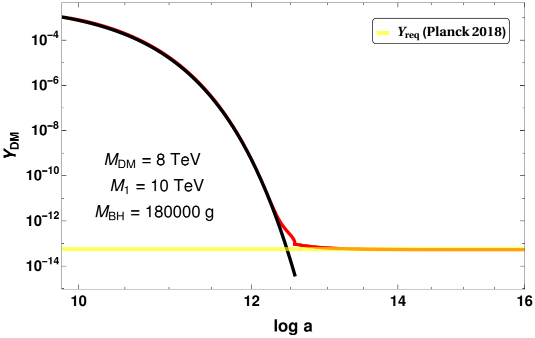
$$\boxed{\Omega_{\rm DM}^{\rm total} h^2 = \Omega_{\rm DM}^{\rm BH} h^2 + \Omega_{\rm DM}^{\rm fo} h^2 \text{ (P. Gondolo et al. 2009.02424).}}$$

$$T_{fo} > T_{ev} \implies M_{DM} > 3\, MeV\, (trivially\ satisfied).$$

Dark Matter in the presence of PBH

$$\boxed{\Omega_{\rm DM}^{\rm total} h^2 = \Omega_{\rm DM}^{\rm BH} h^2 + \Omega_{\rm DM}^{\rm fo} h^2}$$ (P. Gondolo et al. 2009.02424).

$$T_{fo} > T_{ev} \implies M_{DM} > 3\, MeV\, (trivially\ satisfied).$$



Dark Matter in the presence of PBH

DM from PBH (P. Gondolo et al. 2009.02424) :

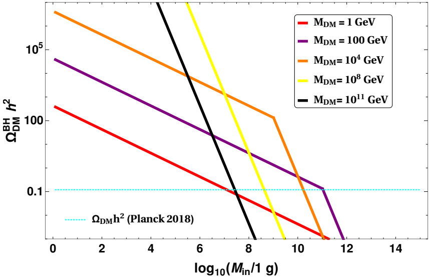
$$Y_{\rm DM} = \frac{n_{\rm DM}(T_0)}{s(T_0)} \simeq \frac{3}{4} N_{\rm DM} \times \begin{cases} \beta \frac{T_{\rm in}}{M_{\rm in}} & \text{for RD, } \beta \leq \beta_c, \\ \frac{\bar{T}_{\rm ev}}{M_{\rm in}} & \text{for MD, } \beta \geq \beta_c. \end{cases}$$

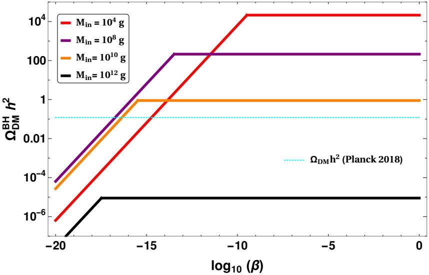
$$N_{\rm DM} = \frac{15\zeta(3)}{\pi^4} \frac{1}{g_*(T_{\rm BH})} \times \begin{cases} \left(\frac{M_{\rm in}}{M_{\rm Pl}}\right)^2 & \text{for } M_{\rm DM} \leq T_{\rm BH}^{\rm in}, \\ \left(\frac{M_{\rm Pl}}{M_{\rm DM}}\right)^2 & \text{for } M_{\rm DM} \geq T_{\rm BH}^{\rm in}. \end{cases}$$

DM from PBH (P. Gondolo et al. 2009.02424) :

$$Y_{\rm DM} = \frac{n_{\rm DM}(T_0)}{s(T_0)} \simeq \frac{3}{4} N_{\rm DM} \times \begin{cases} \beta \frac{T_{\rm in}}{M_{\rm in}} & \text{for RD, } \beta \leq \beta_c, \\ \frac{\bar{T}_{\rm ev}}{M_{\rm in}} & \text{for MD, } \beta \geq \beta_c. \end{cases}$$

$$N_{\rm DM} = \frac{15\zeta(3)}{\pi^4} \frac{1}{g_*(T_{\rm BH})} \times \begin{cases} \left(\frac{M_{\rm in}}{M_{\rm Pl}}\right)^2 & \text{for } M_{\rm DM} \leq T_{\rm BH}^{\rm in}, \\ \left(\frac{M_{\rm Pl}}{M_{\rm DM}}\right)^2 & \text{for } M_{\rm DM} \geq T_{\rm BH}^{\rm in}. \end{cases}$$



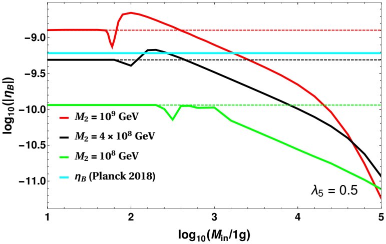


N_2 leptogenesis and fermion dark matter.

- Leptogenesis from N_2 decay.
- N_1 : FIMP DM candidate ($lW^{\pm}(Z) \longrightarrow N_1\eta$, $l\eta \longrightarrow W^{\pm}(Z)N_1$, $\eta \rightarrow N_1 l$).

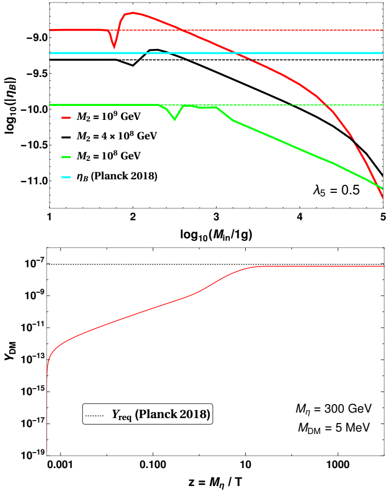
N_2 leptogenesis and fermion dark matter.

- Leptogenesis from N_2 decay.
- N_1 : FIMP DM candidate ($lW^{\pm}(Z) \longrightarrow N_1\eta$, $l\eta \longrightarrow W^{\pm}(Z)N_1$, $\eta \rightarrow N_1 l$).

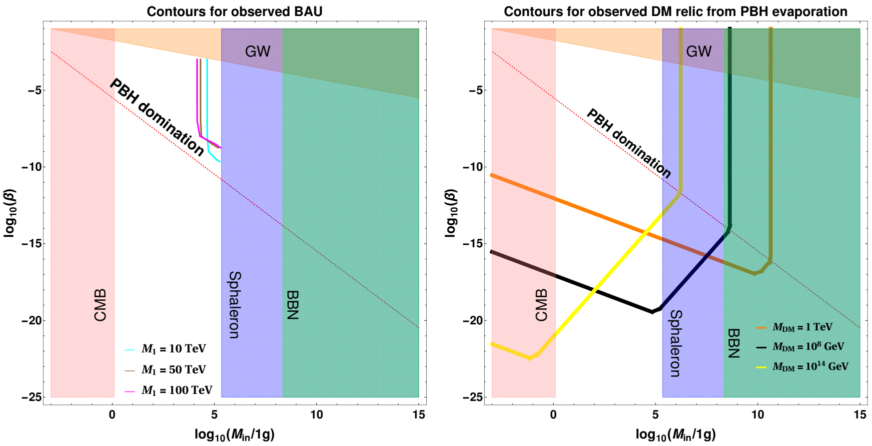


N_2 leptogenesis and fermion dark matter.

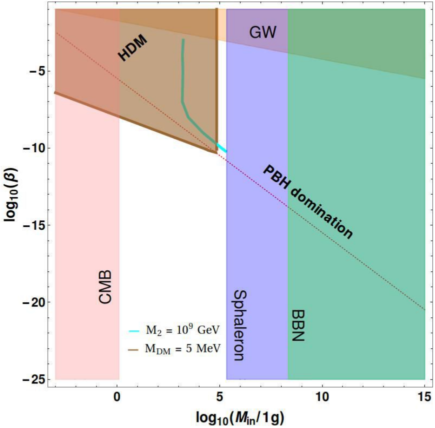
- Leptogenesis from N_2 decay.
- N_1 : FIMP DM candidate ($lW^{\pm}(Z) \longrightarrow N_1\eta$, $l\eta \longrightarrow W^{\pm}(Z)N_1$, $\eta \rightarrow N_1 l$).

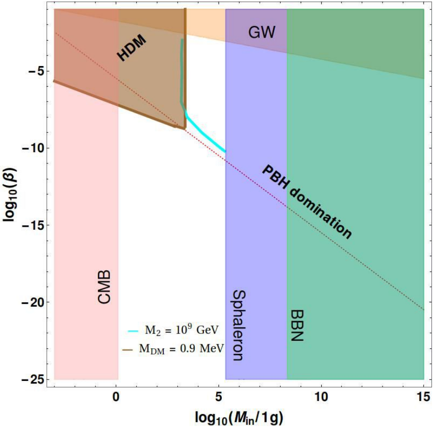


N_1 leptogenesis and scalar DM



N_2 leptogenesis and fermion DM





Conclusion

- We have studied leptogenesis and DM in a common setup (Scotogenic Model), in the presence of PBH.
- PBH lead to non-thermal source of leptogenesis as well as dilution of asymmetry.
- For N_1 leptogenesis and scalar DM, no region of PBH parameters can simultaneously affect both.
- N_2 leptogenesis and fermion DM : cogenesis possible with PBH dependency.
- Light DM constrained from mixed DM astrophysical bounds.
- Observational consequences like gravitational waves in future experiments.


Thank you!

- CP asymmetry functions :

$$F(r_{ji},\eta_i) = \sqrt{r_{ji}}\left[f(r_{ji},\eta_i) - \frac{\sqrt{r_{ji}}}{r_{ji}-1}(1-\eta_i)^2\right],$$

$$f(r_{ji},\eta_i) = \sqrt{r_{ji}}\left[1 + \frac{(1-2\eta_i+r_{ji})}{(1-\eta_i^2)^2}\ln(\frac{r_{ji}-\eta_i^2}{1-2\eta_i+r_{ji}})\right].$$

- CP asymmetry functions :

$$F(r_{ji},\eta_i) = \sqrt{r_{ji}}\left[f(r_{ji},\eta_i) - \frac{\sqrt{r_{ji}}}{r_{ji}-1}(1-\eta_i)^2\right],$$
$$f(r_{ji},\eta_i) = \sqrt{r_{ji}}\left[1 + \frac{(1-2\eta_i+r_{ji})}{(1-\eta_i^2)^2}\ln\left(\frac{r_{ji}-\eta_i^2}{1-2\eta_i+r_{ji}}\right)\right].$$

- Washout parameters :

$$W_{\mathrm{ID}} = \frac{1}{4}\Gamma^T_{N_1}K_2(z)z^2,$$
$$\Delta W = \frac{36\sqrt{5}M_P M_1 m^{\bar{2}}_{\xi} H}{2\sqrt{\pi}\sqrt{g_*}v^4 z\lambda_5^2}.$$

- Boltzmann equations (WIMP) :

$$k\frac{d\ Y_{\rm DM}}{dz} = -\frac{<\sigma v> s}{Hz}\left(Y_{\rm DM}^2 - Y_{\rm eq}^2\right).$$

- Boltzmann equations (FIMP) :

$$\frac{dY_\eta}{dz} = -\frac{4\pi^2}{45}\frac{M_{\rm Pl} m_\eta}{1.66}\frac{\sqrt{g_*(z)}}{z^2}\left[\sum_{p\equiv{\rm SM\ particles}}\langle\sigma v\rangle_{\eta\eta\to pp}\left(Y_\eta^2 - (Y_\eta^{\rm eq})^2\right)\right]$$

$$-\frac{M_{\rm Pl}}{1.66}\frac{z}{m_\eta^2}\frac{\sqrt{g_*(z)}}{g_s(z)}\Gamma_{\eta\to N_1 l}Y_\eta$$

$$\frac{dY_{N_1}}{dz} = \frac{M_{\rm Pl}}{1.66}\frac{z}{m_\eta^2}\frac{\sqrt{g_*(z)}}{g_s(z)}\Gamma_{\eta\to N_1 l}Y_\eta$$

$$+\frac{4\pi^2}{45}\frac{M_{\rm Pl} M_\eta}{1.66}\frac{\sqrt{g_\star(z)}}{z^2}\times\left(\sum_{x=W^\pm,Z,\eta}\langle\sigma {\rm v}_{lx\to N_1 x}\rangle\left(Y_x^{eq}Y_l^{eq} - Y_{N_1}Y_x\right)\right)$$

PBH evaporate after leptogenesis scale (N_2 leptogenesis) :